ADDITIVE MANUFACTURING FOR SUPERALLOYS – PRODUCIBILITY AND COST

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Abstract

Multiple additive manufacture technologies were evaluated for applicability to gas turbine engine components. Generic features were designed to be used in the program that represented typical cost disproportionate geometries found on large static components. Deposits of similar size and shape were created utilizing Laser Powder, Electron Beam, and Shaped Metal Deposition on both flat and curved panels. Bulk deposits of Alloy 718 using the various deposition processes were made for mechanical property testing. Full scale and subscale sample cases were then created to demonstrate these features on slim ring substrates (e.g. 0.5" thick). All hardware was subsequently machined to verify that the depositors were capable of producing features to a desired dimension, non-destructively evaluated (i.e. FPI, ultrasonic, and radiographic inspections), and destructively evaluated to confirm that all processes were still capable of producing high quality deposits. Finally, an Alloy 718 sample case was fabricated which was an exaggerated representation of actual parts and was intended to demonstrate the full process potential of Additive Manufacturing. In addition to the deposition tasks; a cost analysis was also performed which evaluated various aspects of the value stream that were affected by the use of additive manufacturing. Appropriate cost models were subsequently created for the various processes using notional and actual hardware.

Introduction

The primary goal of this effort was to achieve cost and lead-time reductions of up to 50% for high-temperature static engine components such as diffuser and turbine cases. Such components are used in virtually all aerospace gas turbine engines with the majority of these components fabricated from Alloy 718. These components are made from either forgings or castings. Each of these material forms presents some common and unique issues that result in these parts being some of the most expensive found in typical turbine engines. This effort addresses these cost-driving issues through the development and application of additive manufacturing techniques, resulting in a methodology that can be used to determine the most cost-effective way to fabricate the target structures based on overall part and feature specific geometries. The developed additive technologies can also be utilized in other areas, such as repair, for additional benefits.

This effort examines the feasibility of adding features that disproportionately increase the cost of superalloy components onto simple to produce, high yield backbone shells. The features in question (bosses, instrumentation ports, etc.) such as that shown in Figure 1, result in a disproportionate cost due to poor utilization of input material, high cost of quality, and other

associated drivers. In establishing optimum processes for manufacturing, a methodology by which various factors relating to total fabrication costs, for example deposition, backbone, and machining costs, are also critical. The processes evaluated in this study were (1) Shaped Metal Deposition (SMD, 3D Weld Deposition), (2) Laser Powder Deposition (LPD), and (3) Electron Beam Wire Deposition (EBWD). These processes, while in various states of technology readiness, were fairly well understood such that there was a solid basis for examining their feasibility in performing bulk deposition on superalloys. The key technical and economic characteristics of additive processes investigated include: deposition and metallurgical characteristics, preliminary mechanical properties, and cost modeling and integration into manufacturing assessment.
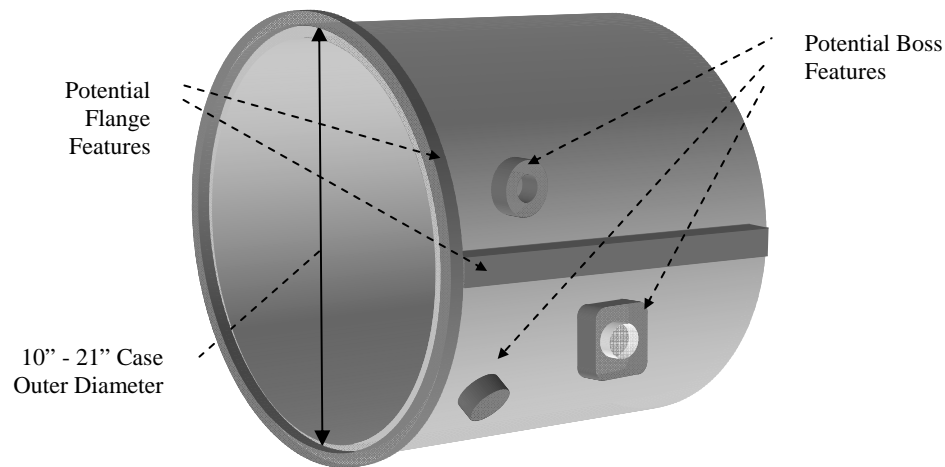

Figure 1: Typical representative hardware.

Experimental Procedures

Feature Depositions and Inspection

Based on current case designs, features that would be candidates for additive manufacturing were identified. Using this information, a set of generic deposition geometries was developed for study. These geometries shown in Figure 2, represented a rectangular pad, flange/stiffening ring, and an annular boss. Deposition was performed by each of the 3 identified processes SMD, LPD and EBWD. Deposits were made using typical 718 composition input materials and were evaluated for mechanical performance, quality, and repeatability for manufacture of the components of interest.

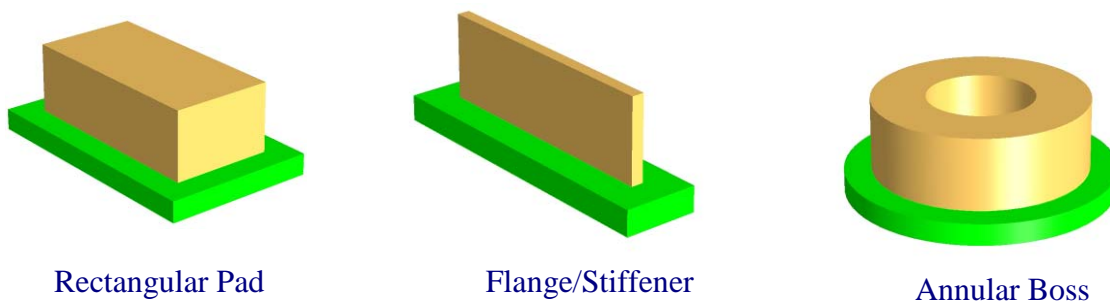Rectangular Pad   Flange/Stiffener   Annular Boss

Figure 2: Feature Deposition Geometries

Deposition of Representative Hardware

Hardware representative all three engine company components of interest were fabricated at sub scale or full scale including demonstration articles and a prototype. The dimensions of the features were generic in nature but within the range of what would be found in typical gas turbine hardware.

Results

Feature Making Capability Depositions and Inspection

Laser Powder Deposition (LPD)
Laser powder deposition was performed by GE. The low heat input and high solidification rate characteristic of the LPD process typically resulted in low distortion, a small heat affected zone (HAZ), and minimal substrate dilution. The feature geometries (rectangular, annular, and flange) were created on flat and curved substrates. All deposits were subjected to visual, radiographic, and ultrasonic inspections. No non-conforming indications were seen under radiographic inspection. Using ultrasonic inspection, some isolated pores were observed, but were at a size and configuration considered acceptable. Metallography of the deposits was also performed and samples of the deposited material and microstructures are shown in Figure 3.
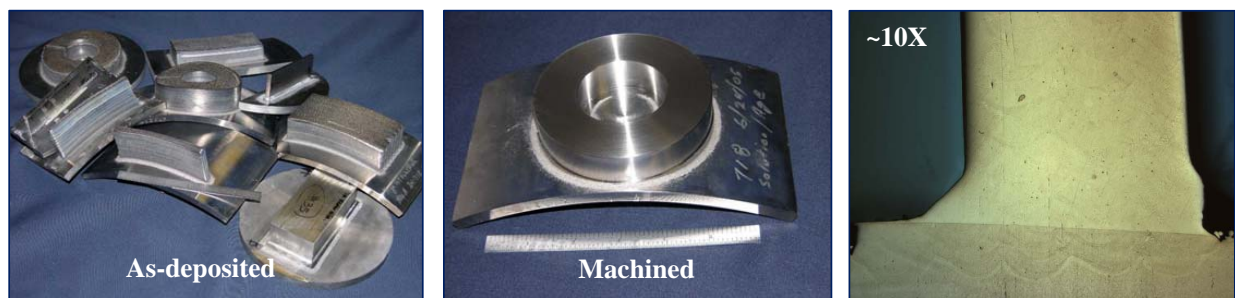

Figure 3: Typical laser powder depositions

Electron Beam Wire Deposition (EBWD)
Electron beam wire feed depositions were performed by Pratt & Whitney at Acceleron (East Granby, CT). Under visual inspection, surface cracks were observed on three of the deposits, which were associated with stress concentrations at the cusps of the substrate/deposit interfaces. All cracks, however, were outside of the intended final dimension envelope and would be removed during subsequent machining. Radiographic inspection also revealed fine random internal micro porosity in some of the deposited samples. As with the LPD material, ultrasonic inspection showed isolated pores on some specimens, but all were considered acceptable. Examples of the micro defects are shown in Figure 4.

Figure 4: Typical electron beam weld depositions

Shaped Metal Deposition (SMD)

Shaped Metal Deposition was performed by Rolls-Royce. A surface examination revealed some surface cracks and porosity, but all cracks were shown to be outside of the machining envelope and would thus be removed. Under ultrasonic examination, some rejectable voids were found in the rectangular and annular specimens. The cause was attributed to processes/equipment issues and was subsequently rectified. Metallographic examination exhibited acceptable microstructure as shown in Figure 5.
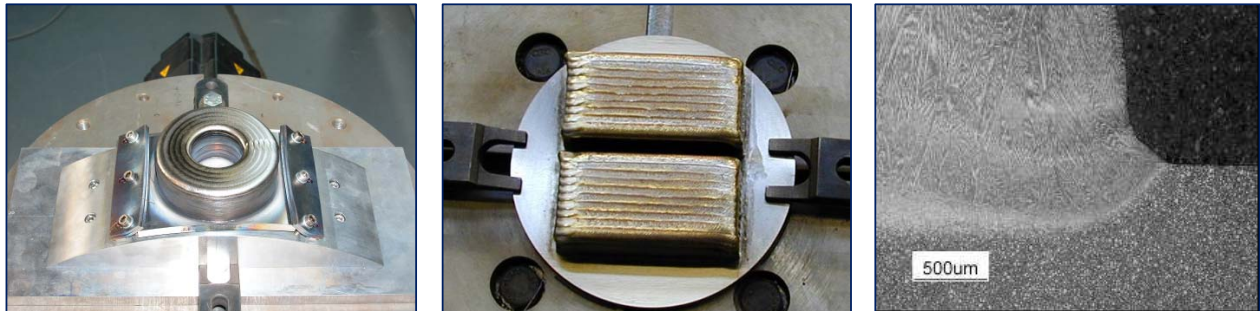

Figure 5: Typical shaped metal depositions

Mechanical Property Characterization

A typical alloy 718 solution and age heat treatment (1750° F, 1hr, air cool; 1325° F, 8 hrs, cool to 1150° F, 8 hrs, air cool) was given to all deposited material prior to testing. Samples were evaluated for tensile, creep/rupture and low cycle fatigue performance and compared, to cast minimum properties derived from literature and industry specifications for tensile (Table 1) [1,2]. Conditions used for stress rupture testing were 1000° F and 125ksi and creep testing was 1200° F and 75 ksi. These test conditions were chosen by Rolls-Royce in order to achieve stress rupture at 1000°F in 100-200 hours, and 0.2% creep at 1200°F in 100-200 hours.

Table 1: Typical Cast 718 Tensile Specification Minimums

Test Temperature (°F)	UTS (ksi)	YS (ksi)	% elongation	%RA
Room Temp.	120	105	3	8
1000°F	108	95	3	8
1200°F	96	84	3	8

Testing of additional baseline cast 718 material was performed for use in comparisons of low cycle fatigue performance. LCF testing of deposits was performed and was compared to this cast baseline material that was homogenized at 2000° F, then subjected to the same solution and age heat treatment and testing parameters as the deposits. All LCF testing was strain controlled at 1000°F, A = 1.0, and Strain = 0.4%. A strain range of 0.4% was selected for evaluation and the resulting baseline average number of cycles to failure was determined to be 62K cycles.

Deposits were made from each of the three deposition processes for mechanical property evaluation such that samples could be extracted to test the bulk deposit properties in the X, Y, and Z directions as well as the deposit-to-base-metal interface (Z direction).

Laser Powder Deposition (LPD)
Deposits were made using plasma rotating electrode powder (PREP). Tensile testing was performed and the results showed that the LPD material surpassed the typical cast minimum tensile properties.   Creep (1200°F) and stress rupture (1000°F) results also exceeded cast minimum properties as shown in Figure 6. LCF testing results are shown in Figure 7 and the results for X, Y, and Z directions exceeded the baseline cast 718 average life of 62k cycles under the conditions tested. X and Y directions show equivalent LCF lives, while the z-direction LCF life was higher, due to material anisotropy resulting in lower effective load stress. Initial testing of interface LCF lives did not meet the baseline life; however, examination of the fracture surfaces revealed that all specimens from the deposition trial used to make interface samples showed lack-of-fusion (LOF) defects. All other mechanical test plates were acceptable and contained no evidence of LOF defects. The occasional appearance of LOF was subsequently addressed using deposition parameter control and refinement.   This validated the need for process control for validation of production repeatability. Subsequent testing of a replacement block of deposited material resulted in LCF performance similar to other bulk deposit orientations evaluated in this study.
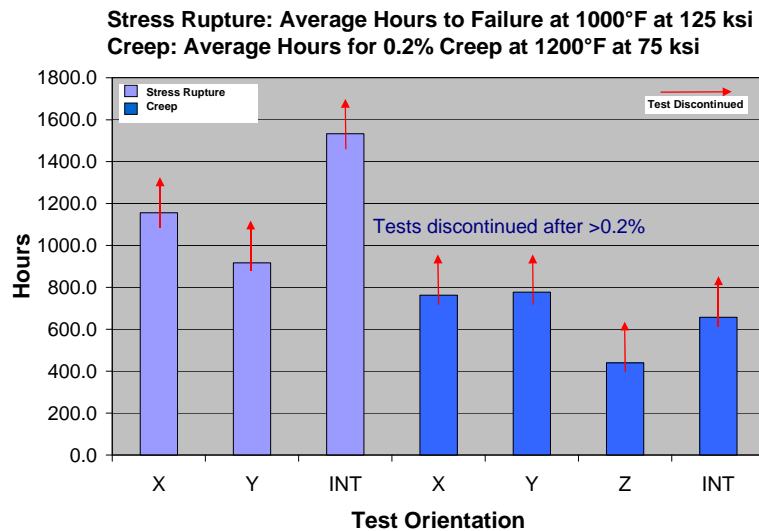
Stress Rupture: Average Hours to Failure at 1000°F at 125 ksi
Creep: Average Hours for 0.2% Creep at 1200°F at 75 ksi

Figure 6: LPD Creep and Stress Rupture Test Results
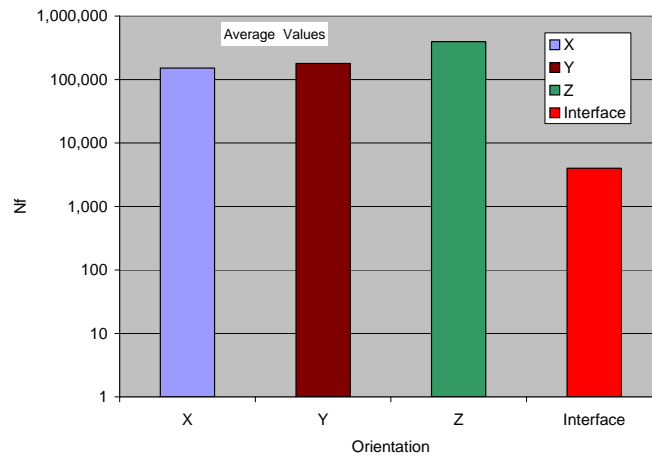

Figure 7: LPD LCF Results Strain Controlled LCF at 1000°F, A=1.0 Strain=0.4%

Electron Beam Wire Deposition (EBWD)

Tensile properties for EBWD material were well above the required cast minimums for all temperatures and directions tested. Values were very close and sometimes exceeded the wrought minimums. Additionally in contrast to the LPD material, EBWD z-direction strength is comparable to the x and y direction values. Due to time, material, and budget restrictions resulting from contaminated wire, not all directions were tested at all temperatures. Stress rupture and creep results are shown on Figures 8 and 9, respectively. Creep testing was performed until 0.2% creep was achieved. Stress rupture testing was discontinued after specimens had accumulated 500 total hours of test time. All specimens reached this 500 hour cut-off (no failures). As seen in the figures, EBWD specimens exceeded cast property minimums for both stress rupture and creep for all directions tested. Average LCF results are shown on Figure 10. Performance exceeded the cast 718 baseline for all directions tested. All EBWD LCF specimens were tested to a minimum of 100,000 cycles, with no failures observed.
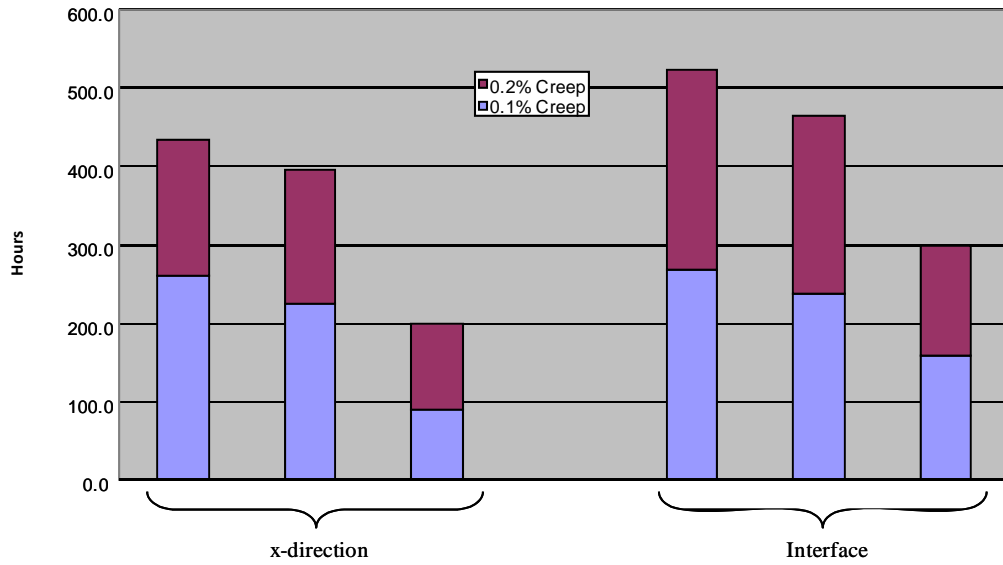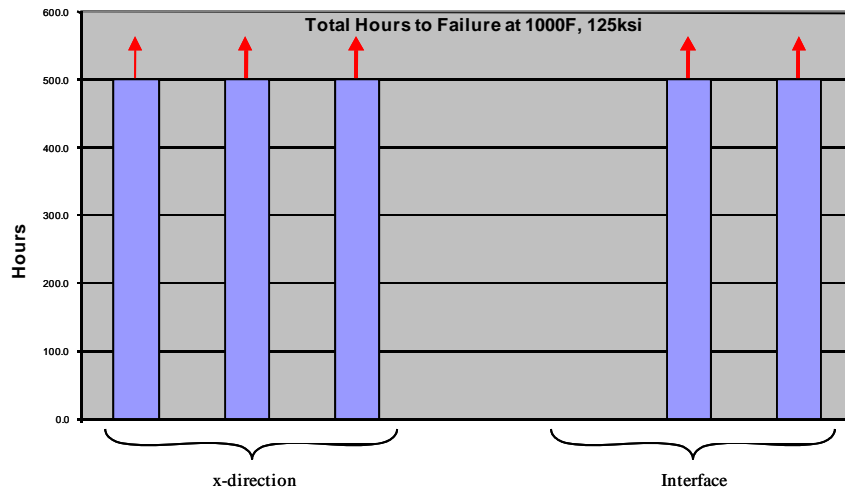
Figure 8: EBWD Creep Results
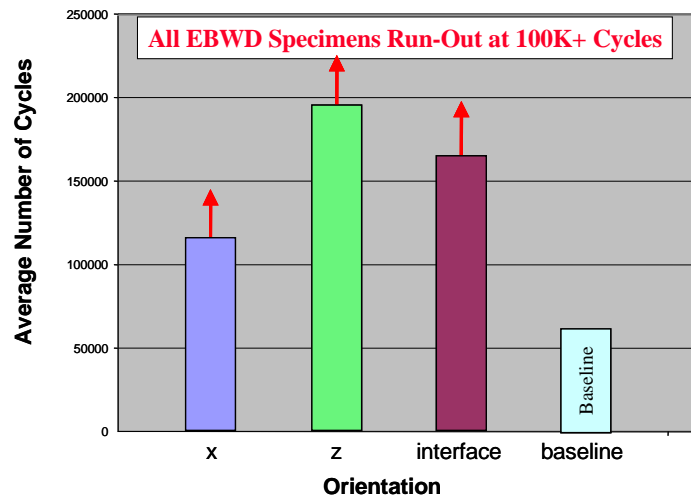

Figure 9: EBWD Stress Rupture Results

Figure 10: EBWD LCF Results

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Shape Metal Deposition (SMD)

Initial parameter development was carried out on development-scale equipment. In order to produce sufficient material for evaluation, parameters and programming techniques were transferred to a manufacturing cell to perform deposition under more standard production conditions using newer welding-industry standard equipment and a more robust atmospheric chamber with a greater working volume. Deposits performed in the manufacturing cell exhibited quality issues which were determined to be the result of differences between the optimized development scale arrangement and the larger scale, newly commissioned manufacturing cell. These differences included substrate clamping, in-process vision, and wire feed guide alignment. As a result, it was felt that the larger scale deposits were not optimized for quality. Leaks within the system and operator inexperience also contributed to the inferior quality of the mechanical test evaluation deposits. Despite the quality issues, the majority of tensile, creep and stress rupture samples met the established requirements. LCF testing however was not performed on the SMD material because of the deposit quality concerns. No further evaluation was made in this study using the SMD process.

## Deposition of Representative Hardware

Hardware deposition was performed using a conventionally produced wrought ring in which no features or overstock for feature machining was present. The thickness of all starting slim, strong-back cases was approximately 0.5" with diameters ranging from 10" to 21" and heights ranging from 3" to 6" (see Figures 11 - 13). Companion separate metallurgical samples and mechanical test samples were also deposited for evaluation except in the case of LPD where sufficient deposit material was added to the ring for extraction of samples directly.

Evaluation of the LPD sample case showed negligible heat discoloration and minimal distortion after all heat treat (see Figure 14). Metallographic sections taken from the bulk deposit and interface showed microstructural quality equivalent to the deposits used for mechanical testing; there were no significant defects detected (see Figure 15). The EBWD samples from Pratt & Whitney did exhibit a noticeable heat discoloration but the resultant distortion was minimal (see Figures 12 and 16). Rolls-Royce deposited their EBWD features on three different sample cases that were used to verify non-destructive and metallographic quality, machining, and distortion. All Pratt &Whitney and Rolls-Royce EBWD deposits exhibited microstructural quality equivalent to the deposits that were created for EBWD mechanical testing (see Figures 17 & 18). Deposits also showed minimal NDE defects, and met the intended dimensions for all features (see Figures 19 – 23).
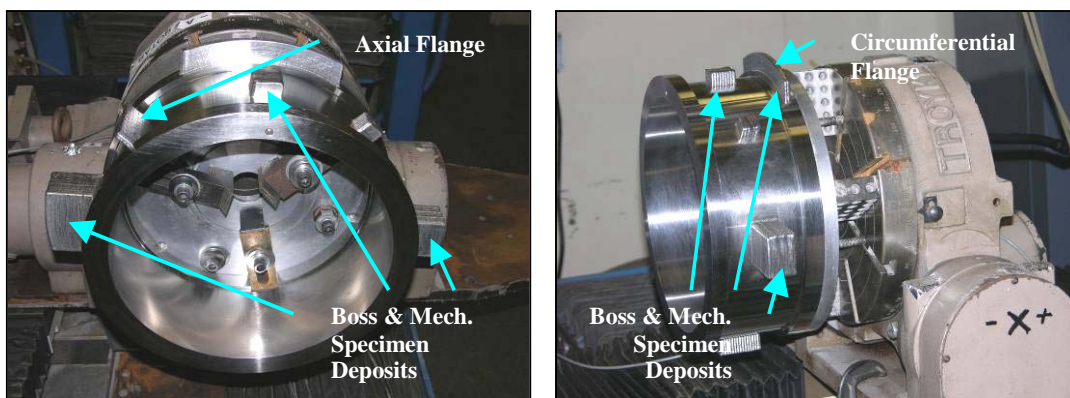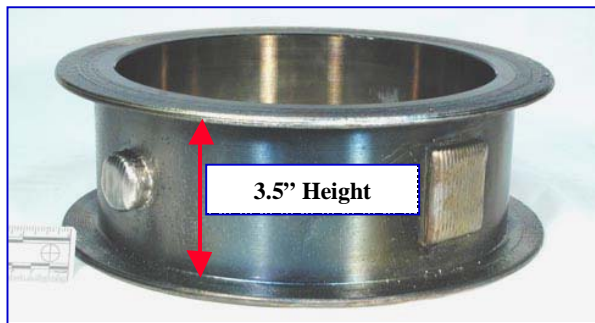

Figure 11: Photograph of LPD deposited features on representative case strong-back
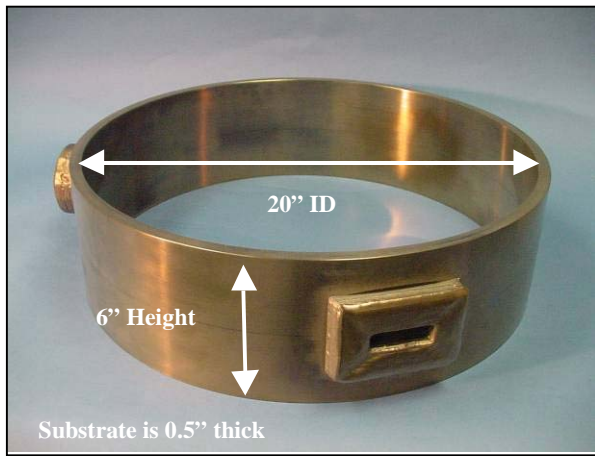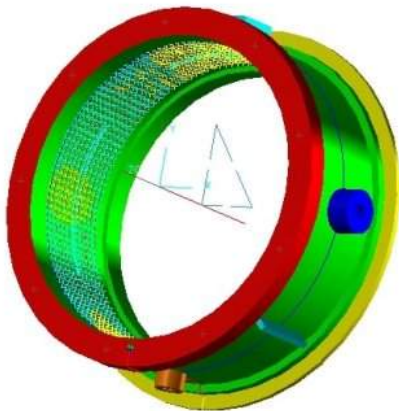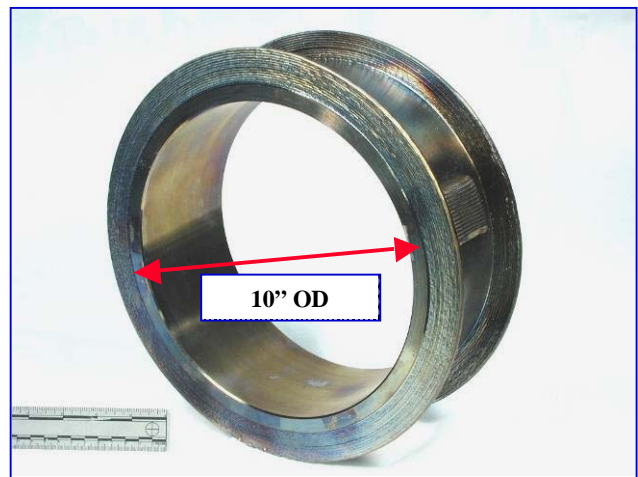
Figure 12: Images of Pratt & Whitney case that was fabricated from two 3" tall AMS 5662 rings EB welded together and machined to the nominal wall thickness of 0.5".


Figure 13: Representative photo of as deposited Rolls-Royce rings. Substrate was 0.5" thick Alloy 718 forged ring.


Figure 14: CMM inspection of LPD sample case before deposition, in as-deposited condition, and after post deposition HT

- CMM scans on the ID along the full length
- Max. localized distortion ~0.015" on radius (shrinkage) in as deposited condition and no change after post deposition HT
- Yellow points indicates distortion near deposits
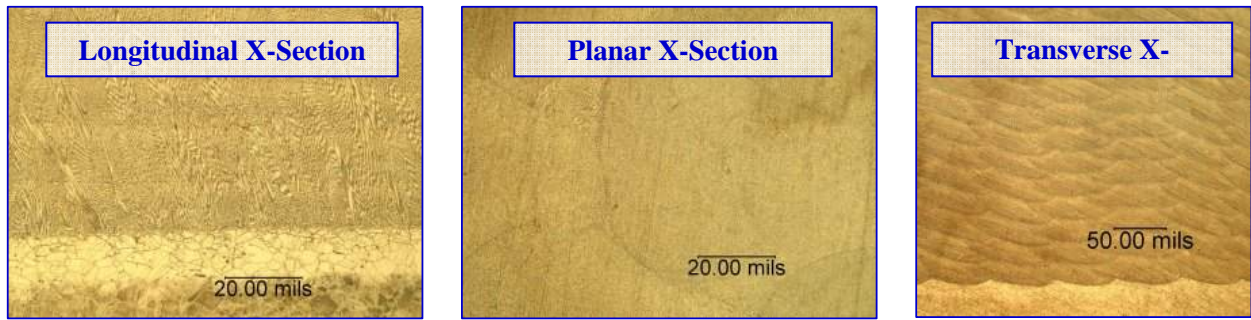
**Figure 15:** Representative micrographs of the GE LPD post heat treatment
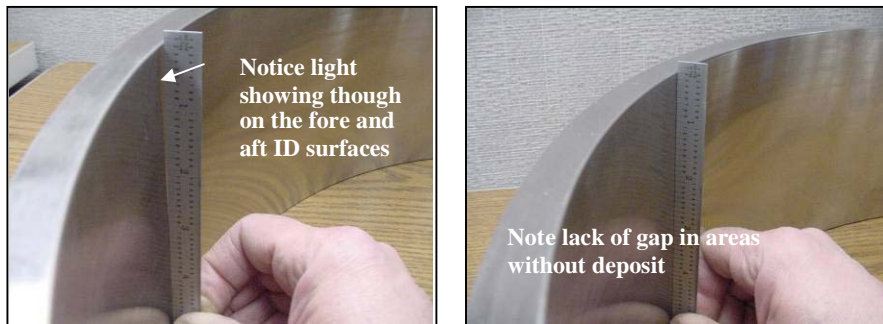
Figure 16: OD has increased 0.050" - 0.060" (0.025" - 0.030" radially) due to a slight cupping at each deposit. This created a concave profile facing radially outward.
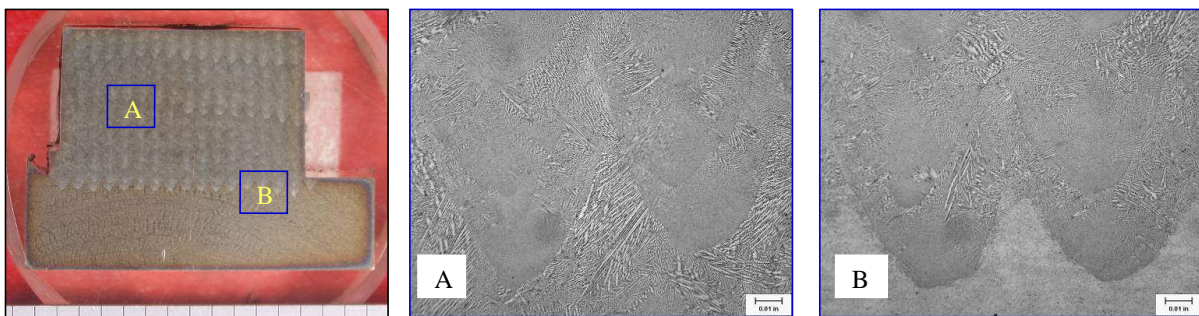

Samples exhibited and average weld penetration of ~0.100".

Figure 17: Representative images in the transverse orientation from the rectangular boss deposit. Note lack of significant defects (e.g. cracks, large pores).
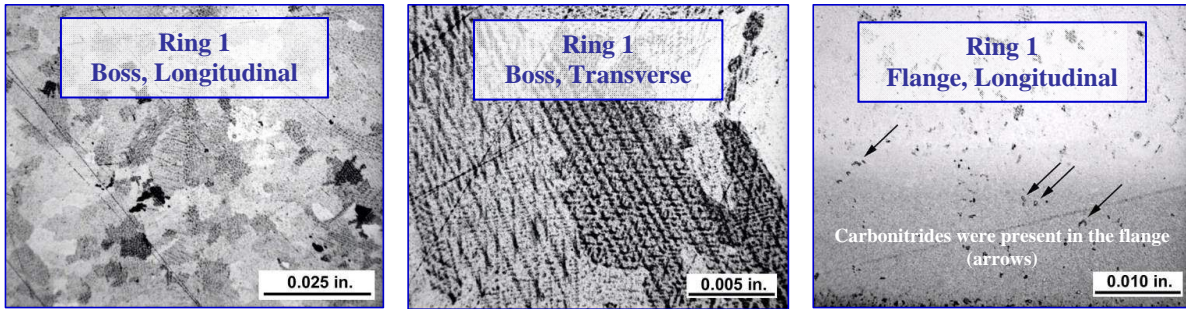
Figure 18: Rolls-Royce EBWD representative, post heat treat metallurgical examination images of the boss and flange deposits. Note lack of significant defects (e.g. cracks, large pores).
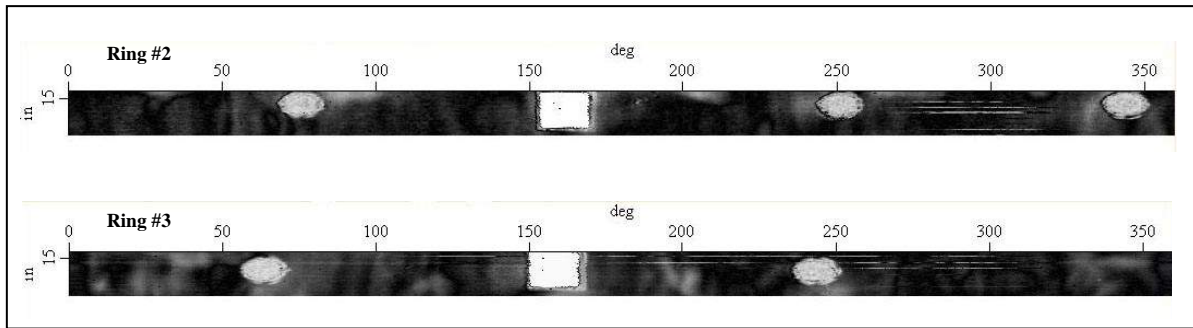
Figure 19: Image of the Rolls-Royce ultrasonic inspection, both rings passed inspection criteria for cast material
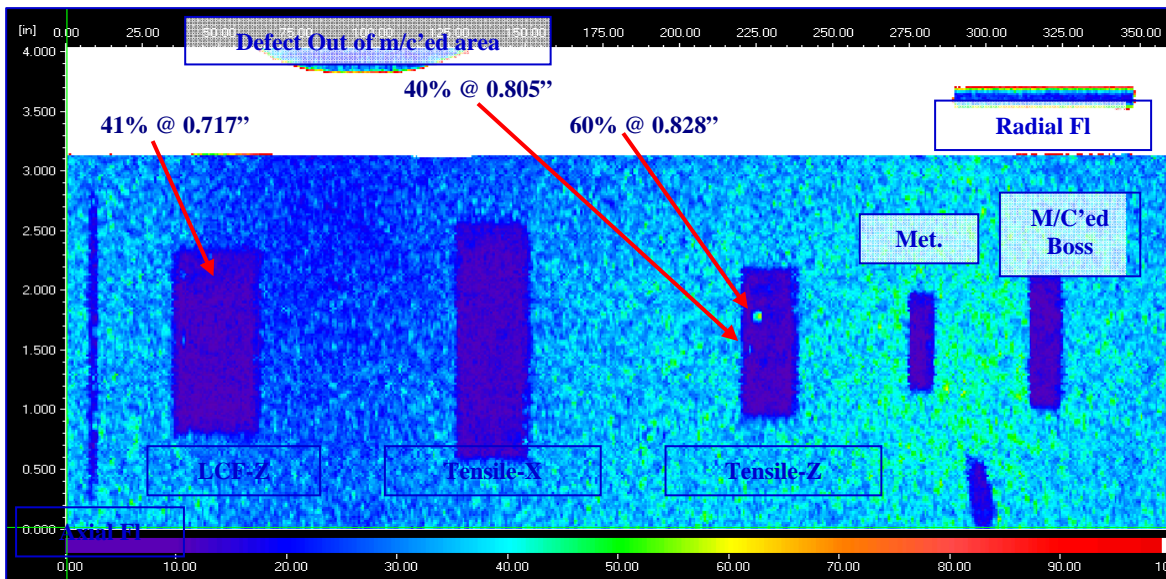
Figure 20: Image of GE ultrasonic inspection. Deposited material conformed to the acceptability criteria, indications and process interruptions were all outside of machined areas.

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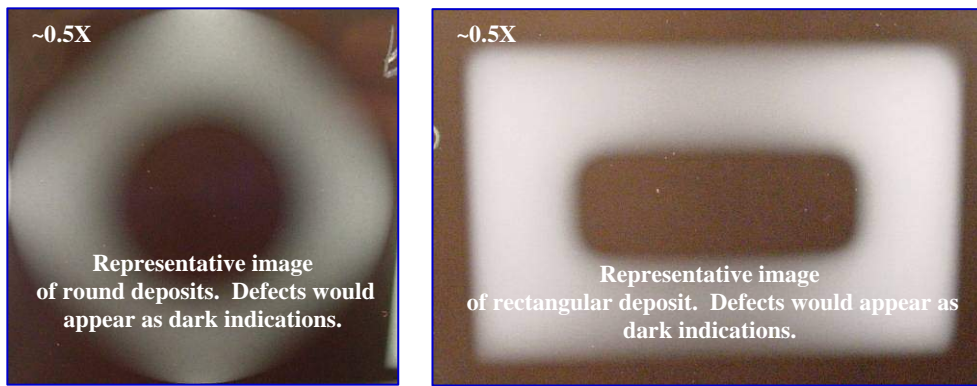
Figure 21: Radiographs taken with a 2-2T sensitivity did not show any defects.
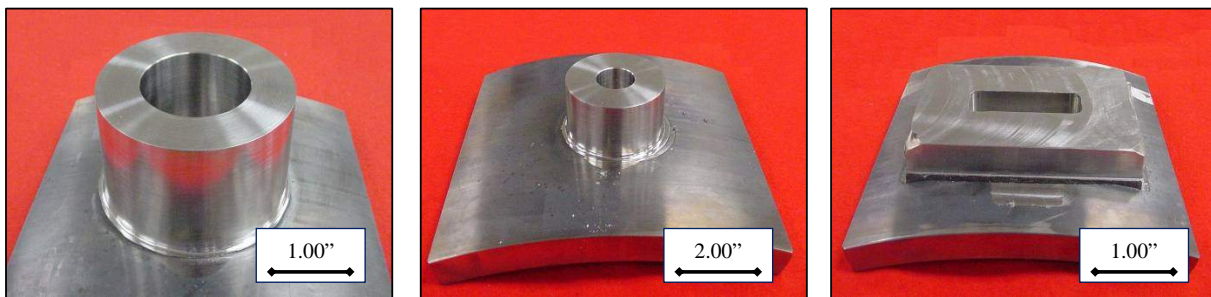
Figure 22: Images of Pratt & Whitney EBWD samples, all samples met the intended dimensions post machining

Skim-Cut
Round Boss

Skim-Cut
Flanges

Figure 23:
Photograph of EBWD deposited features on Rolls-Royce case section.

As Deposited
Rectangular
Boss

In addition to the demonstration articles, EBWD was used to fabricate a representative Alloy 718 prototype case with circumferential flanges and several boss features. The deposited features were generic in nature, while still being in the range typically used on actual case hardware. The Electron Beam Deposition process was selected because it was common to two of the three gas turbine engine manufacturers investigating this area.

The prototype feature geometries (see Table 2 and Figure 24) and relative orientation were established. A substrate ring was fabricated from Alloy 718 material. The substrate ring was machined to a 23" inner diameter, 3" height, and 0.5" thickness. The 0.5" dimension represents the minimum forged + pre-machined thickness anticipated for use in additive manufacturing. This thickness will support minimal HAZ penetration into the pressure vessel wall and potential distortion from the deposition process.

| Table 2: Prototype Deposition Plan and Target Dimensions						
Feature Type	Quantity	Diameter (OD)	Length	Width	Thickness/ Height	Hole Dimension (Diameter/Length)
Circular Integrated Boss	2	1.75"	N/A	N/A	1.75"	0.75"
Square Integrated Boss	2	N/A	1.75"	1.75"	1.75"	0.75"
Circular Boss	8	1.0"	N/A	N/A	1.25"	N/A
Square Boss	8	N/A	1.0"	1.0"	1.25"	N/A
Circumferential Flange	2	N/A	N/A	0.375"	0.75"	N/A

Recognizing that the prototype layout was aggressive with respect to the quantity and location density (i.e. relative proximity around the circumference) of the features, it was necessary to plan the deposition sequence to account for potential accessibility and distortion issues. Initially the sixteen smaller bosses were deposited. This was followed by the stand alone circumferential flange and the integrated medium bosses/flange. Once the deposition was underway, it became apparent that the feature location density was resulting in vapor deposition on the adjacent substrate surfaces. The EBWD process inherently vaporizes a portion of the weld wire during deposition. Typically this is accounted for by burning a dry layer (i.e. electron beam without filler) at the onset of each feature deposition. Additionally when the chamber was pumped down between feature groupings, adjacent substrate surfaces were cleaned with abrasive media (e.g. silicon carbide wheel) followed by a solvent wipe. Metallographic evaluation of the deposits performed in close proximity and quantity, as demonstrated in this prototype, would be required to determine if further cleaning is required.
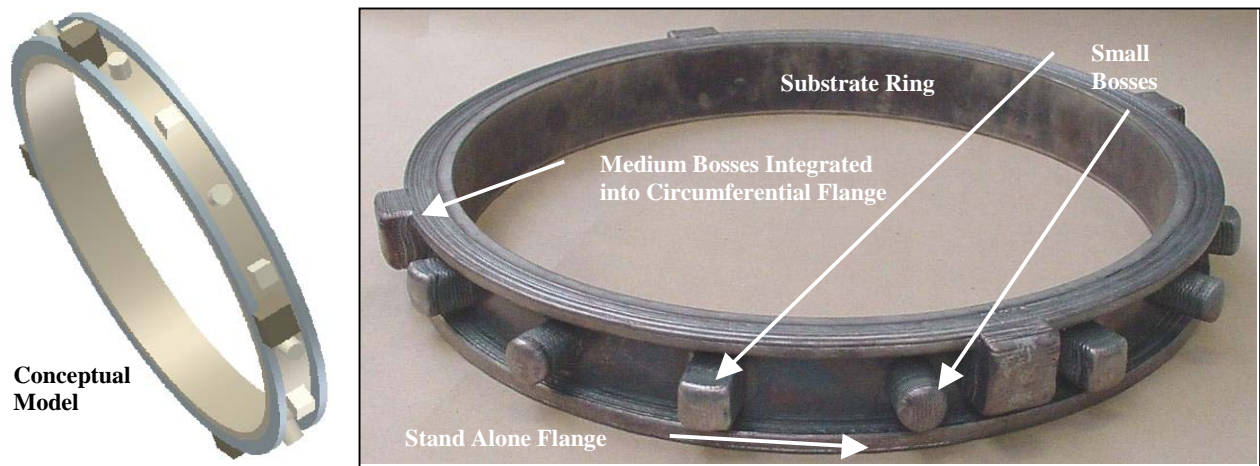
**Figure 24: Prototype Ring in the Post Deposition and Heat Treat Condition**

Post Deposition Processing and Non-Destructive Evaluations

Following all deposition activities, the prototype ring was solution heat treated to relieve solidification stresses and verify that the deposition sequence did not adversely affect the dimensional stability of the ring (see Figure 24). The ring was also partially machined to prepare it for ultrasonic inspection by Rolls-Royce. Specifically the forward and aft axial surfaces in addition to most radial surfaces were machined to a 32 Ra finish. This permitted access to all deposited features from both the ID and OD (see Figure 25).
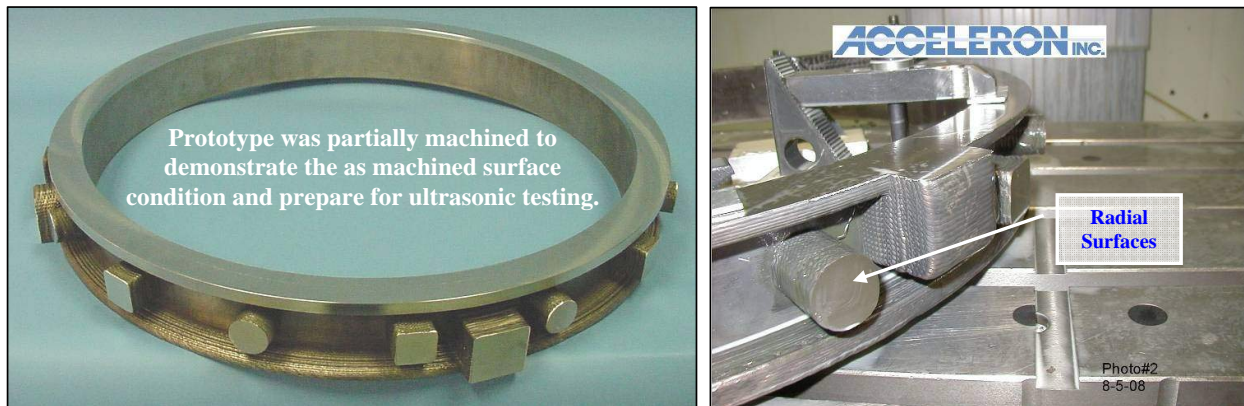
Figure 25: Post Deposition Machining

FPI did not reveal any indications on the finished machined surfaces while ultrasonic did reveal some isolated indications though the overall bulk continuity was acceptable. After all non destructive inspections were completed, a rough dimensional inspection was performed with a surface plate and manual gages to verify that the level of distortion was commiserate with what was observed in prior demonstration parts and that the intended feature dimensions were met. The post deposition distortion was similar to the levels seen in demonstration parts and all features were within the intended dimensions listed in Table 2 (see Figure 26).
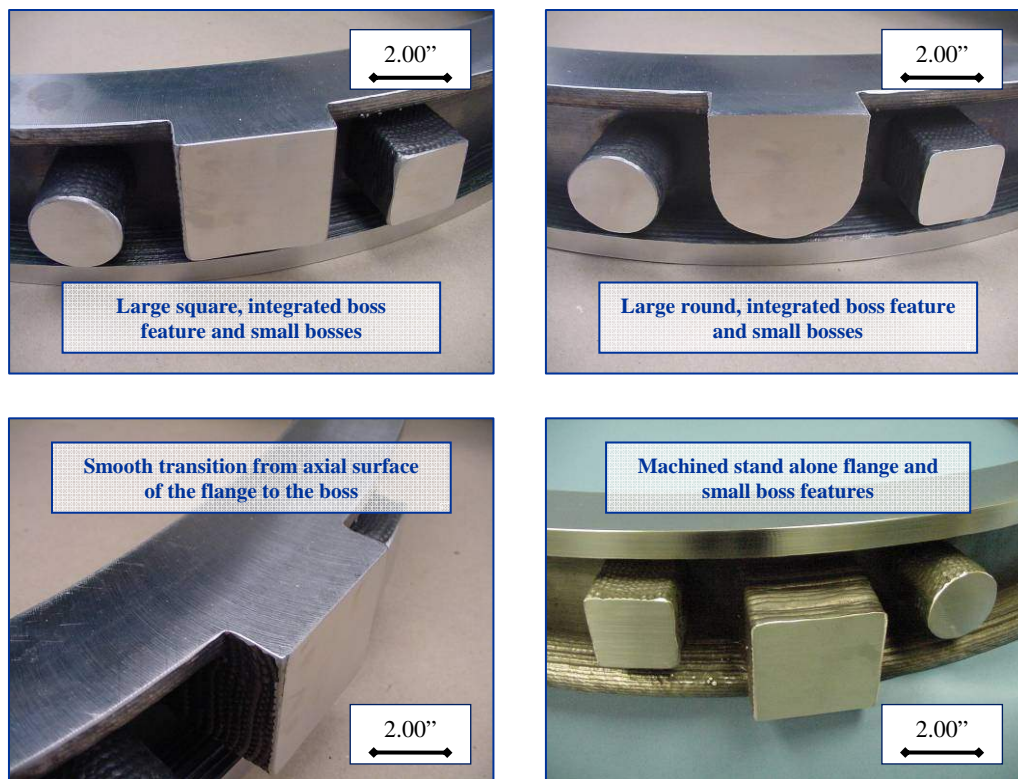
Figure 26: EBWD Prototype Case Dimensional Evaluation

Discussion

Results of this study identify the technical and configurational viability of several additive manufacturing processes for making components from alloy 718. In total, forty-three deposits were made in the three target geometries, and most specimens did not reveal any nonconformities using visual, radiographic, or ultrasonic inspections. Process capability was demonstrated for all three shapes. Additionally it was felt that process parameter refinement, including proper deposition path programming and time/temperature control, would produce totally defect-free deposits.

Mechanical evaluation of deposit samples demonstrated that LPD and EBWD depositions met or exceeded tensile, creep, rupture, and LCF property specification minimums of cast 718. Further testing of demonstration articles showed that the X and Z-direction tensile and the Z-direction LCF samples were within 10% of the results from demonstration samples.

Full scale (Pratt & Whitney) and subscale (GE & Rolls-Royce) sample cases were created to demonstrate deposition of features on slim ring substrates (e.g. 0.5" thick). All hardware was subsequently machined to desired dimensions, non-destructively and destructively evaluated confirming that all processes were capable of producing high quality depositions.

The full potential of the additive processes was demonstrated by creating a representative Alloy 718 case of 0.5" thickness with circumferential flanges and several boss features using the Electron Beam Deposition process. FPI evaluation did not reveal any indications on the finished machined surfaces while ultrasonic did reveal some isolated indications though the overall bulk

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continuity was acceptable. The defects that were observed were not completely unexpected because the prototype ring was intended to demonstrate the additive process potential rather than an actual part. Also the amount of deposited material nearly doubled the starting weight of the substrate ring in addition to the fact that 37% of the OD surface area contained deposited material. While the quantity of EBWD is excessive when compared to actual hardware, the results / observations support the need for a fully automated system to ensure process robustness when scaled up to a production level. After all non destructive inspections were completed, a rough dimensional inspection was performed with a surface plate and manual gages to verify that the level of distortion was commiserate with what was observed in demonstration depositions and that the intended feature dimensions were met.

A study was also conducted to examine the potential for cost savings using additive manufacturing for different part types. Estimations were done on actual hardware for multiple components. The results showed that a greater than 30% savings is estimated for complex wrought components. A specific analysis was also performed for a large structural casting. Previous value stream analysis of large structural castings showed that 20% of the cost was the result of rework. However, in general, net shape castings require minimal final machining and are highly cost effective. Therefore, additive manufacturing for the large structural casting presents minimal opportunity for cost savings. It is doubtful that additive manufacturing will totally eliminate the need for rework. If metal deposition could reduce rework by 50% to 60%, the total impact to the delivered casting cost would be ~ 10% or less. While there would be some savings on other aspects of the value streams, for example material savings and melt/pour costs, these savings would be offset by deposition costs. There are some instances where additive manufacturing for large structural castings may make sense. A business case could possibly be made for castings with chronic defects and high rework costs. These would have to be evaluated on a case-by-case basis. Also, highly complex castings that cross the capability limits of investment casting technology may benefit from additive manufacturing. Lastly, a performance and/or weight improvement could be realized by replacing a large structural casting with a forged rings plus feature addition.

From an implementation point of view, the primary aspect of any candidate hardware is the quantity and size of deposited features. Characteristics such as the physical size of the slim substrate shell will have less of an impact because deposition equipment could be procured to handle a wide size range of parts. For a 20 cases / month delivery schedule, production can begin with a "relatively" low capital investment that would be needed to fully automate existing equipment. For expanded capacity (e.g. 40 cases / month), additional units or higher capacity power supplies would be needed to allow for parallel processing of multiple parts or higher deposition rates on any given part. This higher capacity is estimated to require additional capital, facility, and personnel costs. Process and design engineers knowledgeable in deposition technology could further extrapolate these estimates to scale up (or down) the production volume as required to meet capacity and/or feature quantity needs. For the purposes of estimation, a notional case was designed to have roughly 20 lbs. of added features in the above analysis. This amount of additive Alloy 718 would yield approximately 67 cubic inches of material which could include various geometric combinations (e.g. 16 features at 2" width x 2" length x 1" height; 67 features at 1" width x 1" length x 1" height; or 11 features at 4" width x 3" length x 0.5" height).

In order to fully implement additive technologies into a design system, a process specification is typically required to provide manufactures with the necessary material performance standards. As part of the effort a draft AMS specification was created for Nickel Additive Deposition. To create this document, AMS 4999 (Titanium Alloy Laser Deposited Products 6Al - 4V Annealed) [3] and AMS 2680 (EB Welding for Fatigue Critical Applications) [4] were utilized as reference points. Additionally the draft specification was designed to be capability based so it would not be limited to any one current or future additive technology.

Conclusions

Additive manufacturing was demonstrated from feasibility through prototype production scale hardware. It was determined that:
1. Additive manufacturing technologies (LPD & EBWD) have proven to be capable of producing high quality features in aero-engine configurations.
2. The use of additive manufacturing can be an enabling technology to produce experimental/development or low volume hardware.
3. Additive manufacturing can be used as a weight saving enabler for cast structures by permitting the use of higher strength wrought substrates.
4. Additive manufacturing can be a highly effective cost saving technology (up to 50%) when implemented on high volume wrought structures with relatively few cost disproportionate features.

Acknowledgements

References

1. AMS 5383 "Nickel Alloy, Corrosion and Heat-Resistant, Investment Castings," SAE International, 2007.

2. Tensile cast minimums at 1000°F and 1200°F corresponded to 90% & 80% retention per MMPDS-01 (Jan 2003) Figure 6.3.5.1.1 using data from Reference 1. Elongation and RA were assumed to be equivalent to Room Temperature.

3. AMS 4999, "Titanium Alloy Laser Deposited Products 6Al - 4V Annealed," SAE International, 2002.

4. AMS 2680, "EB Welding for Fatigue Critical Applications," SAE International, 2001.