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ADDITIVE MANUFACTURING FOR SUPERALLOYS–PRODUCIBILITY AND COST VALIDATION (PREPRINT)

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14. ABSTRACT
The primary goal of this project, Additive Manufacturing for Superalloys – Producibility and Cost Evaluation, is to achieve cost and lead-time reductions of up to 50% for high-temperature static turbine 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 the engine. This program addresses these cost-driving issues through the development and implementation 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 implemented into other areas, such as repair, for additional benefits.

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Additive Manufacturing for Superalloys – Producibility and Cost Validation

A Cooperative Technology Program of the Metals Affordability Initiative (MAI) with USAF-AFRL

Submitted by: Andrew Debiccari (Pratt & Whitney), Benjamin Lagow (Rolls Royce),
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The primary goal of this project, *Additive Manufacturing for Superalloys – Producibility and Cost Evaluation*, is to achieve cost and lead-time reductions of up to 50% for high-temperature static turbine 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 the engine. This program addresses these cost-driving issues through the development and implementation 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 implemented into other areas, such as repair, for additional benefits

This program aims to demonstrate 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.) result in a disproportionate cost due to poor utilization of input material, high cost of quality, and other associated drivers. This program also plans to develop a methodology by which various factors relating to total fabrication costs, for example deposition, backbone, and machining costs, will be integrated into a single model. The combination of a technical effort to prove the feasibility and utility of additive manufacturing processes and an economic study aimed at quantifying and integrating the cost drivers of these related manufacturing processes intends to provide the tools required to achieve the stated goals of up to a 50% reduction in both final part cost and lead time. There are many options currently available for additive manufacturing. Based on past experience and technology maturity level, the processes evaluated in this study were:

- *Shaped Metal Deposition (SMD, 3D Weld Deposition)*
- *Laser Powder Deposition (LPD)*
- *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. In addition to the technical aspects associated with depositing material; cost models were developed and periodically refined to compare the deposition costs associated with the different processes and to estimate the potential cost savings from fabricating large static structures using additive manufacturing. To achieve the stated goals of this program, the determination of key technical and economic characteristics of additive processes, along with the impact of these processes on other aspects of the supply chain is required. These key characteristics include:

- *Deposition capabilities and resulting metallurgical characteristics of additive processes*
- *Preliminary mechanical properties of deposits including tensile strength, low cycle fatigue (LCF), stress rupture, and creep of both deposits and interfaces.*
- *Development of cost models for individual additive processes and related supply chain activities such as backbone fabrication and subsequent machining.*
- *Integration of individual cost models into a comprehensive tool to determine the optimal manufacturing method.*
- *Potential component weight savings which may influence the overall engine cost. If the current product is a cast structure, the use of a wrought material strong-back would permit the use of a thinner, lighter part.*

In addition to the goals stated above, which relate to the fabrication of static structures, additional pervasive goals of this program include:

- *Development of cost modeling and integration methodology that can be extended to other part families and/or allow for the incorporation of new additive processes as they are developed*
- *Extension of the additive process capabilities developed as part of this study to other areas such as repair and rapid prototyping in support of engine development programs*

Program Summary

A contractor team comprised of Pratt & Whitney, GE Aviation, Rolls Royce, Ladish, Lockheed Martin, Acceleron, ARGO, and NASA-Langley (the last three as subcontractors) has demonstrated that additive manufacturing can be a cost-effective way to fabricate static structural components from superalloys, with cost reductions of up to 50% over current practices. The overall program was divided into five tasks designed to carry out the program in a gated approach that gave the MAI Technical Oversight Committee visibility to the program accomplishments at the end of each task. This manuscript will focus on the activities performed on Alloy 718 by aero-engine team members: GE Aviation, Pratt & Whitney, and Rolls Royce.

Task 1 – Concept Identification:

The project team defined the needs and concepts for achieving the stated cost and lead-time reduction goals.

Task 2 – Feasibility Investigation:

The team defined generic features 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. Initially Alloy 718 and Waspaloy were evaluated but a comparison of the metallurgical quality and an assessment of the global business case determined that Alloy 718 should be the primary focus.

Task 3 – Technical and Business Evaluation:

Bulk deposits of Alloy 718 using the various deposition processes from Task 2 were made for mechanical property testing. Given that three processes were being evaluated, and testing was done at multiple locations and in multiple directions though a complete characterization could not be performed within the program's timeframe and budget.

In the original proposal, an evaluation comparing the deposition precision versus speed of deposition was also included. However, during the execution of Task 2, it was determined that deposition speed had a relatively marginal impact on the overall cost savings. Other aspects of the value stream that were affected by the use of additive manufacturing (e.g. backbone fabrication) were also evaluated and appropriate cost models developed. These models were then integrated into a single model to determine the most cost effective way to make components.

Task 4 – Testing and Validation:

The engine OEMs selected parts that would serve as the model for creating depositions representative of actual features. Full scale (P&W) and subscale (GE & RR) sample cases were 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. In addition to the deposition tasks; a limited amount of mechanical property testing was completed to verify continued deposition quality, cost models were updated, and cost analyses were performed on actual parts to confirm previous conclusions about the cost savings using additive technologies.

Task 5 – Production Implementation Planning:

This task fabricated a fully representative Alloy 718 sample case. The sample case was an exaggerated representation of actual parts and was intended to demonstrate the full process potential of Additive Manufacturing. In addition, this task also planned the basic logistics and financial requirements needed to incorporate additive manufacturing into the OEM design system.

Task Level Discussion

Task 2: Feasibility Investigation

The primary efforts for Task 2 included developing acceptance criteria for additive deposits, preparing substrates for sample deposits, defining the various deposition shapes, making and evaluating said deposits utilizing the additive methods under investigation, and developing models to assess deposition costs and cost saving potential. The goals for Task 2 are show in Table 1.

Table 1: Task 2	
1.	Generic geometries that capture the range features to be added will be defined
2.	Ability of additive methods under investigation to make deposits of required size and shape on both flat and curved surfaces using both Alloy 718 and Waspaloy will be assessed.
3.	Metallurgical quality of Alloy 718 and Waspaloy deposits assessed
4.	Material down selection will be made
5.	Preliminary cost assessment completed
6.	Any process that cannot show technical and financial viability with the selected material will be eliminated from further investigation

Note evaluations on Waspaloy material are not discussed in this manuscript.

Prior to making any deposits, it was necessary to establish a set of acceptance criteria for the depositions. This was required to provide an objective measure by which to judge process capabilities in order to determine technical feasibility and down select processes that met the technical requirements. Rolls Royce proposed criteria based on previous work with their Shaped Metal Deposition (SMD) process. Iterations on these criteria, with input from all OEMs, resulted in a finalized set of acceptance criteria that was used for Task 2 evaluation purposes (see Table 2). It was understood that acceptance criteria for additive features on actual components would be dependent on the specific stresses, temperature levels, engine operating conditions, and company specific material property data and lifing methodologies.

Based on current case designs, features that would be candidates for additive manufacturing were identified by the Aero OEM team members. Using this information, a set of generic deposition geometries were developed for the Task 2 feasibility study. These geometries and dimensions represented a rectangular pad, a flange/stiffening ring, and an annular boss (see Figure 1).

Figure 1: Task 2 Deposition Geometries

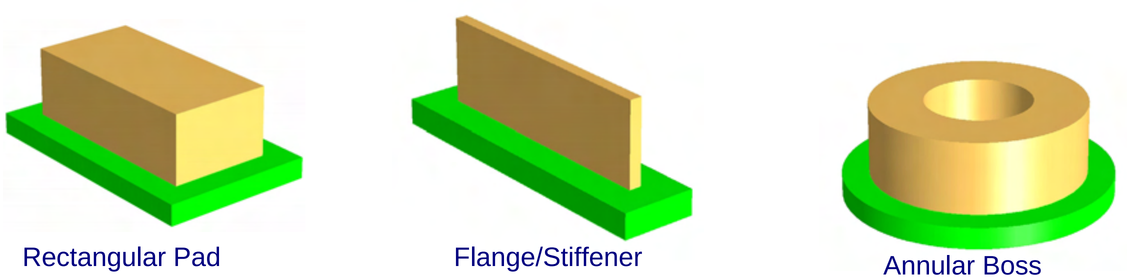
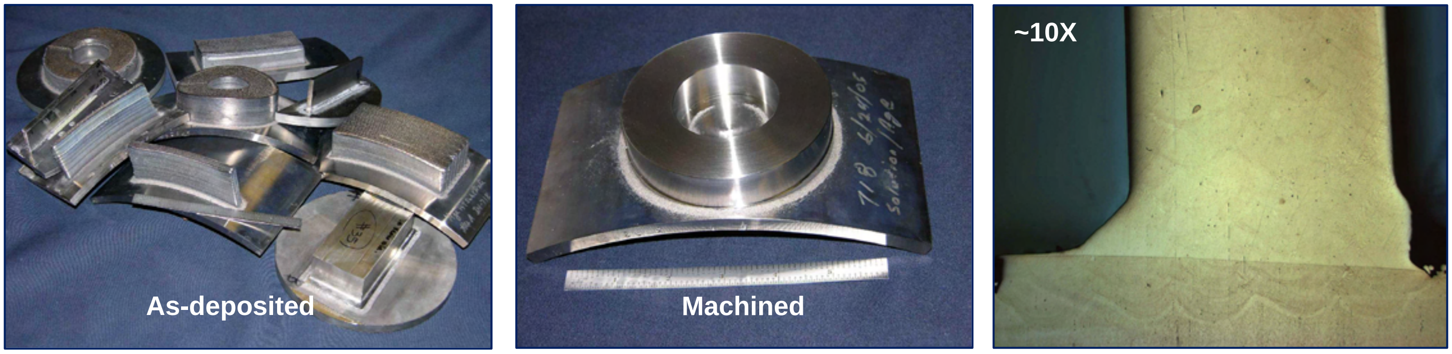


Table 2: NDT Flaw Size Acceptance Criteria For MAI Additive Manufacturing For Superalloys Producibility And Cost Validation Program	
- Inspection of microstructure to be in the delivery heat treatment condition.	
- Inspection to include the substrate Heat Affected Zone (HAZ).	
Reject Criteria	
- Cracks / sharp voids	
Reportable Characteristics	
- Elongated chains of segregate-rich phases - Precipitate morphology, location, size, distribution (in deposit) - Precipitate morphology and size in HAZ - Heat Affected Zone dimensions - Depth of penetration of fusion zone into substrate - Surface inspection should be both in the as-deposited and in the as-machined condition - Deposition strategies involve layers, overlapping paths and corners. Lack of fusion connected with these issues shall be specifically sorted out by the appropriate volumetric inspection standard.	
Surface Inspection Acceptance Criteria	
Deposit must fill the design envelope entirely. Deposit to be subsequently machined on all faces, removing all deposited surfaces.	
ISOLATED PORES: *(Only acceptable with round bottom)*	- Maximum diameter 0.039" (1.00 mm) - 0.394" (10.0 mm) minimum separation
Linear chain of small pores:	- Maximum length 0.039" (1.00 mm)
Clustered pores:	- Max size of defect in cluster 0.016" (0.40 mm) diameter. - Min separation between defects 0.016" (0.40 mm) - Max number of defects in cluster 6. - Min distance between clusters 0.394" (10.0 mm).
Cracks, Stop-Start Craters, Oxidation, and Lack of Fusion:	Not permissible
All isolated non-clustered indications less than 0.016" (0.40 mm) in size are considered non-interpretable and are acceptable provided the minimum separation between them is 0.049" (1.25 mm).	
Volumetric Inspection Acceptance Criteria	
Rounded pores:	- Maximum diameter 0.039" (1.00 mm)
Linear chain of small pores:	- Maximum length 0.039" (1.00 mm)
Clustered pores:	- Max size of defect in cluster 0.016" (0.40 mm) diameter. - Min separation between defects 0.016" (0.40 mm) - Max number of defects in cluster 6. - Min distance between clusters 0.394" (10.0 mm).
Cracks, Inclusions, Oxidation, Lack of Fusion:	Not permissible
All isolated non-clustered indications of size less than 2% of section thickness or 0.005" (0.13 mm), whichever is greater, are considered non-interpretable and are acceptable.	

Laser Powder Deposition - LPD (GE-Aviation)

The primary deposition parameters utilized for this process include laser power, powder feed rate, substrate traverse speed, and laser focus location relative to the substrate. The low heat input and high solidification rate characteristic of the LPD process typically results in low distortion, a small heat affected zone (HAZ), and minimal substrate dilution. The required 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 all were acceptable under the established criteria. Metallography of the deposits was also performed and samples of the deposited material and microstructures are shown in Figure 2.

Figure 2: Typical LPD Deposits



Electron Beam Wire Deposition (P&W)

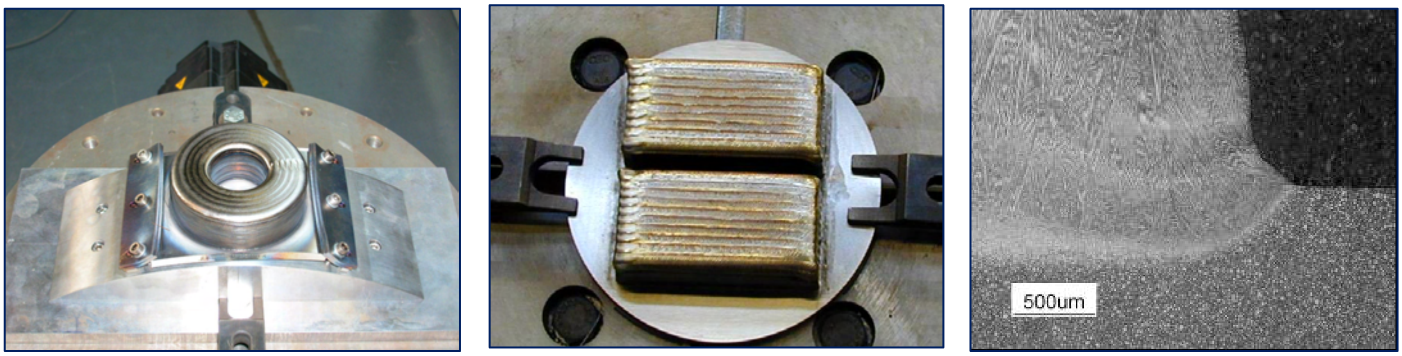
Electron beam wire feed deposition efforts were performed by Acceleron, (East Granby, CT) under subcontract to P&W. Initial process parameters were developed on subscale test deposits. These subscale specimens were then evaluated using visual, x-ray, ultrasonic, and metallographic techniques. The evaluations showed that defect-free material, per the developed acceptance criteria, could be produced using the EBWD process. Subsequently the required deposits for Task 2 were completed with typical deposits shown in Figure 3. The deposits were delivered to P&W for inspection. Under visual inspection, surface cracks were observed on three of the deposits, which was associated with stress concentrations at the cusps of the substrate/deposit interface. 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 acceptable per the established criteria. Examples of the micro defects are shown in Figure 3.

Figure 3: EBWD Deposits on Alloy 718

Shaped Metal Deposition (RRC)

Rolls Royce successfully fabricated the required deposition samples for Task 2 (see Figure 4). 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 good microstructure (see Figure 4).

Figure 4: Typical SMD Deposits



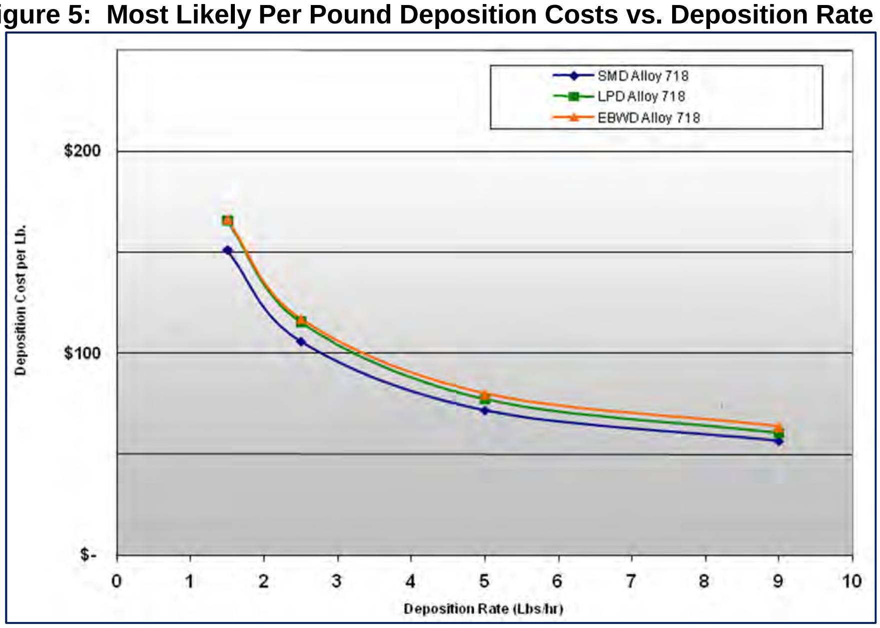
Summary of Task 2 Deposition

In total, forty-three deposits were made in the three target geometries, 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.

Task 2: Cost Modeling Activities

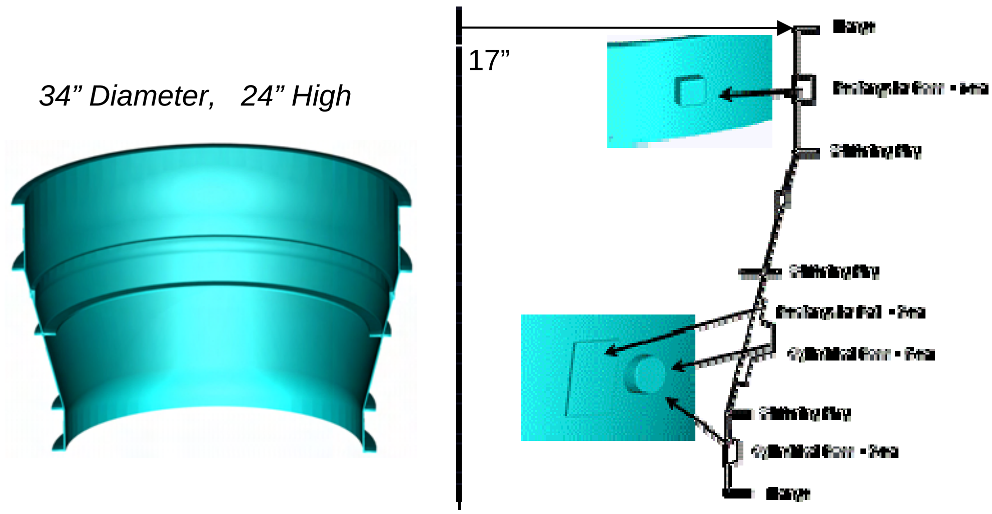
A cost savings assessment was generated using a model created by ARGO Enterprises to compare baseline forging geometries and their associated costs relative to simplified backbone forgings. The combined results of theses preliminary cost assessments are summarized in Figure 5. This graph shows the "most-likely" costs to deposit a pound of metal for each of the deposition processes plotted against the largest driver in the model, the deposition rate. While deposition rate is shown here to be a significant driver for deposition costs, it has only a secondary effect on the overall cost savings, which are primarily driven by a reduction in the starting input weight.

Figure 5: Most Likely Per Pound Deposition Costs vs. Deposition Rate



These preliminary cost models were completed as the first step in determining the degree of cost savings offered by the concept of additive manufacturing. Essentially, a notional forged case based on actual production hardware, was developed. A notional case was used so that no specific design data from any OEM would be required and therefore could be shared. The result was a case component (see Figure 6) with rectangular bosses, cylindrical bosses, and rectangular pads. This had a rough machining and forging shape based on design rules typical of the ring rolling industry. This forging shape became the starting point for the determination of savings potential for the deposition process alternatives.

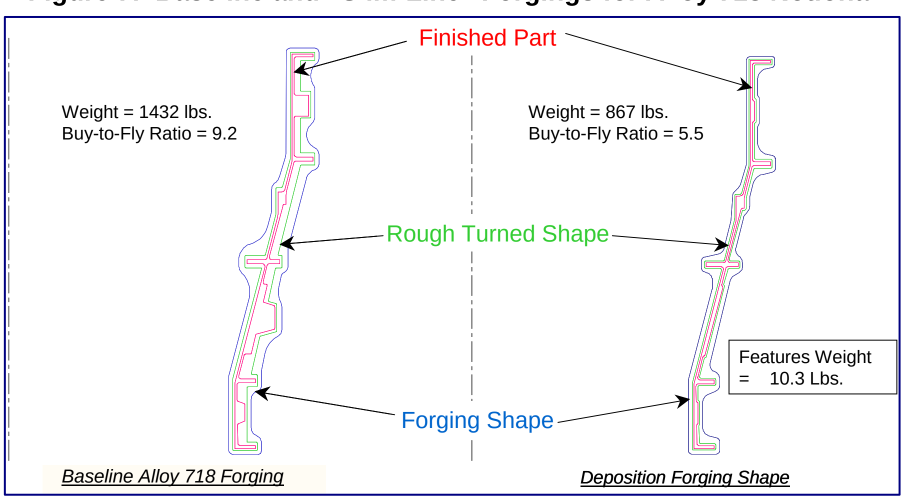
Figure 6: Engine Case Component Configuration for Calculation of Cost Benefits.



The notional forged case was analyzed to estimate the cost savings that could be realized using additive manufacturing compared to traditional methods. Conventional ring rolling design rules were employed to develop rough turned shapes and a subsequent forging shape that would be required for the manufacture of said notional case. Based on these generated forging shapes, current material cost, estimated material removal rates, and other factors related to the production of rolled rings, a baseline estimate of the cost of the case was established.

For additive manufacturing costs, the features to be added were removed from the component and a new forging shape was developed. These “slim line” cases required substantially less input material than the conventional forgings, resulting is dramatic weight reductions and associated material cost savings. Figure 7 shows the baseline and “slim-line’ forging shapes of the notional forged case for Alloy 718. The figures show that for Alloy 718, the forging weight can be reduced by over 550 pounds. In comparison, less than 15 pounds of material needed to be added to each notional case to produce the required features.

Figure 7: Baseline and “Slim-Line” Forgings for Alloy 718 Notional



The developed deposition costs were then used to estimate the cost of adding these features back on to the substrate, and subsequent machining and other costs (heat treatment, fixturing) were accounted for to estimate the cost to fabricate the notional case via additive manufacturing. The results show estimated cost savings of approximately 35-40% for Alloy 718 cases fabricated using additive manufacturing. Shaped Metal Deposition (3D welding) showed the highest cost saving, followed by LPD and then EBWD. However, savings for all three processes were comparable.

Task 3: Technical and Business Evaluation

The primary focus of Task 3 was to perform mechanical testing of deposited material on sample substrate. Activities to support this included mechanical testing, determining evaluation criteria, making the required deposits, and machining/testing of the specimens. Also included as part of Task 3 is the development of cost models for backbone fabrication and machining, as well as updating the models developed in Task 2. The goals for Task 3 and original testing matrix are shown in Tables 3 and 4, respectively.

Table 3: Task 3	
1.	Both bulk deposit and deposit/substrate interface will show mechanical properties equivalent to cast Alloy 718 or better. Target cast properties will be derived from the open literature. Any process that cannot meet these minimum requirements for all properties tested will be eliminated from further study
2.	Activity based cost models for each remaining additive process will be refined.
3.	Cost models for producing simplified forging and casting backbones will be developed.
4.	Cost models (backbone production, additive processes, machining) will be integrated.
5.	Cost savings analysis will be updated. Process must show minimum 30% cost savings or it will be eliminated from program.

Table 4: Task 3 Mechanical Properties Testing Matrix

	Material Location	Direction	Number of samples at test temperature					
			Tensile			LCF	SR only	Creep/SR
			RT	1000°F	1200°F	1000°F	1000°F	1200°F
1	Bulk Deposit	x	6	6	6	6	4	4
2	Bulk Deposit	y	6	6	6	6	4	4
3	Bulk Deposit	z	6	6	6	6	4	4
4	Deposit Interface	z	6	6	6	6	4	4

All specimens to be tested in aged condition: 1750°F, 1hr, air cool; 1325°F, 8 hrs, cool to 1150°F, 8 hrs, air cool per AMS 5383

Mechanical Test Conditions

Cast minimum properties derived from open literature, where available and used for deposited material minimums. Data was available for tensile properties; the exit criteria for Task 3 tensile testing are given in Table 5.

Table 5: Task 3 Tensile Testing Exit Criteria Values

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

For creep and stress rupture testing, the developed test matrix called for stress rupture testing at 1000° F and creep testing at 1200° F. A target value of 0.2% creep was decided upon for the 1200° F test with a target test time of 100 - 200 hours. Rolls Royce ran some preliminary tests on deposited material to help determine test stress levels to achieve the targeted test times. Based upon these tests, stress levels of 125 ksi for 1000° F stress rupture and 75 ksi for 0.2% creep @ 1200° F were set.

Unfortunately, values for stress rupture and creep at the specified test temperatures were not found in the open literature. Therefore, it was decided that each OEM would compare results to their existing material specifications. Since this information is company confidential, when comparing to exit criteria, results are reported as meeting (or failing to meet) the company specific values.

As with the creep and stress rupture testing, no open literature data existed for strain-controlled LCF testing at the temperature of interest. However, in this case, the AIPT decided to run additional testing on cast material to determine a baseline (exit criteria) value. Cast material was obtained by P&W, and this material was first homogenized at 2000° F (standard practice for cast Alloy 718) then subjected to the same solution and age heat treatment (1750° F, 1hr, air cool; 1325° F, 8 hrs, cool to 1150° F, 8 hrs, air cool) given to all deposited material prior to testing. LCF specimens were subsequently machined from this material. A series of tests were performed to determine the appropriate strain range to achieve approximately 50K cycles to failure. Once this strain range was determined, additional specimens were tested at this condition to determine the exit criteria value. The strain range of 0.4% was set. Using this strain range, the resulting baseline average was determined to be 62K cycles to failure.

Laser Powder Deposition (LPD)

GE completed all of the deposits required using plasma rotating electrode powder (PREP). Tensile testing was performed per the matrix shown in Table 3 and the results showed that the LPD material surpassed the cast minimum tensile properties. Creep (1200°F) and stress rupture (1000°F) results are also exceeded cast minimum properties when compared to GE cast Alloy 718 specifications (see Figures 8 & 9). LCF testing results are shown in Figure 10 and the results exceeded the established criterion of 62K cycles. 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. The interface LCF lives were well below the established criterion. Examination of the fracture surfaces revealed that all specimens showed lack-of-fusion (LOF) defects which prompted parameter refinement.

Electron Beam Wire Deposition (EBWD)

Tensile properties for EBWD material were well above the required cast minimums for all temperatures and directions tested. In fact, these values were very close and sometimes even exceed 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 11 and 12, respectively. Test conditions for stress rupture were 1000° F, 125 ksi. Conditions for creep testing were 1200° F, 75 ksi. 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 P&W cast minimum requirement for both stress rupture and creep for all directions tested.

Average LCF results are shown on Figure 13. LCF testing was strain controlled at 1000°F, A = 1.0, and Strain = 0.4%. Again, minimum property requirements were exceeded for all directions tested. Baseline LCF testing of homogenized and heat treated Alloy 718, performed under the conditions listed above, was used to determine minimum property requirements. As shown in the figure, minimum property requirements were exceeded for all directions tested. In fact, all EBWD LCF specimens were tested to a minimum of 100,000 cycles, with no failures observed.

Shaped Metal Deposition (SMD)

The Task 2 work was carried out on university development equipment, which facilitated parameter development, but lacked capacity for volumetric scale-up. Task 3 efforts transferred the parameters and programming techniques to the manufacturing cell located at Advanced Manufacturing Research Centre (AMRC) Sheffield. The rationale was to implement development in production standard conditions (on newer welding-industry standard equipment), including a more robust atmospheric chamber enabling a greater working volume.

Deposits performed at AMRC exhibited quality issues which were determined to be the result of differences between the optimized university arrangement and the newly commissioned development cell. These differences include substrate clamping, in-process vision, and wire feed guide alignment. As such the deposits performed for Task 3 were not optimized for quality. Leaks within the system and operator inexperience also contributed to the inferior quality of the Task 3 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 LCF is typically much more susceptible to flaws in the material. As a result of the unresolved issues with deposition quality and the inability to perform meaningful LCF testing, the decision was made to eliminate the SMD process from the program.

Figure 8: LPD Creep Test Results

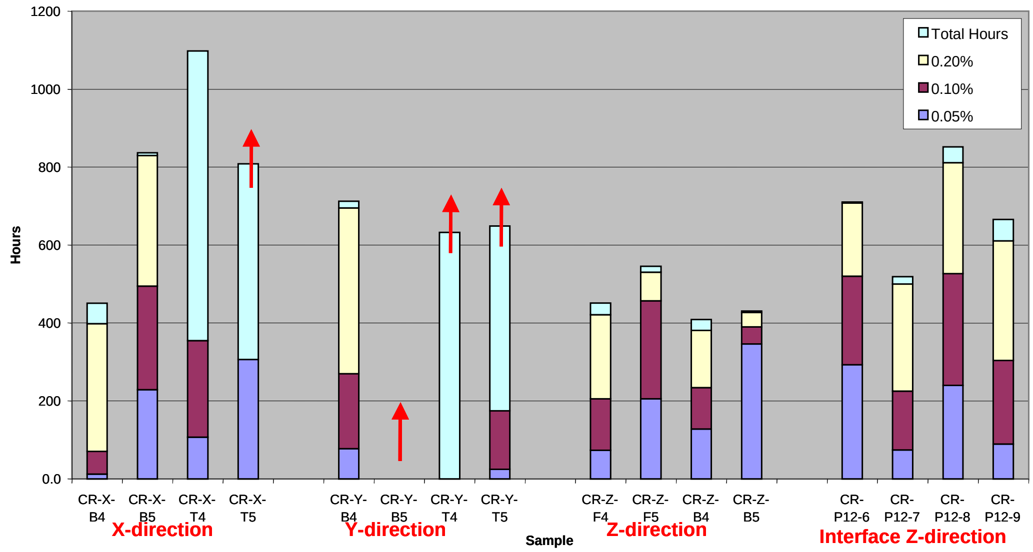


Figure 9: LPD Stress Rupture Test Results

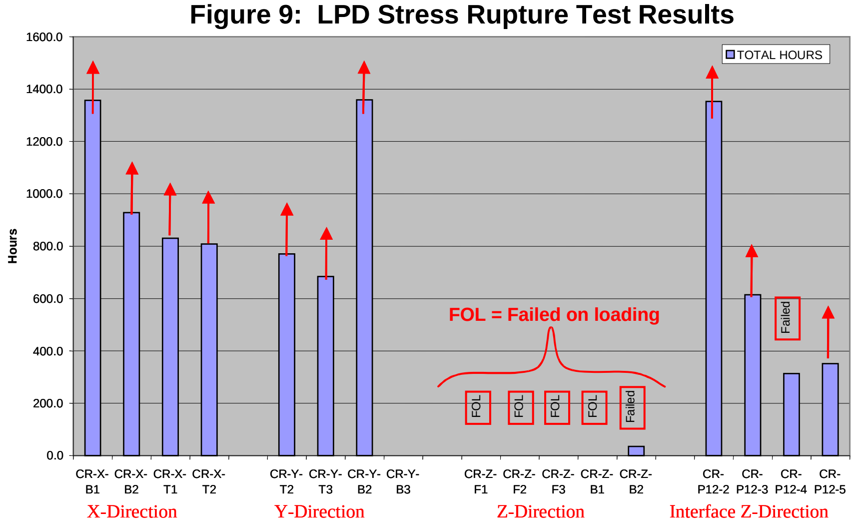


Figure 10: LPD LCF Results

Strain Controlled LCF at 1000°F, A=1.0 Strain=0.4%

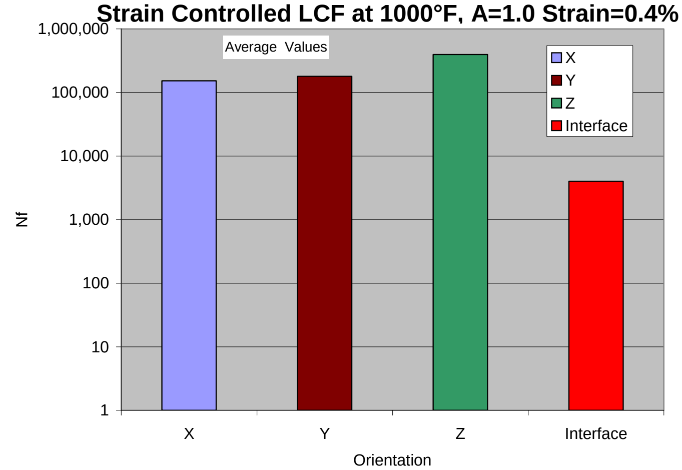


Figure 11: EBWD Creep Results

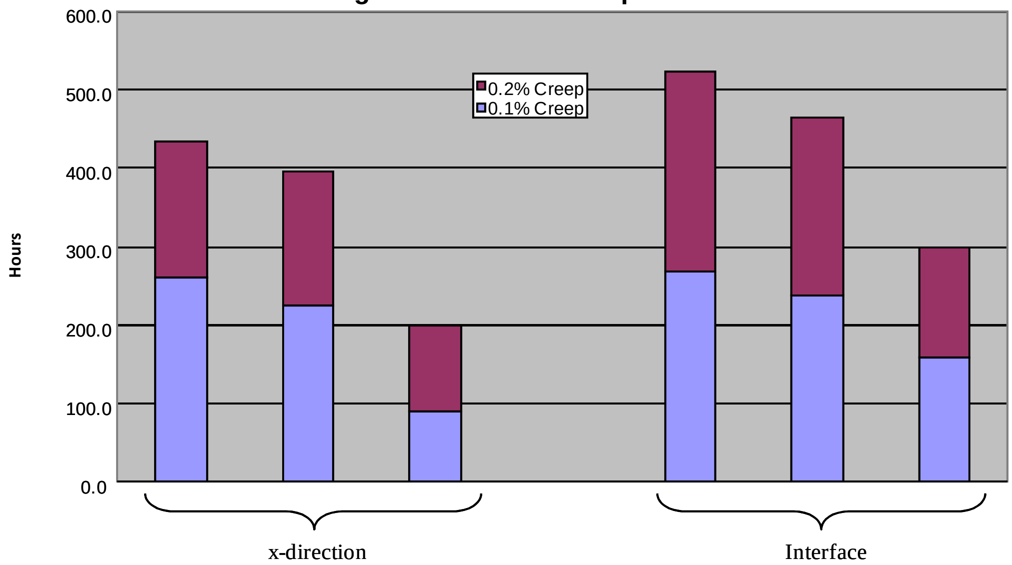


Figure 12: EBWD Stress Rupture Results

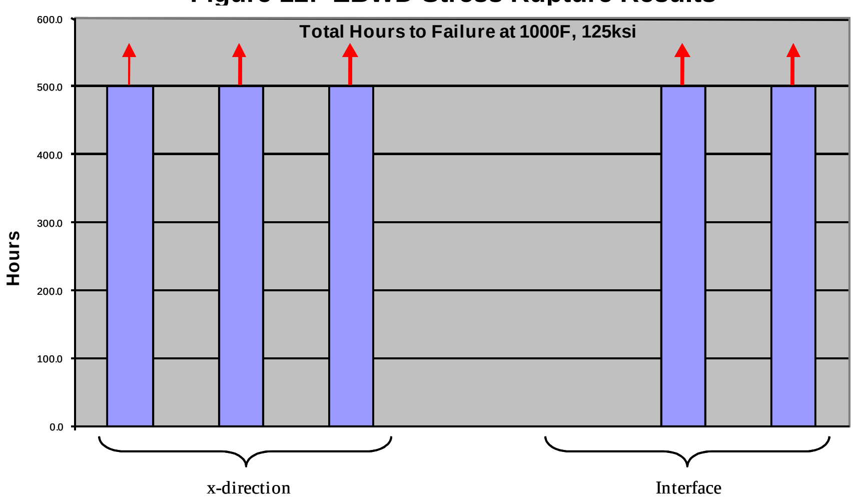
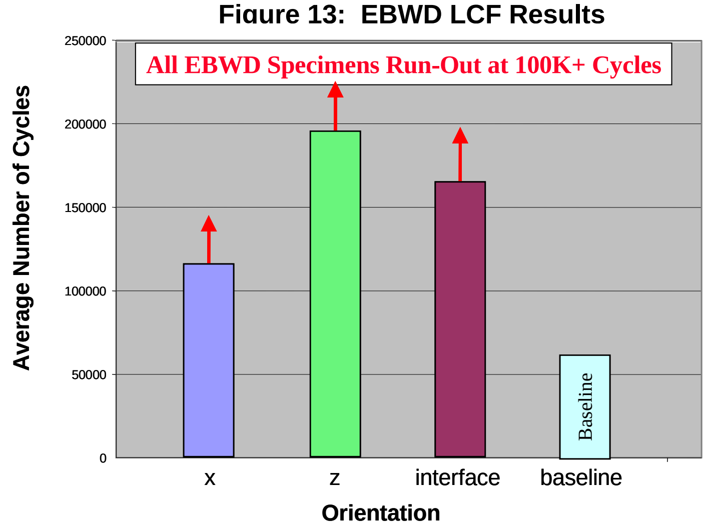


Figure 13: EBWD LCF Results



Task 3: Cost Modeling Activities

In Task 3 deposition cost models were updated to reflect current raw material prices, refinement of the process input distributions, and more accurate rough machining costs. The AIPT members also worked on identifying target parts to be used in estimating cost savings. Previous estimates on cost savings were based on a notional case. The revised goal for Task 3 was to now calculate cost savings based on actual hardware. In order to protect company sensitive information relative to the level of information shown, the components under consideration are just referred to as Component 1 and Component 2. The results show that a greater than 30% savings is estimated for both components considered (see Figures 14 & 15).

In Task 2, cost models for the three metal deposition processes were developed based on projections of future cost and capability of the processes. Each of the models was developed using identical or similar cost elements such that there would be commonality across the processes to reveal the basic differences that would influence cost. As an example, all labor wage rates were common across the processes; however specific deposition rates or metal yield values were unique to each process. In Task 3 ARGO merged these models into one integrated Microsoft Excel workbook, so the user could define a single additive application and to derive cost data from the three deposition processes while only having to input most of the data only once. This process is illustrated in Figure 16.

Figure 14: Cost Savings Estimate for Component 1

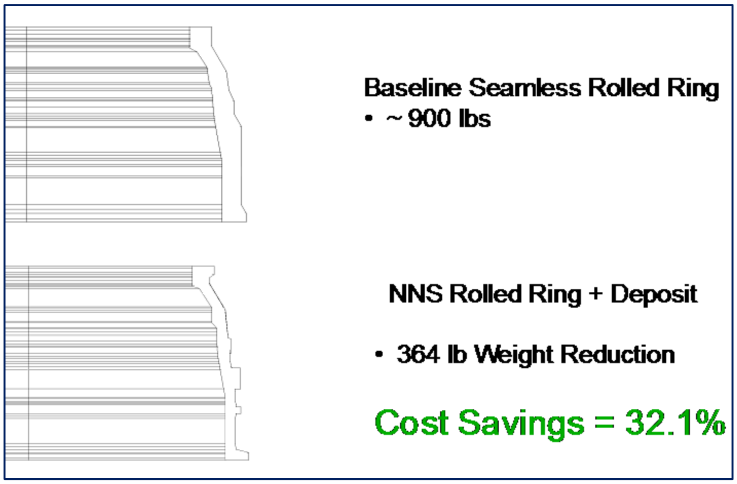


Figure 15: Cost Savings Estimate for Component 2

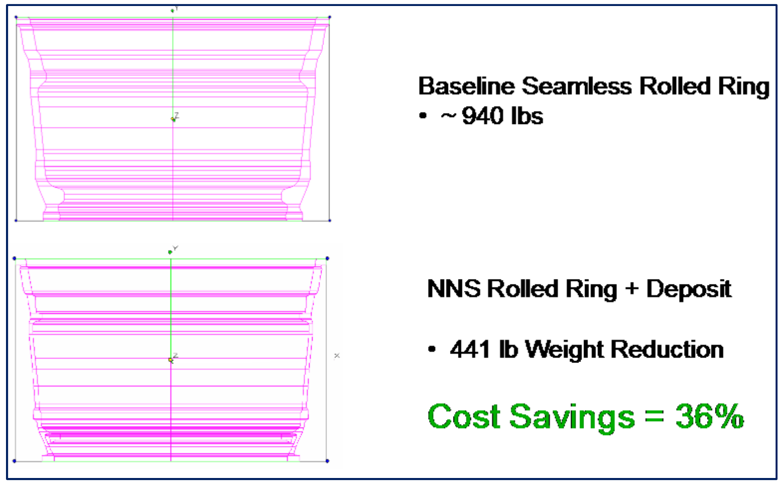
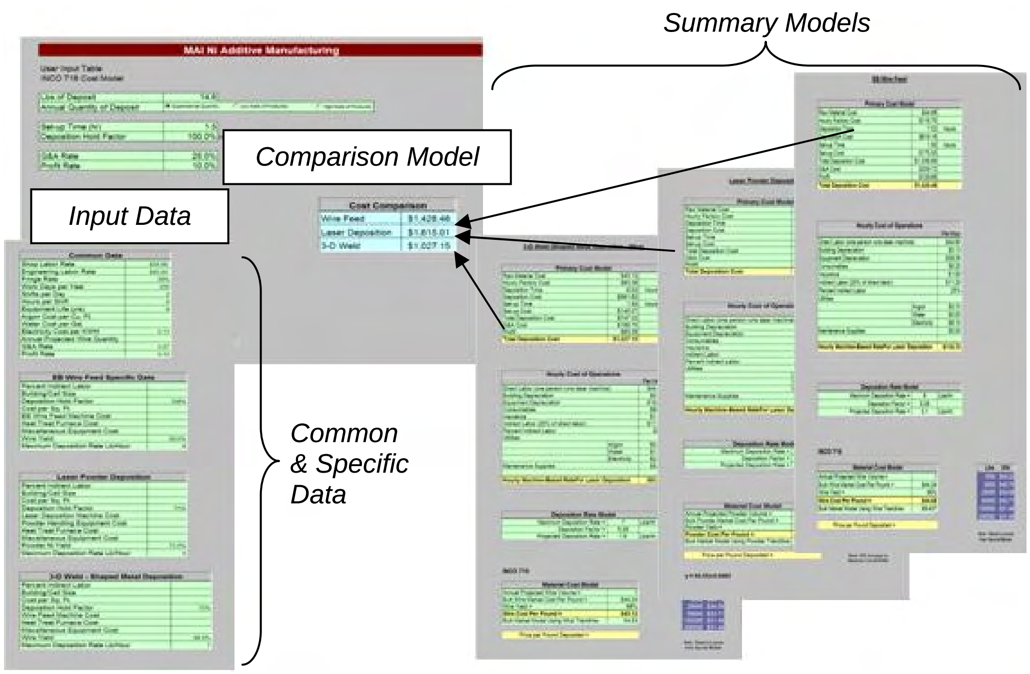


Figure 16: Schematic of Integration of Deposition Cost Models



A study was also conducted to examine the potential for cost savings using additive manufacturing for 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 requiring minimal final machining are highly cost effective. Therefore, additive manufacturing presents minimal opportunity for cost savings on these components. 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.

Task 4: Testing and Validation

The purpose of Task 4 was to create representative case features on full scale slim substrates (see Figure 17), perform limited equivalence mechanical testing to ensure that the deposition processes continued to produce acceptable quality material, update the cost savings models, and perform actual cost saving analyses on the respective OEM hardware to validate prior conclusions. The goals for Task 4 are shown in Table 6.

Figure 17: Task 4 - Typical Representative Hardware

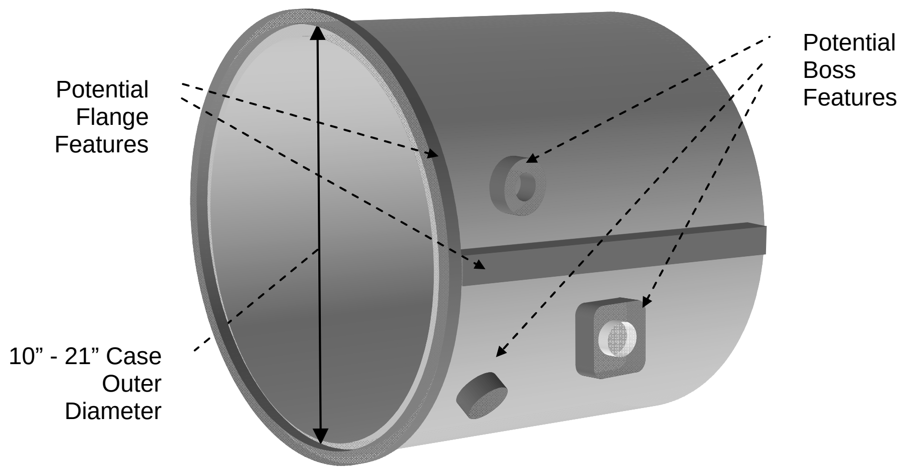


Table 6: Task 4	
1.	Successful full scale demonstration ▪ Feature Addition (i.e. deposition geometry, final geometry, NDE ▪ Mechanical testing in relevant environment ▪ Metallurgical Results
2.	Refinement and validation of cost models
3.	Cost of deposition and savings favorably compared to targets

Deposition Activity

All three engine OEM team members fabricated representative sample hardware; GE and RR subscale and P&W full scale. The dimensions of the features were generic in nature but within the range of what would be found in typical gas turbine hardware. The thickness of all starting slim cases was approximately 0.5" with diameters ranging from 10" to 21" and 3" to 6" in height (see Figures 18-20). GE deposited enough material to extract metallurgical samples and mechanical test samples whereas P&W and RR extracted sample from separate deposits (see Table 7). As P&W and RR were now testing the same technology, cooperative testing was performed to minimize duplication of efforts (see Table 8).

Figure 18: Photograph of LPD deposited features on representative case strong-back.

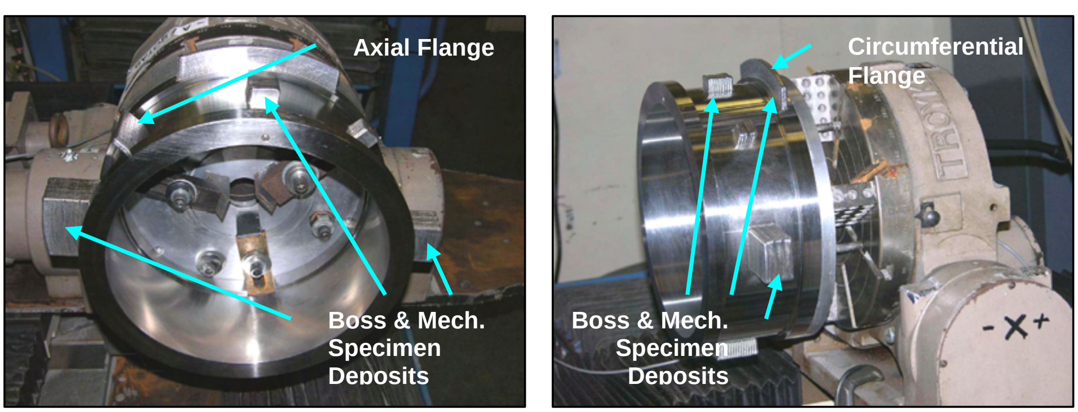
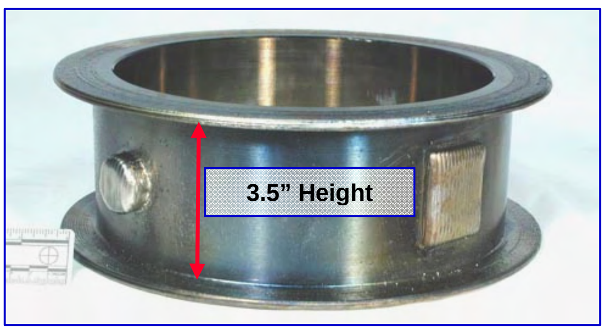


Figure 19: Images of P&W case that was fabricated from two 3" tall AMS 5662 rings EB welded together and machined to the nominal wall thickness of 0.5".

Figure 20: Representative photo of as deposited RRC rings. Substrate was 0.5" thick Alloy 718 forged ring



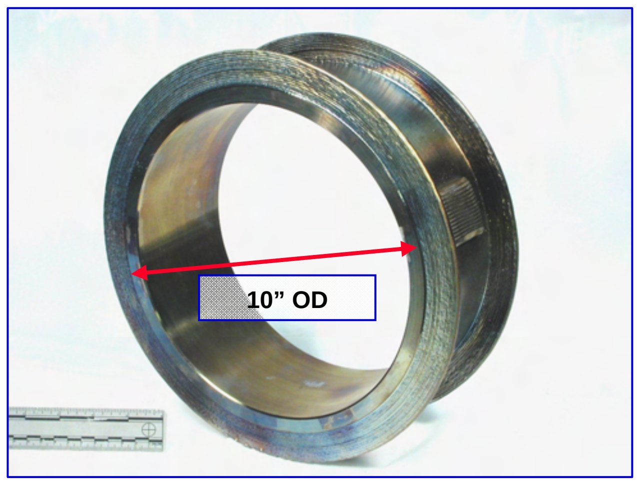


Table 7: GE LPD Proposed Deposition Plan					
Feature Type		**Diameter (OD)**	**Length**	**Width**	**Thickness/ Height**
Rectangular Pads*	*Ten X*	N/A	1.80"	2.30"	0.80"
	Ten Z	N/A	1.80"	1.20"	2.30"
	LCF Z	N/A	1.50"	2.30"	2.70"
Rectangular Boss		N/A	1.20"	1.00"	0.80"
		N/A	0.80"	0.80"	0.80"
Flange (axial)		N/A	4.00"	0.25"	0.80"
Flange (circumferential)		N/A	6.00"	0.25"	0.80"

**Note: These are features which will also be used to extract the required mechanical test specimens.*

Table 8: P&W EBWD Proposed Deposition Plan					
Feature Type	**Diameter (OD)**	**Length**	**Width**	**Thickness/ Height**	**Hole Diameter (Center of Deposit)**
Round Bosses	3.00”	N/A	N/A	1.75”	2.00”
	2.00”	N/A	N/A	1.00”	N/A
Rectangular Pads	N/A	3.50”	2.50”	0.75”	N/A
Tensile X Block	N/A	3.00”	2.00”	1.75”	N/A
Tensile Z Block	N/A	2.75”	2.75”	3.25”	N/A
RRC EBWD Proposed Deposition Plan					
Round Bosses	0.75”	N/A	N/A	0.75”	N/A
	0.75”	N/A	N/A	0.50”	0.25”
Rectangular Pads	N/A	1.50”	2.00”	0.25”	N/A
Flanges (circumferential)	N/A	TBD	0.15”	0.75”	N/A
LCF Z Block	N/A	3.00”	3.25”	3.50”	N/A

The LPD sample case exhibited negligible heat discoloration and minimal distortion after all heat treat (see Figure 21). Metallographic sections taken from the bulk deposit and interface showed microstructural quality equivalent to the deposits that were created for Task 3, there were no significant defects detected (see Figure 22). The EBWD samples from Pratt & Whitney did exhibit a noticeable heat discoloration but the resultant distortion was minimal (see Figures 19, 23). 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 P&W and RRC EBWD deposits exhibited microstructural quality equivalent to the deposits that were created for Task 3 (see Figures 24 & 25) All Task 3 deposits also showed minimal NDE defects (i.e. within the established criteria of prior tasks), and met the intended dimensions for all features (see Figures 26 - 30).

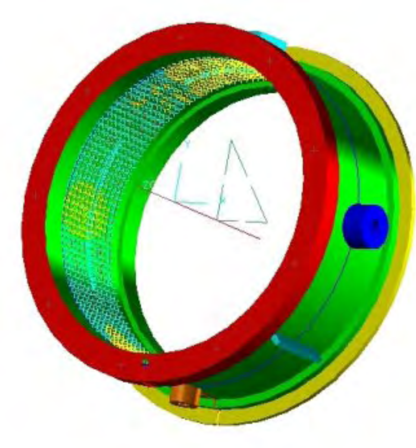


Figure 21: CMM inspection of LPD sample case before deposition, in as-deposited condition, and after post deposition HT

- 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
- No distortion in locations away from deposits

Figure 22: Representative micrographs of the GE LPD post heat treatment

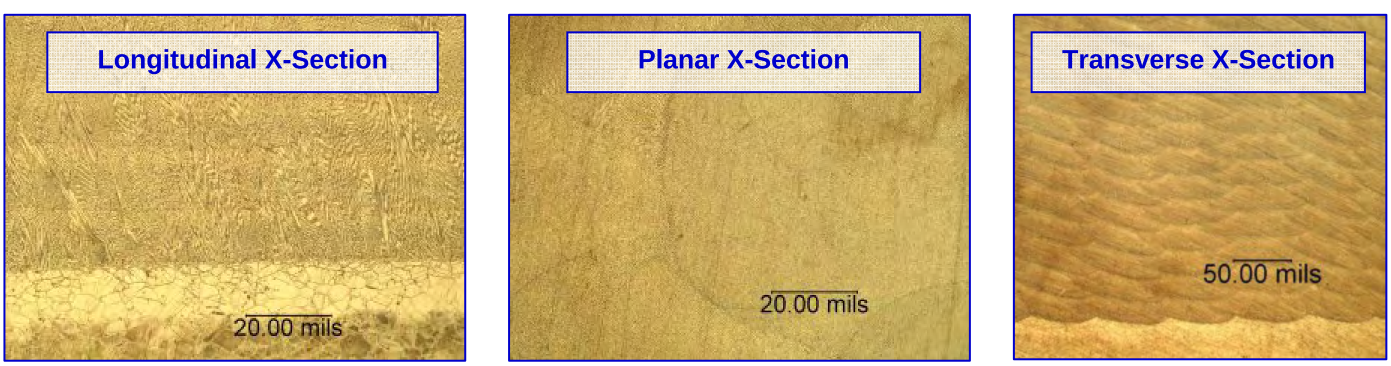


Figure 23: OD has increased 0.050" - 0.060" (0.025" - 0.030" radially) due to a slight cupping at each deposit. This created a concave profile facing radially outward.

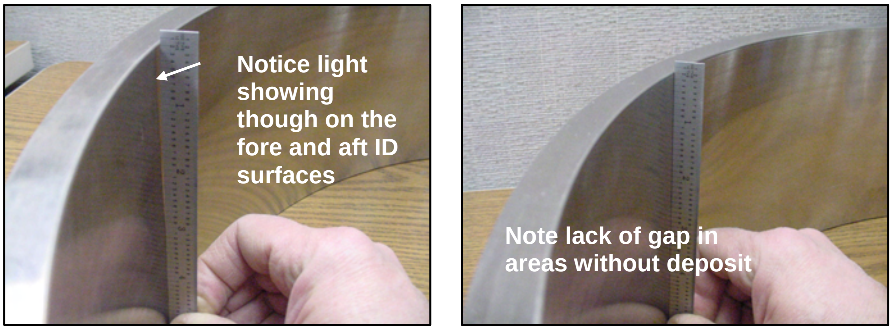
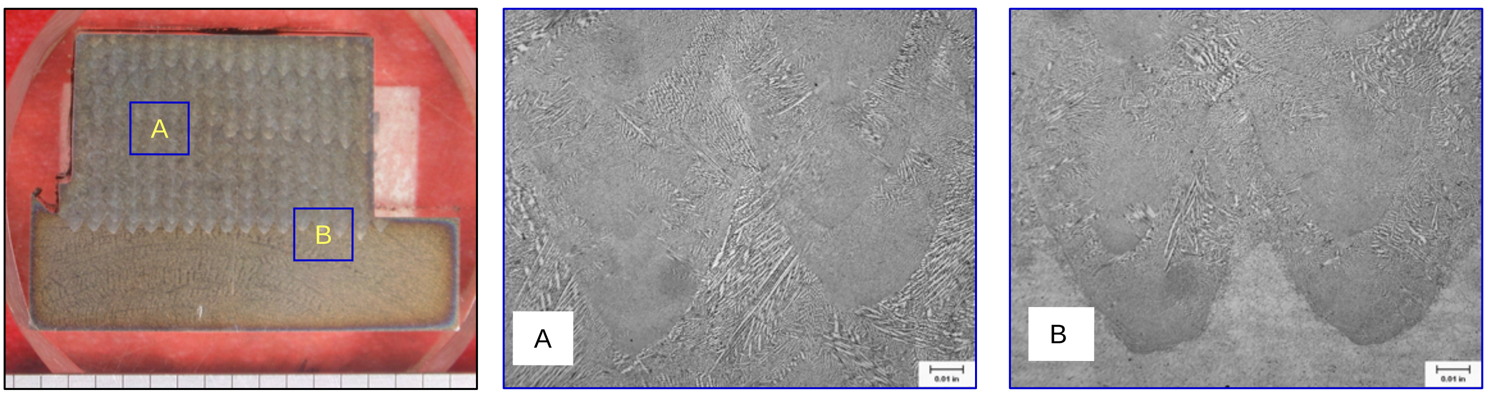


Figure 24: Representative images in the transverse orientation from the rectangular boss deposit. Note lack of significant defects (e.g. cracks, large pores).



Samples exhibited and average weld penetration of ~0.100".

Figure 25: RRC EBWD representative, post heat treat metallurgical examination images of the boss and flange deposits. Note lack of significant defects (e.g. cracks, large pores).

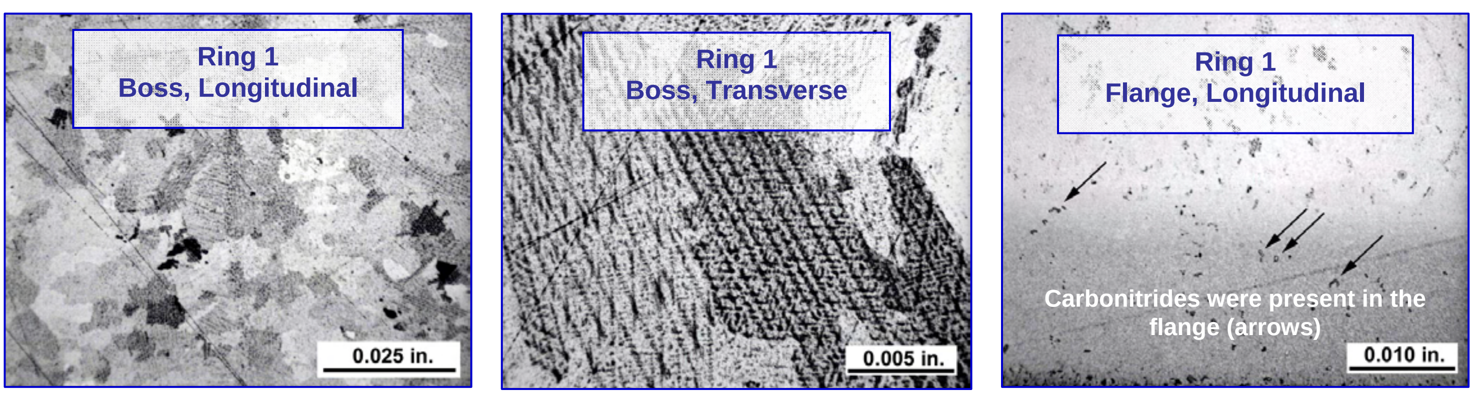


Figure 26: Image of the RRC ultrasonic inspection, both rings passed inspection criteria for cast material

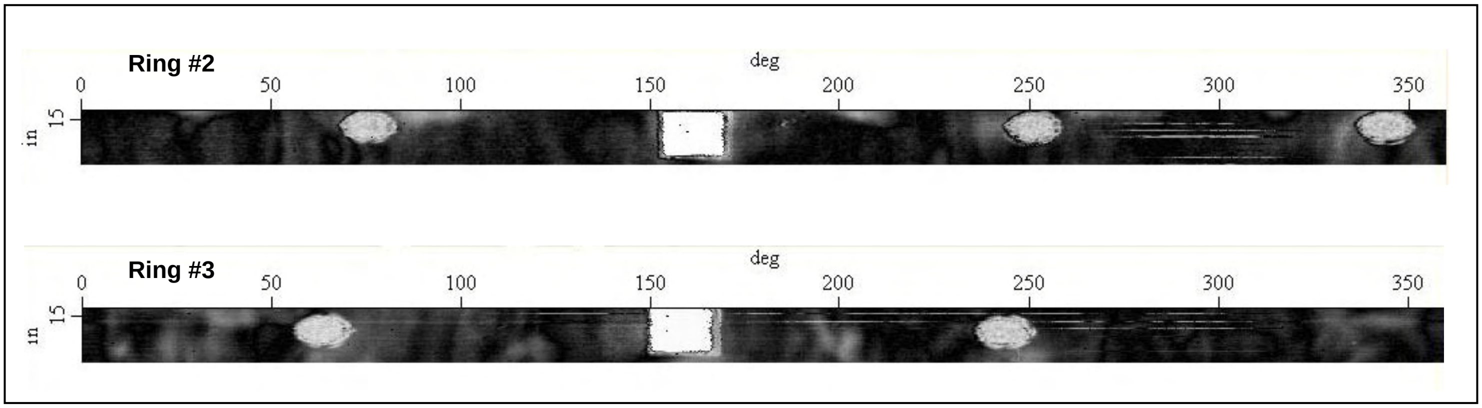


Figure 27: Image of GE ultrasonic inspection. Deposited material conformed to the acceptability criteria, indications and process interruptions were all outside of machined areas.

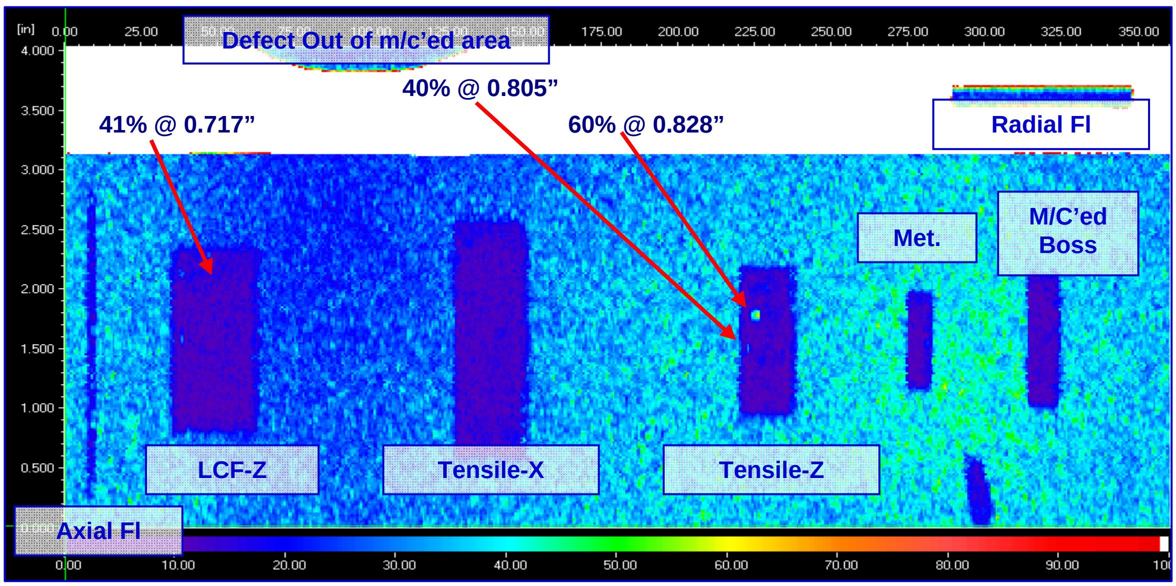


Figure 28: Radiographs taken with a 2-2T sensitivity did not show any defects.

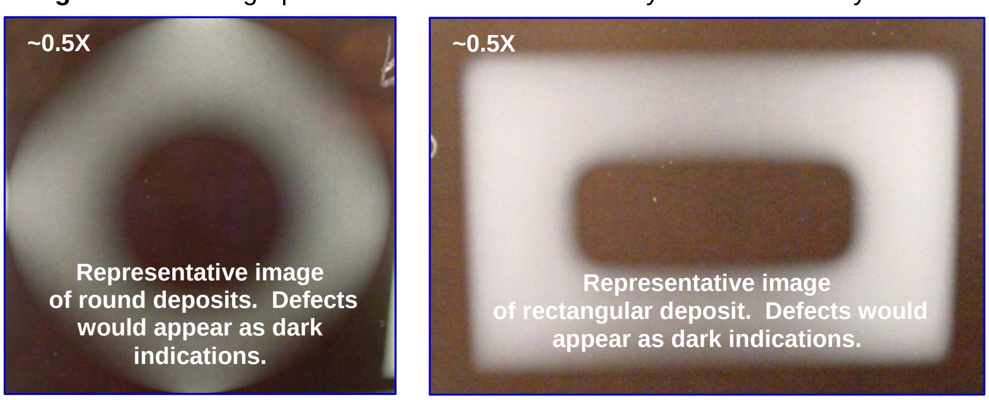
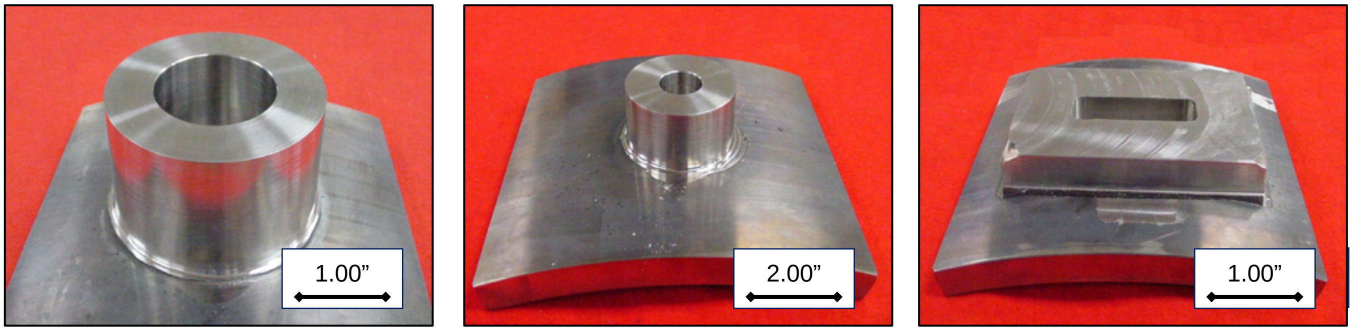


Figure 29: Images of P&W EBWD samples, all samples met the intended dimensions post machining



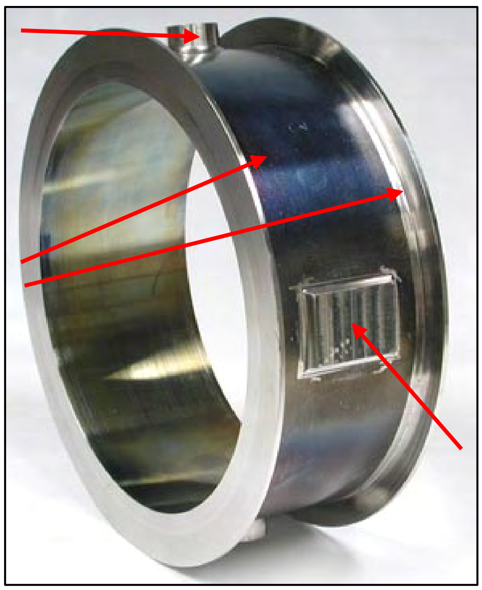


Figure 30: Photograph of EBWD deposited features on RRC case section.

Task 4 Mechanical Testing Activities

The purpose of Task 4 was to verify that the additive material continued to provide performance observed in Task 3. Because of this, the AFRL agreed to a limited amount of mechanical testing to verify that the deposition facilities continued to produce high quality material. The mechanical testing plan for Task 4 consisted of room temperature tensile testing of X and Z-direction samples (see Table 9). Testing in Task 3 did not show a significant difference between the performance of the X and Y orientations, as a result it was not necessary to retest both directions. Additionally, the AFRL requested that team members supply deposited material to extract LCF test samples in the Z orientation for testing by the AFRL. GE chose to test their own LCF specimens and provide data to the AFRL whereas Pratt & Whitney and Rolls Royce provided an EBWD test block for the AFRL to test. The results of both the X and Z-direction tensile and the Z-direction LCF samples were within 10% of the results from Task 3.

Table 9: Mechanical Testing Requirements for Task 4

Test Type	Specimen Location	Control Type	Temp	Strain	Target Values
Tensile X	Bulk Deposit	N/A	RT	N/A	90% Equivalence to T3 Data
Tensile Z	Bulk Deposit	N/A	RT	N/A	90% Equivalence to T3 Data
LCF Z	Bulk Deposit, interface and parent material can be in grip	Strain Control	1000 °F	0.4%	▪ 90% Equivalence to T3 data. ▪ Target Life in T3 was 62K

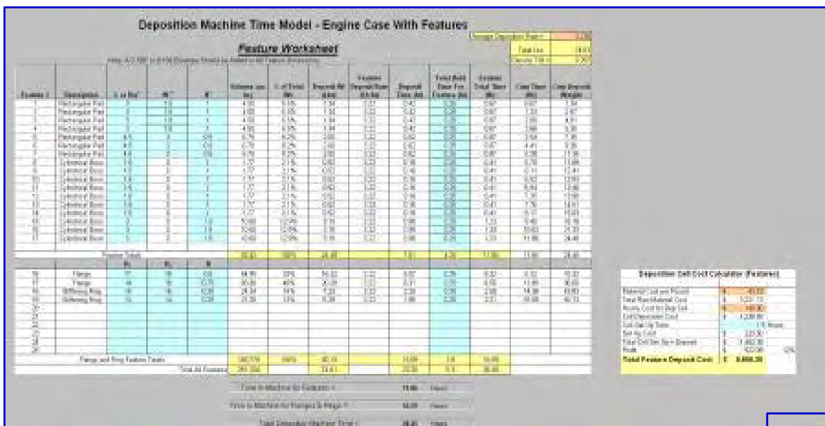
Note: Since P&W & RRC are utilizing the same additive technology the team members are working cooperatively in the mechanical testing activities. P&W is providing the tensile data, RRC is performing the LCF deposition.

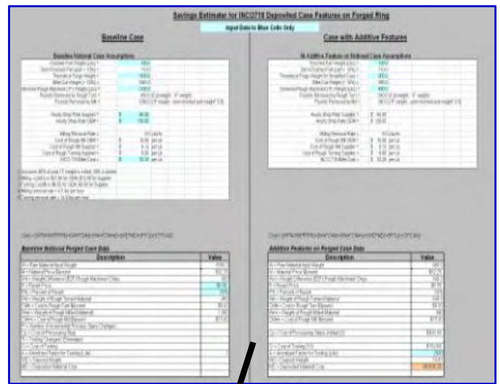
Task 4 Cost Modeling Activities

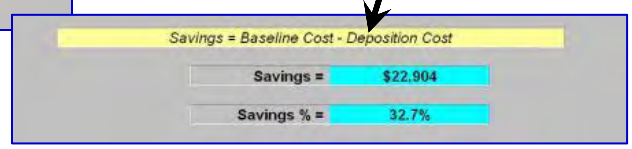
During Task 4, the cost model was updated to include the current market price for raw nickel material (as of 2008) and provided a comparison between baseline wrought cases, cases manufactured using additive processes, and cast hardware. A user version of the model (see Figure 31) was then provided to the team members, (i.e. P&W, GE, & RR) and cost analyses on actual hardware were performed which validated the original Task 3 conclusions; minimal cost benefit for cast hardware and significant potential cost benefit (20-50%) for wrought hardware. Additionally, P&W performed a generic weight savings analysis and determined that a case fabricated with a wrought shell and additive features could reduce an equivalent cast product's weight by up to 10 % (see Figure 32).

Figure 31: Representative Images from Argo Updated Cost Savings Model.

Feature Worksheet

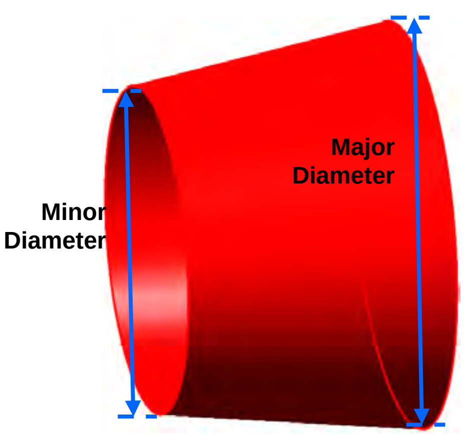






Note: This is a representation of the refined cost model provided by ARGO Enterprises utilizing fictional feature dimensions and cost figures.

Figure 32: P&W Weight Savings Analysis for **Cast** Structure



Up to 10% Potential Weight Savings Using AMS 5663/5832

Alloy	*AMS 5663 / 5832*
Diameter ID Major (in)	Unchanged
Diameter ID Minor (in)	Unchanged
Length (in)	Unchanged
Wall Thickness (in)	~15% Reduction
Calculated Volume (in^3)	~15% Reduction
% Weight Reduction	~10%

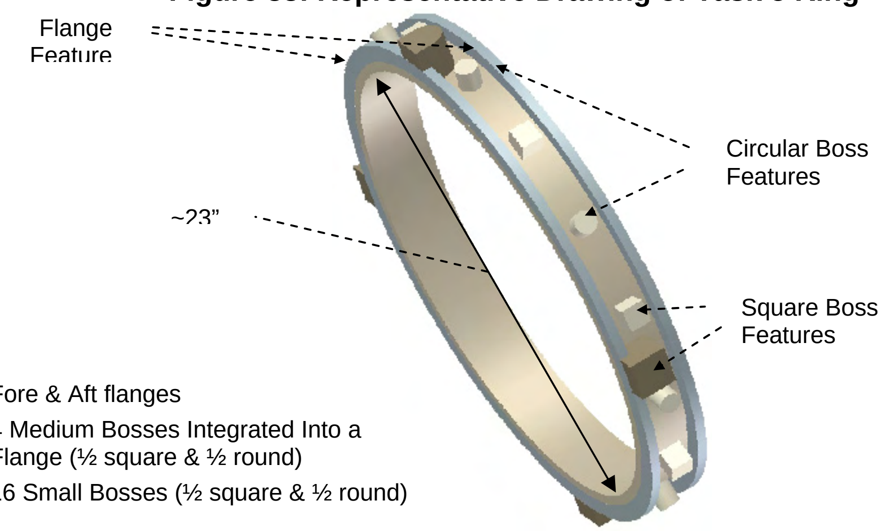
- Initial analysis based on a volumetric reduction using a 15% reduction in wall thickness for a uniform thickness cone (i.e. no bosses or flanges). Wall reduction % was an estimate based on increased mechanical properties of wrought material.
- Additional analysis performed by P&W Engineering based on known mechanical properties of wrought material confirmed initial results.

To fully evaluate the potential weight savings associated with a wrought design; other factors (e.g. operating frequency, containment issues, etc.) would need to be investigated.

Task 5: Production Implementation Planning

Task 5 focused on demonstrating the full potential of the additive processes by creating a fully representative Alloy 718 case with circumferential flanges and several boss features (see Figure 33). The deposited features were generic in nature, while still being in the range typically used on actual case hardware. Budgetary constraints required the selection of one deposition technology to fabricate the required case. As the Electron Beam Deposition process was being used by both Pratt & Whitney and Rolls Royce, it was selected as the demonstration process for Task 5. Because Pratt & Whitney was the closest in proximity to the depositor, Acceleron, they were selected to oversee the deposition efforts. GE and RRC subsequently assisted in the post deposition processing activities and remaining Task 5 goals which are listed in Table 10.

Figure 33: Representative Drawing of Task 5 Ring



- Fore & Aft flanges
- 4 Medium Bosses Integrated Into a Flange (½ square & ½ round)
- 16 Small Bosses (½ square & ½ round)

Table 10: Task 5	
1.	Creation of a draft specification for Nickel Additive manufacturing using current specifications as references (e.g. AMS 2680 & 4999).
2.	Creation of an implementation plan for scaling up to production readiness. ▪ Estimate the required capital needed to meet the current lead times for existing forgings through rough machining (relative to OEM's) ▪ Estimate the required lead time to create the slim line forgings ▪ Quantify the amount and cost of additional testing that will be required to introduce a new material into the OEM design system (this may have to be in generic terms due to proprietary information). ▪ Obtain estimates from GE (or subcontractor) & Acceleron to meet current lead times for conventionally fabricated hardware. ▪ Obtain estimates from Ladish (raw material) slim line forging relative to current product.
3.	Update cost model to include post deposition NDT & machining. Also upgrade to be fully user friendly.
4.	Fabrication of a fully representative case with flanges and multiple bosses placed around the entire circumference of the substrate shell. This case shall meet all NDT and dimensional stability requirements of Task 4.

Prototype Fabrication Activities

The prototype feature geometries (see Table 11) and relative orientation were determined by the AIPT at the onset of this task. The proposed layout was specifically selected to demonstrate the capability of additive manufacturing while providing a platform for the respective engine OEM's to project future applications of this technology. A substrate ring was fabricated from the remaining Alloy 718 material that was used in Task 4. 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 11: Task 5 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.

Post Deposition Processing and Non-Destructive Evaluations

Following all deposition activities, the prototype ring was solution heat treated to A) relieve solidification stresses and B) verify that the deposition sequence did not adversely affect the dimensional stability of the ring (see Figure 34). Prior to being transferred to Rolls Royce for non destructive evaluation, the ring was also partially machined to prepare it for ultrasonic inspection. 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 35).

Figure 34: Task 5 Prototype Ring in the Post Deposition and Heat Treat Condition

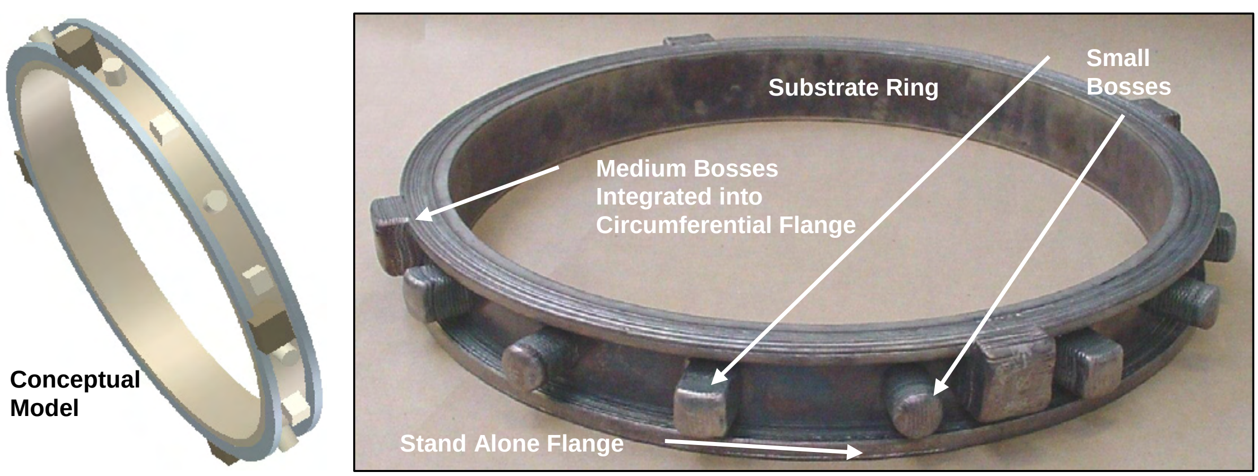
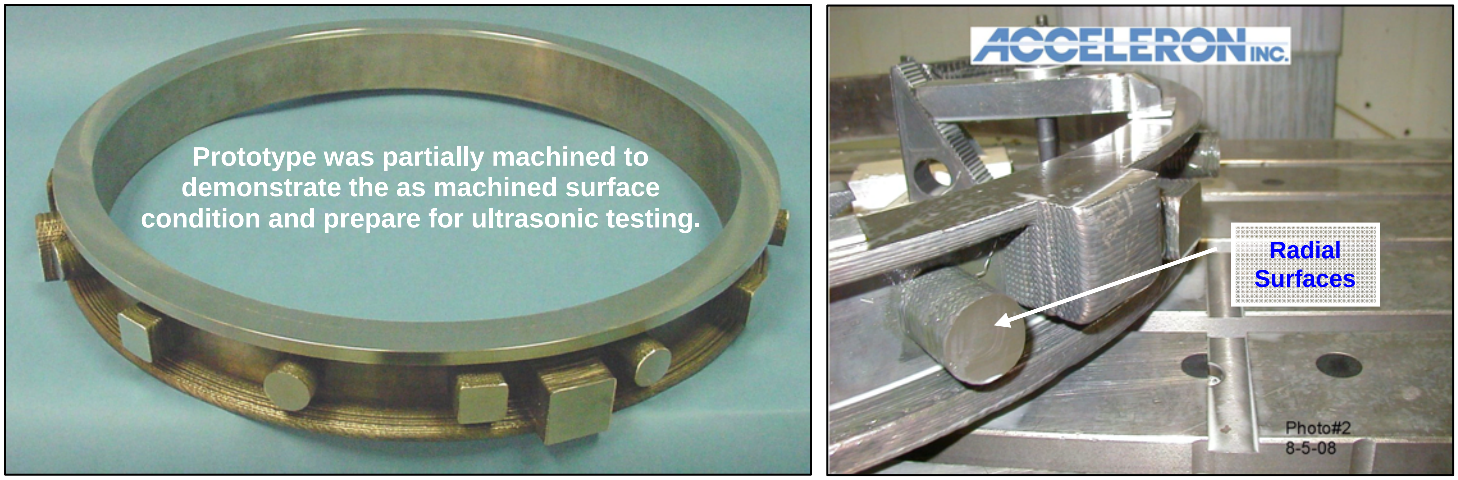


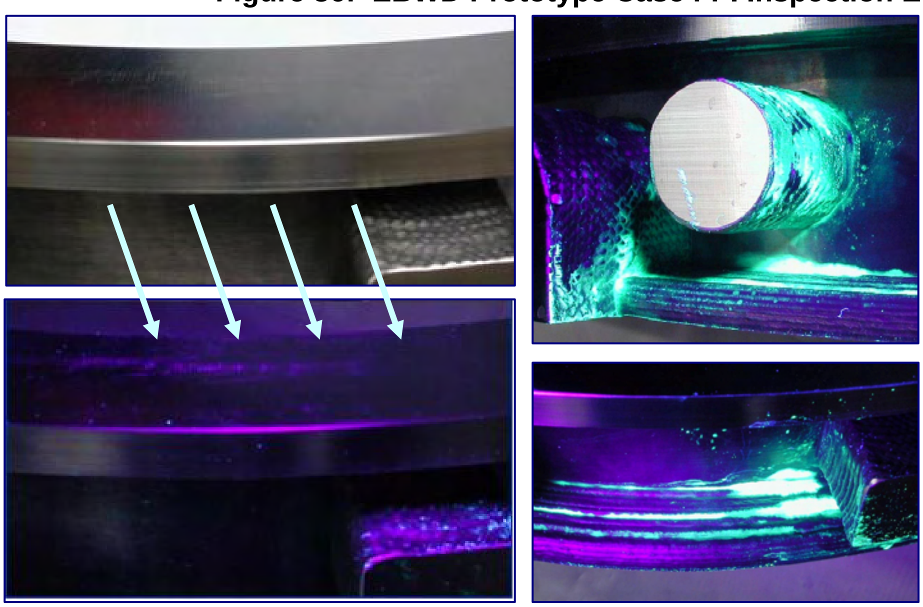
Figure 35: Post Deposition Machining



Radial and axial surfaces were machined to a 32 Ra surface finish to facilitate ultrasonic inspection.

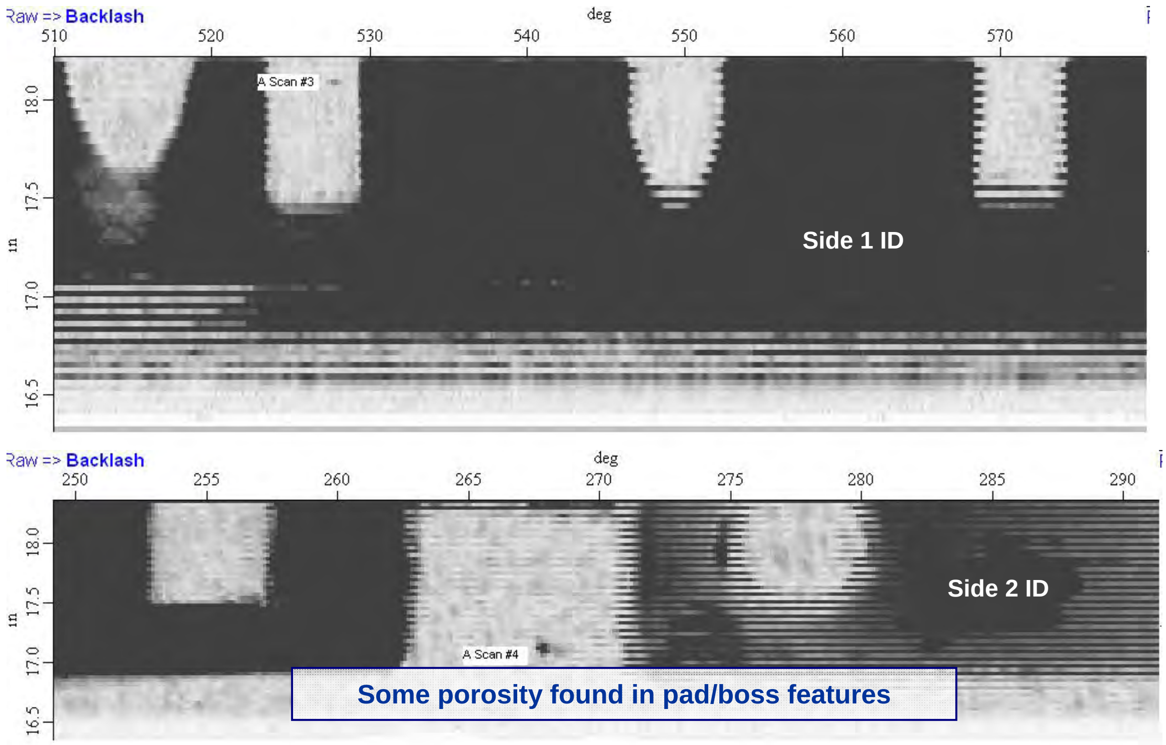
The ring was transferred to Rolls Royce for non-destructive evaluation (i.e. FPI and ultrasonic inspections). FPI did not reveal any indications on the finished machined surfaces (see Figure 36) while ultrasonic did reveal some isolated indications (see Figure 37) though the overall bulk continuity was 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 insure process robustness when scaled up to a production level.

Figure 36: EBWD Prototype Case FPI Inspection Evaluation



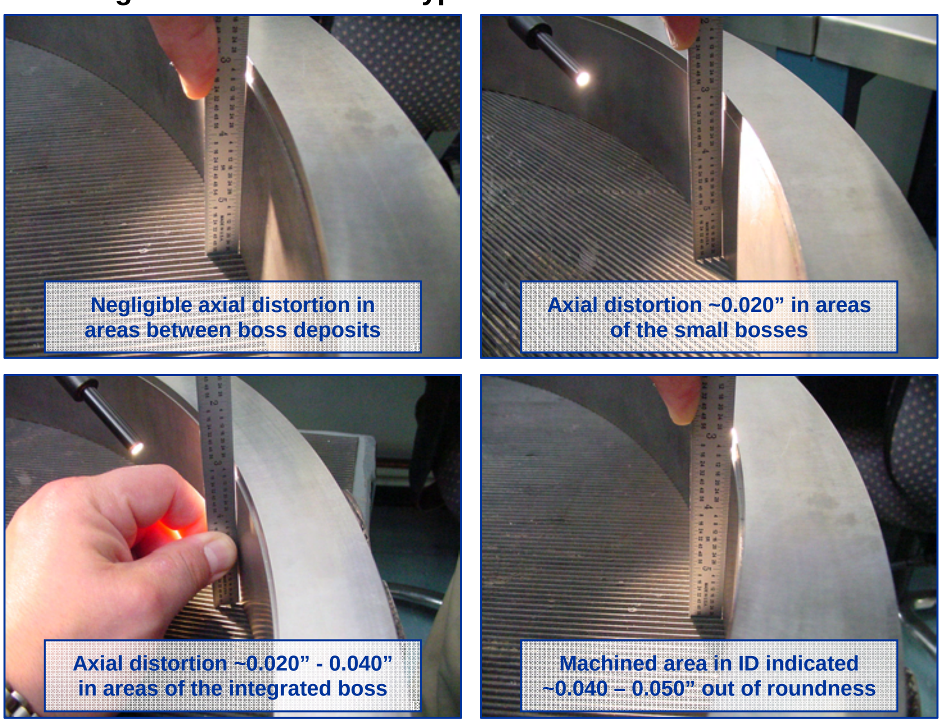
- Local FPI performed on machined and as-deposited surfaces
- No indications found in machined surfaces (left)
- As-deposited (right) essentially not inspectable by FPI

Figure 37: EBWD Prototype Case Ultrasonic Inspection



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 Task 4 and that the intended feature dimensions were met. The post deposition distortion was similar to the levels seen in Task 4 (see Figure 38) and all features were within the intended dimensions listed in Table 12 (see Figure 39).

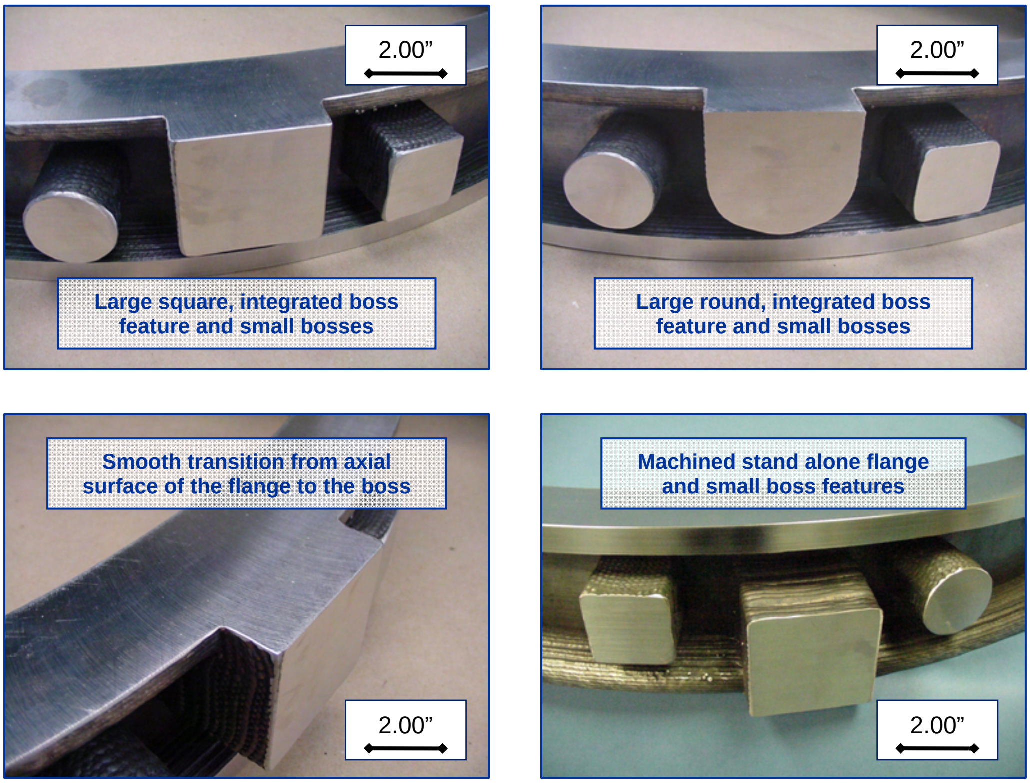
Figure 38: EBWD Prototype Case Distortion Evaluation



- Gage inspection was used to perform the distortion analysis
- Minimal distortion was noted on prototype ring post deposition and heat treat
- Levels were commiserate with those found in Task 4

Table 12: Task 5 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

Figure 39: EBWD Prototype Case Dimensional Evaluation



Draft Specification for Nickel Additive Deposition

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 Task 5, a draft AMS specification was created for Nickel Additive Deposition. This draft specification was intentionally designated as AMS because it was necessary that it be recognized by all engine OEM's while not being a company unique specification. To create this document, AMS 4999 (Titanium Alloy Laser Deposited Products 6Al - 4V Annealed) and AMS 2680 (EB Welding for Fatigue Critical Applications) 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.

Cost and Business Evaluations

The goals of the Task 5 business evaluation focused on the necessary implementation logistics for scaling up to production readiness and the update of the existing cost models to make them more user friendly. The latter was necessary to allow an end user to more readily determine if a part configuration can benefit from additive manufacturing. The specific areas that were evaluated to implement additive manufacturing were:

- The required capital required for machining equipment
- The requirements for scale up of deposition sources
- The lead time and relative “should be” cost of the slim line forgings relative to traditional ring forgings
- The quantity/cost of the required characterization testing needed to incorporate additive manufacturing into the OEM design.

Machining Capital:

To determine if any additional required capital was needed to machine additive material versus conventional wrought product, machining experts in Pratt & Whitney were consulted and it was determined that the standard 5 axis equipment currently used to machine forgings would also be capable of machining cases fabricated with additive technology. Optionally, a power monitor with adaptive capability could be added to existing equipment to accommodate surface roughness differences but this type of add on would serve as a process enhancement as opposed to a necessity and would also represent a relatively minor capital investment.

Production Scale Up

To estimate the requirements for the deposition facility (for EBWD or LPD) to scale up to production readiness, the depositors evaluated in the PW-2 program provided estimated scale up figures for their respective additive technologies. For the purposes of this business evaluation, a notional case was designed to have roughly 20 lbs. of added features. 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).

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 a higher deposition rates on any given part. This higher capacity is estimated to require and additional $2.5M - $3M in 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.

Slim Line Substrate:

Because the ultimate goal of this program is to reduce the cost of fabricating conventionally wrought cases, one of the key aspects to evaluate was the cost and lead time of the starting substrate ring that would become the foundation for added features. The specific items evaluated in this program include:

- Lead time estimates for the slim forgings relative to conventional thickness forgings
- "Should be" cost estimates for slim forgings (i.e. 0.5" thick) relative to conventional forgings (i.e. 2" thick).

Initially Ladish Forge was tasked with providing this information for the PW-2 program. During the course of Task 5, Ladish determined that it would no longer participate in slim line technology. Consequently the team contacted Firth Rixson Limited. As a current supplier of Pratt & Whitney, Firth Rixson was in a position to provide a direct comparison of the current cost of an actual high volume part relative to the projected “should be” cost an equivalent, notional slim case. It was determined that slim ring would require a similar level of lead time for fabrication and is estimated to cost between 10% - 30% less than an equivalent, conventional thick ring depending on cross sectional complexity. On a typical P&W military case application, it was in fact estimated that a slim ring configuration would cost approximately 20% less. Because the “should be” costs accounts for capital investment, volume discounts, and any value added that would be related to fabricating a slim ring; it is not directly proportionate to the reduction in raw material.

Material Characterization Requirements:

Several experts in case structural alloy development and case structural design were consulted to determine the requirements to fully characterize a new material for use on fatigue sensitive, structural components. Based on the assumption that that the designing authority would have very little knowledge of any new alloy, tests would be required on up to 625 specimens at a cost of approximately $2M (see Table 13 for test type and quantity breakdown). Utilization of a new form of a well understood material (e.g. LPD or EBWD Alloy 718) may permit the reduction of testing requirements depending on criticality of the launch hardware. This would also permit the upfront launch of this technology on low risk hardware while simultaneously building a service history on additive material. However, this report and all data herein is based upon a limited set of data for each process and as a result does not represent a full data set for design purposes.

Table 13: Rough Order of Magnitude Estimate for a Full Characterization

Test Type	Qty of Specimens
Tensile	*Between 25 - 50, qty may increase if doing multiple directions*
Creep	*Between 50 - 75, qty may increase if doing multiple directions*
Stress Rupture	*Between 25 - 50, qty may increase if doing multiple directions*
High Cycle Fatigue	*Between 75 - 100, qty may increase if doing multiple directions*
Various Modes of Low Cycle Fatigue	*Between 200 - 250, qty may increase if doing multiple directions*
Crack Growth	*Between 75 - 100, qty may increase if doing multiple directions*
Total	**450 – 625 specimens (total cost ~$2M)**

ARGO Cost and Business Evaluations

In previous tasks, ARGO Enterprises was subcontracted to create an integrated, comprehensive cost model that would take into consideration several factors including raw material, inspections, machining, manufacturing labor rates, etc. This model was used to estimate the potential cost savings of conventionally forged cases if they were to be made with additive manufacturing technologies. Previously these evaluations determined that it was possible to save up to 50% though the potential savings could increase or decrease dramatically based on several factors including:

- *Number of features related to the overall part size*
- *Ratio of final shell thickness to cost disproportionate features (increased feature thickness = increased savings)*
- *Cost of the raw material ($$$ / pound)*
- *Additive deposition rate (pound / hour)*

Other factors such as the manufacturing labor rate would increase or decrease the cost of an additive part but it would simultaneously increase the cost of conventionally fabricated hardware as well. Based the aforementioned factors, the optimal candidates for additive technologies would be wrought cases with few (e.g. four- six) cost disproportionate features. This conclusion is demonstrated in Table 14 which shows the results of a cost analysis performed on the Task 5 Prototype Ring and a simplified version with only four large boss features. In this analysis both EBWD and LPD yielded between 30% - 50% savings on the simplified prototype case depending the relative price of nickel.

Table 14: Cost Analysis Using Task 5 Prototype and Updated Argo Cost Model for EBWD & LPD				
Assumed Nickel Cost ($/lb)	**Percentage Cost Difference for EBWD Relative to Conventional Forging**		**Percentage Cost Difference for LPD Relative to Conventional Forging**	
	Prototype T5 Case Using 20 Bosses and 2 Flanges	*Simplified T5 Case Using 4 Large Bosses*	*Prototype T5 Case Using 20 Bosses and 2 Flanges*	*Simplified T5 Case Using 4 Large Bosses*
$20.00 / lb	68% additional	34% savings	96% additional	39% savings
$30.00 / lb	31% additional	44% savings	53% additional	48% savings
$40.00 / lb	9% additional	51% savings	27% additional	53% savings
$50.00 / lb	6% savings	55% savings	9.8% additional	57% savings

Additional enhancements to the Argo cost model included the addition of cost considerations for non destructive inspections associated with additive manufacturing and the addition of explanatory annotations to increase the user friendliness of the model.

PW-2 Program Conclusions

Though the sequential phases of the PW-2 the program; additive manufacturing was demonstrated from feasibility through prototype production scale hardware. Ultimately the program determined that:

- Additive manufacturing technologies (LPD & EBWD) have proven to be capable of producing high quality features in aero-engine configurations.

- The use of additive manufacturing can be an enabling technology to produce experimental/development or low volume hardware.

- Additive manufacturing can be used as a weight saving enabler for cast structures by permitting the use of higher strength wrought substrates.

- 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.

PW-2 CONTRIBUTING TEAM MEMBERS

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