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REPAIR PROCESS TECHNOLOGY DEVELOPMENT & EXPERIENCE OF FRAME 7FA+E, STAGE 1 TURBINE BUCKETS

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ABSTRACT

The 60 Hz, Frame 7F engine has been in commercial operation for more than two decades now with approximately 600 Frame 7 (F, FA, FA+ and FA+e models) machines existing in North America and a total of over 1100 F-class machines throughout the world. Volatile market dynamics in the electrical power generation field continues to force power companies to identify prudent material cost reductions opportunities in their Operations and Maintenance (O&M) business. Today, there is an industry-recognized need for advanced hot gas path component repair and reconditioning capability for operators of F-Class gas turbines that can be highly cost effective with short cycle times.

The first stage buckets of the Frame 7F engine are unshrouded; whereas the next 2 stages are shrouded. Out of these rotating components, the first stage buckets show the worst degradation and thus repair of these components have been a focus point for Power Systems Mfg., LLC (PSM). The technical objective is to develop a comprehensive set of repair schemes for the stage 1 buckets since these components have the highest frequency of replacement. Listed below are some of the special repair processes that have been developed for the first stage bucket:

a) Acid stripping of the MCrAlY coating (and internal aluminide coating having endured 48,000 hours of service)
b) High speed grinding off of the electron beam (EB) or laser beam (LB) welded tip cover plates
c) High frequency gas tungsten arc (GTA) weld repairs of platform cracks using a new and novel developed high strength yet ductile weld filler metal
d) High frequency gas tungsten arc weld attachment of new tip cover plates
e) Laser metal forming/cladding of new squealer tips
f) Rejuvenation heat treatment for buckets that have reached 48,000 hours
g) Application of new internal aluminide coating
h) Application of upgrade design features, such as platform cooling and platform undercut
i) Application of a superior MCrAlY bond coating to that of the Original Engine Manufacturer (OEM)
j) Application of a vertically cracked high density (VCHD) strain tolerant thermal barrier coating (TBC)

This technical paper describes the repair development process, the implementation of the different stages of the repair schemes and presents metallurgical and mechanical characteristics of the repaired regions of the component.

INTRODUCTION

The Frame 7F, FA, FA+ and FA+e gas turbine, an “F” class machine currently rated at 150MW, 159MW, 169MW and 172MW output respectively, is employed exclusively in 60-Hz applications. This 7F, 7FA, 7FA+ and 7FA+e model engine entered service in 1990, 1993, 1998 and 2000 respectively. It is estimated that today there are approximately 600 machines currently commissioned and in operation in the USA alone. All these engines have 18 compressor stages and 3 turbine stages. The firing temperature for the above 4 mentioned gas turbine engines are approximately 1260^{o}C, 1287^{o}C, 1316^{o}C and 1327^{o}C respectively.

Significant degradation has been observed on the stage 1 bucket after 24,000 hours of service prior to first reconditioning as a result of various damage mechanisms. Repair yields of buckets during the second refurbishment (i.e. after 48,000 hours) using “conventional” methods have been relatively low as a result of the severity and location of platform cracks, exhaustion/consumption of the internal aluminide coating and suction side platform and airfoil

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cracking in the "ski-jump" area. As a result of the high cost of new replacement buckets, owners and operators of this equipment require a robust bucket repair process to maximize the yield of serviceable parts as well as service life, while maintaining reasonable cost.

It is therefore of extreme importance to engine operators and owners of these gas turbine to have structurally sound component reconditioning / refurbishment capabilities available to support their maintenance requirements. Special processes to recondition the stage 1 turbine bucket, definitely one of the most expensive and the highest "frequency of replacement" component in the hot section of the turbine, were recently developed at PSM. This is not the first time a novel repair has been implemented for the Frame 7FA, row 1 bucket (Ref 1, 2). Procedures developed include coating removal via acid stripping, removal of degraded (bulged and oxidized) tip plates, rejuvenation heat treatments, full tip cover replacement utilizing high frequency gas tungsten arc welding (GTAW), laser welding/cladding of the squealer tip, high frequency GTAW with a new and novel weld filler metal for platform crack repairs and re-coating, both internally and externally for buckets having operated to 48,000 hours.

TYPICAL DAMAGE OF THE OEM, STAGE 1 BUCKET

The Frame 7FA+e first stage turbine bucket is cast from GTD111, a nickel base superalloy material of nominal composition Ni-3.0Al-0.015B-0.11C-9.5Co-14Cr-1.5Mo-2.8Ta-4.9Ti-3.8W-0.03Zr. The material is investment cast in a directional solidified (DS) structure, and as a result the material is usually designated as DS-GTD111. There are internal serpentine passages as seen in fig 1 (Ref 3), to provide air-cooling; however, unlike the W501F, row 1 blade, (Ref 4) the internal passages are aluminide coated. The airfoil tip possesses one cover plate Electron Beam (EB) welded or Laser Beam (LB) welded into place (depending on whether it a first interval or second interval bucket) to act as core hole closures, and a cooling air metering plate is also brazed to the bottom of the bucket root. An overall view of a first stage turbine bucket after 24,000 engine operating hours is shown in fig 2. Tip degradation and TBC spallation are clearly evident. In addition platform oxidation is also evident. This photograph is not representative of the entire engine set, rather it is the worst one in that engine set, used to illustrate the different distress modes that can be present on the bucket.

The primary damage mechanisms for the Frame 7FA stage 1 turbine bucket are thermal-mechanical fatigue (TMF), low cycle fatigue to crack initiation and oxidation. After 24,000 hours, the bucket can exhibit significant airfoil tip damage as well as platform cracking and thermal erosion as a result of oxidation. Examples of the various modes of degradation are shown in fig's 3-12.

Figures 3 and 4 show bucket tip cracking & fig's 5 and 6 show pressure side TE and LE platform cracking respectively.

Figure 7 shows suction side platform cracking. The pressure side LE fillet and TE fillet platform crack has a tendency to meet each other, i.e. propagate along the fillet radius region and liberate the entire platform as seen fig 8.

In some isolated occasions, as seen in fig 9 part of the tip cover plate liberates and the entire LE burns away.

Figures 10 and 11 show platform oxidation, and tip oxidation + cracking respectively. It is really the platform degradation that lowers the repair yield and is the main challenge for reconditioning this bucket. Figure 12 shows TE cracks. It is very important to understand why the component degraded in order to effectively recondition it.

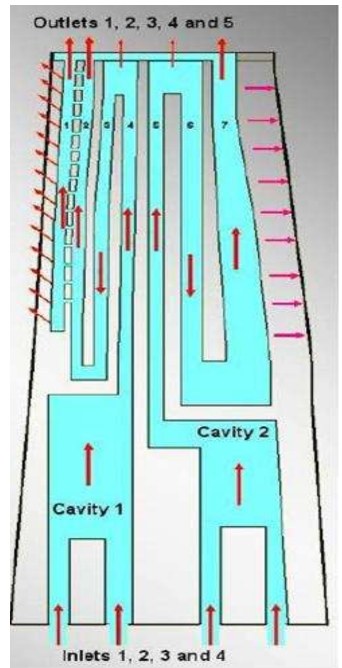

Figure 1 – Schematic of internal serpentine passages of the Frame 7FA, stage 1 bucket (Ref. 3)

Figure 2 - Overall view of the worst engine run Frame 7FA, stage 1 bucket in a particular engine set

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Figure 3 - Airfoil tip oxidation and cracking

Figure 4 - Airfoil tip oxidation and cracking

Figure 5 – Pressure side TE platform cracking

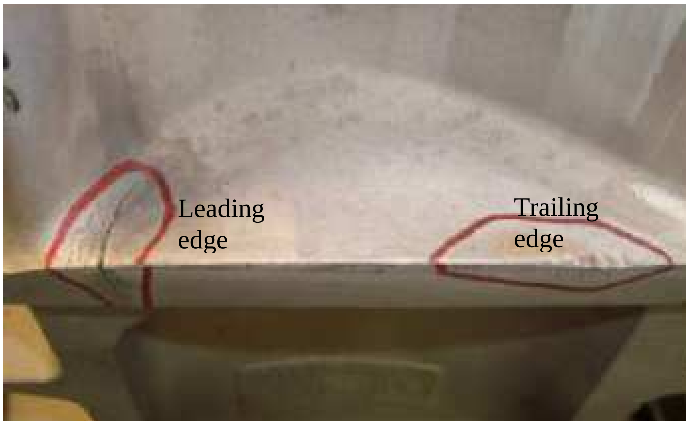

Figure 6 – Pressure side LE and TE platform cracking found during penetrant inspection

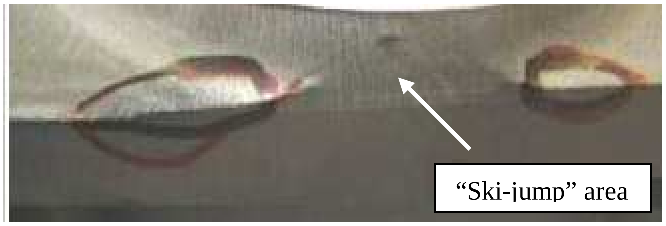

Figure 7 – Suction side platform cracking

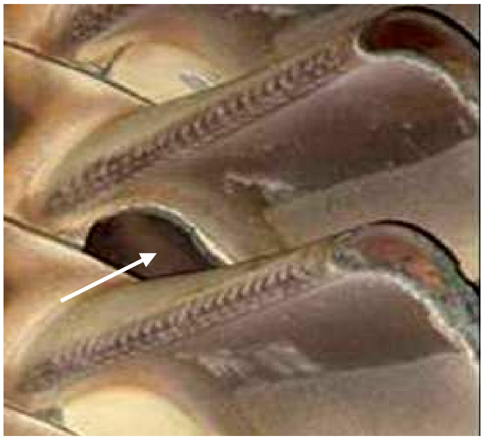

Figure 8 – Liberation of pressure side platform

Figure 9 – Leading Edge Burn Through

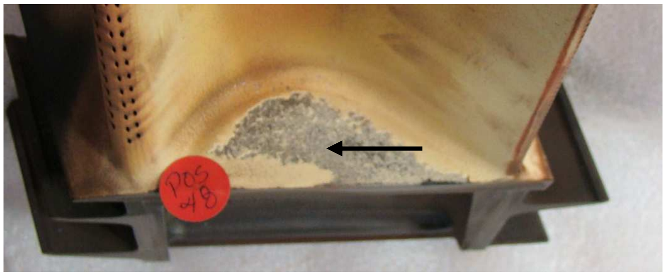

Figure 10 – Platform oxidation

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Figure 11 – Tip oxidation and TMF cracking

Figure 12 – TE cracking

GENERAL WORKSCOPE

For reconditioning of the stage1 turbine bucket, a general workscope can be formulated as follows:

- Receive & inspect
- Blast or Water jet remove thermal barrier coating (TBC)
- Remove MCrAlY coating via acid stripping (if bucket has reached 48K hours, strip internal coating as well)
- Pre-repair inspect
- Grind off entire tip exposing core cavities
- Rejuvenation heat treatment
- Repair airfoil tip via GTA welding and laser cladding
- Repair platform degradation via GTA welding with new novel filler metal.
- Suction side platform repair via brazing
- Post-repair solution heat treatment
- Fluorescent Penetrant Inspect (FPI) and X-ray check
- Add upgrade features like platform cooling to the bucket, full length trailing edge platform undercut
- Apply MCrAlY bond-coat to airfoil and tip cavity
- Coating diffusion and age heat treatment
- Apply vertically cracked high density (VCHD) ceramic topcoat (TBC)
- Final inspect

Reconditioning process development would thus not only need to address repair of physical airfoil and platform damage, but must also consider the safe removal and reapplication of the two-layer airfoil coating. Additionally, rejuvenation heat treatments must be integrated into required repair and coating processes. Since oxidation and thermal fatigue are major degradation modes, the choice of weld filler metal becomes very important. For example, the weld filler metal used at the tip of the bucket has good oxidation resistance, but not equivalent strength when compared to the DS-GTD111 base metal. Conversely the weld filler metal utilized to repair the platform cracks does not have good oxidation, and thus it relies on the coating above it from oxidation protection, but the weld repaired region has good LCF properties.

RECONDITIONING PROCEDURE DEVELOPMENT AND IMPLEMENTATION

General Requirements

The repair procedure development was started by reviewing the geometrical configuration on the Component Measuring Machine (CMM), manufacture, materials, and operating conditions of a typical Frame7FA, Stage 1 bucket. Cooling holes locations at the tip of the airfoil were accurately reverse engineered for redrilling at the end of the repair, since the repair involved grinding off the entire tip region, thus exposing the core cavity. The EPRI published information (Ref 1, 2) pertaining to traditional repair limits and other repair techniques employed by other repair companies, were also judiciously scrutinized and evaluated.

Full appreciation of the synergistic relationships between the GTD111 composition, its structure and properties, applied stresses, strains and temperatures, and subsequent processing such as chemical stripping, rejuvenation and heat treatments, welding and coating was essential in developing a sound reconditioning methodology. The exact assessment of the actual condition of the buckets based on their operational history and on metallurgical evaluations was also an important factor in planning an effective and efficient refurbishment procedure. Grain boundary carbide precipitation, gamma prime precipitate overaging and creep damage manifesting itself as voids are some of the undesirable microstructural features that could occur in the GTD111 buckets after years of service. This microstructural degradation can usually be reversed through rejuvenating heat treatments, which are strategically incorporated in the repair workscope.

The following paragraphs rationalize the approach that was taken with the development and implementation of some of the more sensitive and challenging operations (see general workscope in the previous paragraph) involved in this repair.

Coating Removal and Metallurgical Evaluation

The TBC is removed via manual grit blasting and other than strictly following work process instructions, there is not anything novel regarding removal of the TBC. Some preliminary studies have been conducted using the WaterJet Removal process and results appear promising. However, the MCrAlY bond coating is removed via acid stripping. Stripping of the GT33-(Co-32Ni-22Cr-10Al-0.3Y) MCrAlY coating from the GTD111 base metal needs to be carefully controlled since the acid utilized attacks the Al-rich areas from the coating (i.e. the beta phase) and if the stripping is not controlled properly, the acid could attack the gamma-gamma

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prime eutectic phases along grain boundaries of the base metal, as well as the aluminum-rich gamma prime phases. This results in a process called inter-granular attack (IGA). Therefore the acid solution concentration, temperature of the bath and processing time that was utilized for acid stripping were carefully controlled. Special care utilizing proprietary masking techniques was also taken to prevent chemical degradation of the uncoated critical areas of the bucket, such as the dovetail/root and the internal cavities of the airfoil. A process of heat tinting is utilized to ensure complete removal of the coating. Figure 13 shows that the coating removal was verified by heat tinting, since the buckets turned blue in color and fig 14 shows metallographically that the IGA attack is within acceptable limits. In cases where the heat tint reveals uninterpretable or strange color artifacts, then a grain etch is performed and the results can be seen as evident in fig's 5 and 6, where the DS grains of the airfoil can be seen as well as the large 1 to 4 grains that can also be seen on the platform.

Platform Repair by Welding and Brazing inclusive of Metallurgical Evaluation and Mechanical Property Assessment

Degradation of the platform area in service initiates via the well-known mechanism of thermal-mechanical fatigue (TMF) and then propagates in TMF/Creep (hold time) mode. TMF damage results from the high thermal transient stresses from the unit start-stop cycles, and manifests itself at the bucket platform as numerous heavily oxidized radial cracks along the platform edge (see fig 15). The prevalent location of cracking can be seen in figures 5 and 6. Note, the crack as viewed from the slash face side of the platform does not surprisingly initiate at the grain boundary and actually occurs intragranularly. An example of a platform crack can be seen in fig 16. Since the platform consists of 1 – 4 large grains and its orientation is different from that of the airfoil grains, i.e. it is orthotropic (has the different materials properties or strengths in different orthogonal directions). The stiffness of the platform is dependent on orientation of these grains and it is this stiffness that dictates the strain distribution and where the TMF crack initiates.

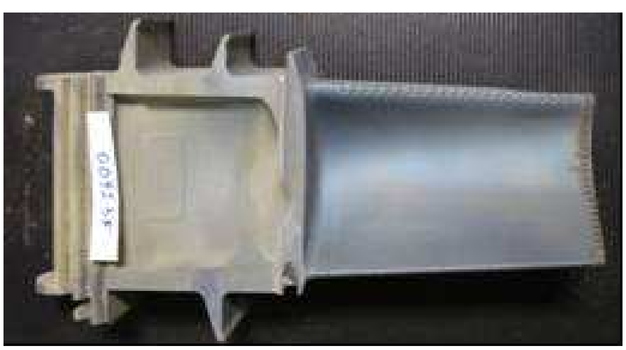

Figure 13 – Pressure side view of the bucket indicating a bluish heat tint condition

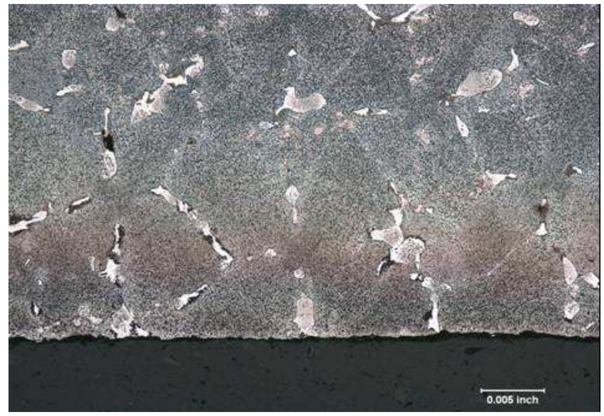

Figure 14 – Metallurgical evaluation of the base metal after acid stripping showing acceptable IGA

Figure 15 – Evidence of TMF cracks and creep voids/cracks in the platform area of the bucket.

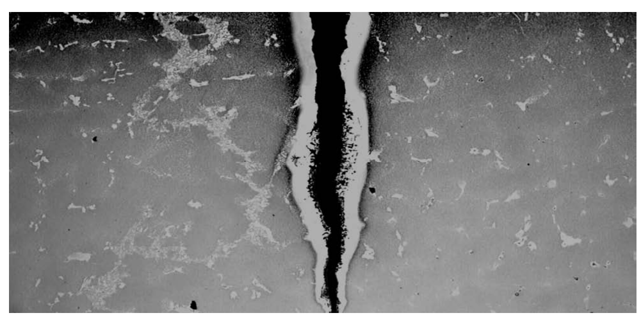

Figure 16 – Oxidized crack found on the platform

Since the transient TMF loading causes localized high strain, it is desirable for the materials deposited in a repair process to be as strain tolerant as possible, i.e., possess good tensile ductility and respectable low cycle fatigue (LCF) properties. Although good high temperature strength approaching base material values is still necessary for the repair material, a more ductile filler material will actually improve TMF cracking resistance in this area of the bucket.

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Strain-age cracking in the heat-affected-zone (HAZ) of the weldment is a particularly frequent problem encountered when welding and postweld heat-treating GTD111. The main factors that can cause cracking in GTD111 are:

- low ductility of the precipitation-hardenable weld metal and base metal heat-affected-zone
- residual tensile stresses produced by the solidification of the weld pool, and
- shrinkage stresses caused by the precipitation of the gamma-prime phase in both the weld metal and the base metal. (Ref 5, 6)

One way of improving the local ductility and reducing the amount of strain caused by the gamma-prime precipitation is to use solid-solution strengthened weld filler metals such as Inconel 625. But the use of this solid-solution strengthened material is prohibited by the high strains/stresses and temperatures experienced in the platform areas. Therefore, the approach taken was to use a specially developed weld filler metal that had good tensile strength, while having significant ductility. The composition of this filler metal is proprietary; however it contains the elements Ni-Cr-Co-Mo-Ti-Al-Si-C-B-Mn-Fe.

Excellent manual high frequency GTA welds were produced at room temperature, as seen in fig's 17 and 18, using the specially developed weld wire in the platform areas, with no post-weld heat-treatment cracking observed. Metallographic evaluation also confirmed that the weld repair was of good quality, since no HAZ microfissuring or fusion zone cracks were evident as seen in fig's 19 and 20. In fact fig 20 shows a weld produced with this high frequency welding process using the novel weld filler metal that occurs over a grain boundary, and one would expect a crack to have developed at the grain boundary, but none was evident.

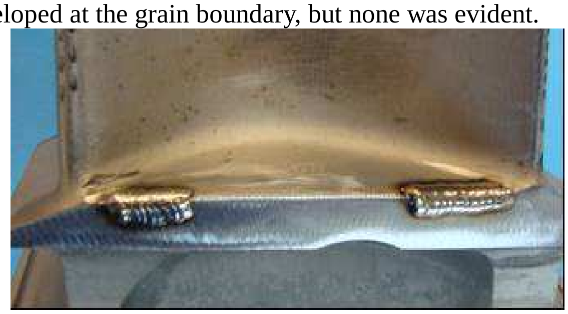

Figure 17: Platform crack repair via high frequency GTAW using new novel weld filler metal

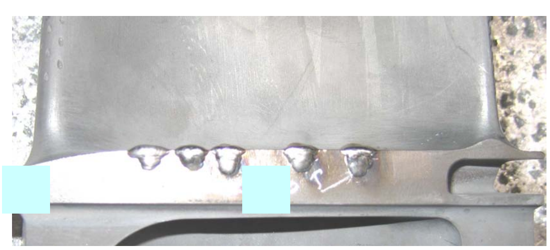

Figure 18: Platform crack repair via high frequency GTAW using the new novel weld filler metal

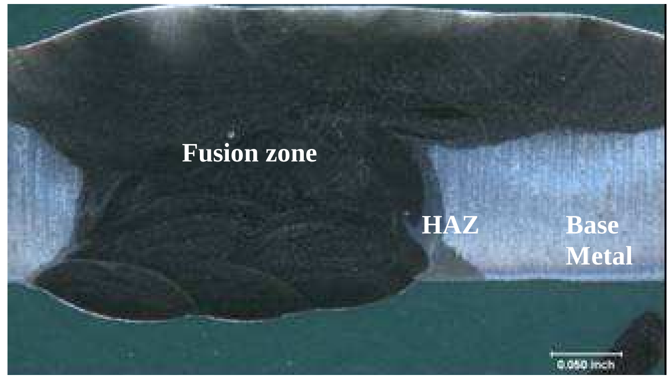

Figure 19 – Cross-section of weld repair showing no microfissuring or post weld heat treatment cracking

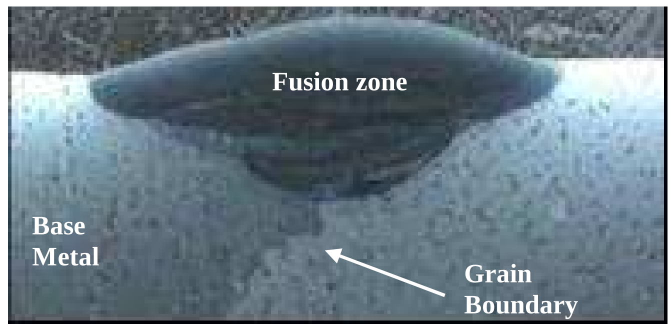

Figure 20: Platform crack repair via high frequency GTAW using new novel weld filler metal

Tensile testing was performed on both DS-GTD111 specimens in the longitudinal and transverse directions, as well as specimens that were welded with the same filler metal used to repair platform cracks. Testing was performed at various temperatures from room temperature to 982°C, and the non-dimensionalized results are shown in fig 21. In summary, the UTS of the weld is equivalent to the YS of DS-GTD111 longitudinal base metal.

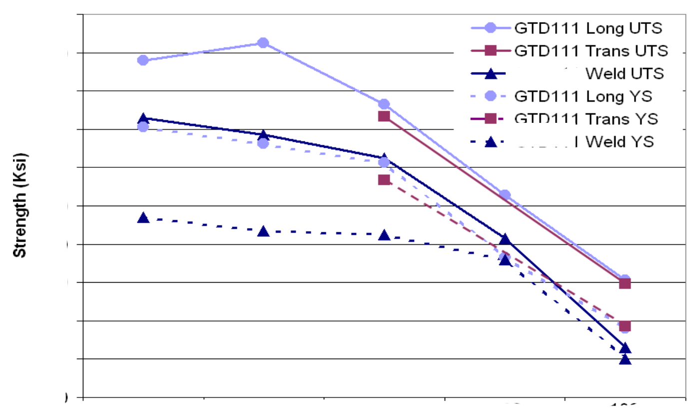

Figure 21 – Tensile properties of the weld repair versus the DS-GTD111 base metal (longitudinal and transverse directions)

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Low Cycle Fatigue (LCF) testing was also performed on both DS-GTD111 specimens in the longitudinal and transverse directions, as well as specimens welded with the same filler metal used to repair platform cracks. Testing was performed at 816°C (1500°F), and the non-dimensionalized results are shown in fig 22. In summary, the LCF life of the weld is equivalent (if not slightly better) compared to GTD111 transverse base metal.

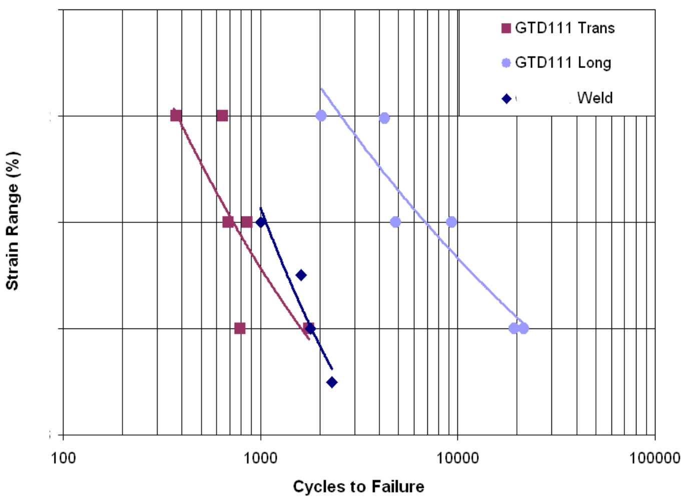

Figure 22 – LCF properties of the weld repair versus the DS-GTD111 base metal (longitudinal and transverse directions)

Since the 1 – 4 large grains have properties equivalent to transverse properties, having the weld with equivalent properties to that of the area being weld repaired is deemed a sound repair strategy.

During development of the weld repair on scrap buckets it was found in some cases that there were numerous cracks on the suction side of the platform as seen in fig 23. When the weld repair was taking place, the cracks propagated into the airfoil region as a result of the thermal heating and contraction rates, during the weld repair process. As a result it was decided to grind off a specific amount, thereby removing all of the cracks and doing a braze build up using a braze preform of proprietary composition as shown in fig 24. Since the bucket had to undergo a post weld heat treatment anyway, the braze cycle was implemented to coincide with the post weld heat treatment temperature, thus avoiding 2 thermal heat treatments, i.e. a post weld heat treatment and a braze run. With diffusion brazing, since the bucket is heated up and cooled uniformly in a vacuum furnace (unlike welding where the heat is localized) cracks did not propagate into the fillet or airfoil regions during heat up and cool down. Figure 24 shows the application of the braze preform to the slash face on the suction side of the platform.

As can be seen in figure 25, the braze preform has bonded well with the DS-GTD111 material. The microporosity is the diffusion brazed region is less than 1%. The tensile strength as seen in Table 1 is equivalent or better than some of the newest solid solution alloys.

Figure 23 – Suction side platform cracks. 6 cracks marked at FPI are evident on the slash face.

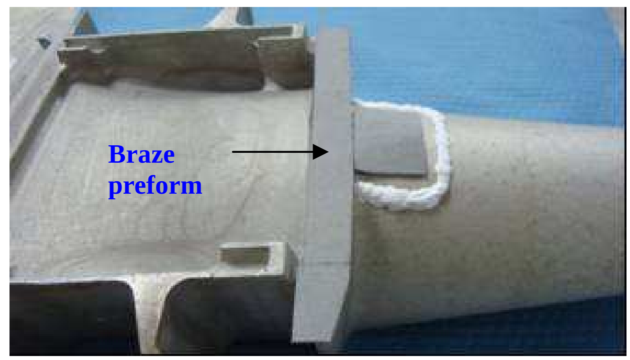

Figure 24 – Application of braze preform for suction side platform build up

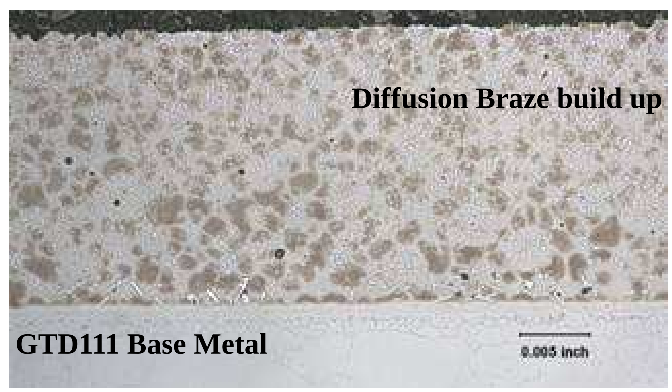

Figure 25 – Micrograph of the diffusion braze build up using a braze preform.

Table 1 – Tensile Properties of the diffusion brazed region

Test Temp	Tensile Strength	Yield Strength	Elongation	Red. in Area
23C	697 MPa	614 MPa	1.5%	3.5%
650C	580 MPa	518 MPa	1.8%	3.7%
760C	497 MPa	455 MPa	1.7%	3.9%
982C	393 MPa	290 MPa	2.0%	4.0%

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Bucket Tip repair by both Manual GTAW and Laser Cladding inclusive of Metallurgical Evaluation and Mechanical Property Assessment

After careful examination of the OEM design of the stage 1 bucket tip, and considering some of the degradation modes associated with the originally EB welded tip plate as observed in fig's 3 and 4, it was decided to find an improved alternative. The repair involved complete removal of the damaged squealer tip, including the EB welded cover plate by surface grinding with CBN grinding wheels, weld repairing the bucket tip cracks, re-attaching 5 new tip cover plates, referred to as "chicklets", using manual high frequency gas tungsten arc welding (GTAW), and finally weld build-up of the squealer tip on top of the 5 new cover plates using laser cladding.

Figure 26 shows the squealer tip and EB welded cover plate that was removed via grinding and one can also see the core cavities exposed as well as that there are numerous cracks on the bucket tip region.

Figure 26 – Squealer tip and EB welded cover plate that were ground off to expose the core cavity

Figure 27 shows the bucket prepped for tip crack weld repair and fig 28 shows the tip cracks weld repaired using the high frequency GTAW process.

Figure 27 – Bucket prepped for tip crack weld repair

Figure 28 – Weld repair of cracks at the tip of the bucket

Figure 29 shows the 5 new chicklets welded on to close the core cavities. The squealer tip originally was manual GTA weld restored but after implementing this process on the first 2 production engine sets it was found that it was extremely labor intensive and as a result the laser cladding repair was developed.

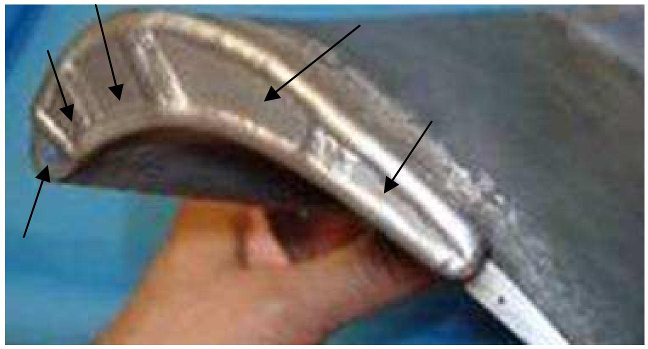

Figure 29 – Five new chicklets GTA welded on the tip of the bucket to close the core cavities

Figure 30 shows the set up of the laser welder during cladding of the squealer tip. Figures 31 and 32 show the difference between the laser clad restoration of the squealer tip versus the manual GTA weld build up. As can be seen the laser cladding restoration is near net shape, resulting in a reduction in not only cycle time but also blending time, (i.e. the squealer tip has to be contoured to that of the bucket shape). In addition the difficulties associated with weld cracking of the GTD111 superalloy while simultaneously trying to find a way of making the repair more productive than by manual GTA welding, resulted in laser cladding technology now being implemented on all production bucket repairs at this facility. The entire bucket tip weld repair, inclusive of chicklet weld attachment and the squealer tip restoration was evaluated metallurgically. The chicklet material was specially chosen and is more oxidation resistant than the GTD111 base metal. Similarly the weld filler for attaching the chicklets to the bucket as well as restoring the squealer wall was specially developed and is more oxidation resistant than the GTD111 base metal.

Figures 33 and 34 show the metallurgical results of the entire chicklet weld attachment and the squealer tip restoration. As can be seen, weld cracking is not evident because a smaller laser weld pool volume usually translates into lower solidification stresses and there is good fusion and bonding to the bucket tip and chicklet material.

Mechanical testing was also performed to verify the choice of weld filler metal utilized for the squealer tip restoration. It should be noted that the stresses at the bucket tip are low and therefore one does not need to weld the squealer tip with GTD111 weld filler. As a result, a specially developed weld filler that was more weldable and more oxidation resistant, was utilized for the squealer tip restoration and the resultant stress rupture properties of the weld filler can be seen

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in the non-dimensionalized fig 35. Obviously there is a reduction in the stress rupture properties of the weld since the weld filler does not have the same gamma prime content as that of the GTD111 base metal. In summary, the GTD111 Long and Trans Base Metal can take 1.5X to 3.5X higher stress for the same stress rupture life as the Weld. Nevertheless, the stress rupture properties exceed the design life of the bucket material at the tip.

Figure 30 – Laser cladding during repair of the squealer tip

Figure 31 – Laser cladding of the entire squealer tip

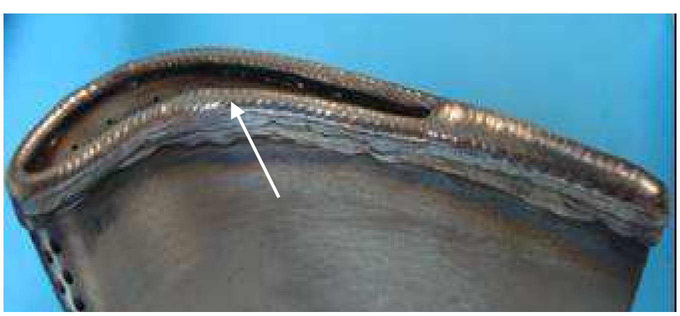

Figure 32 – Manual GTA weld restoration of the bucket squealer tip

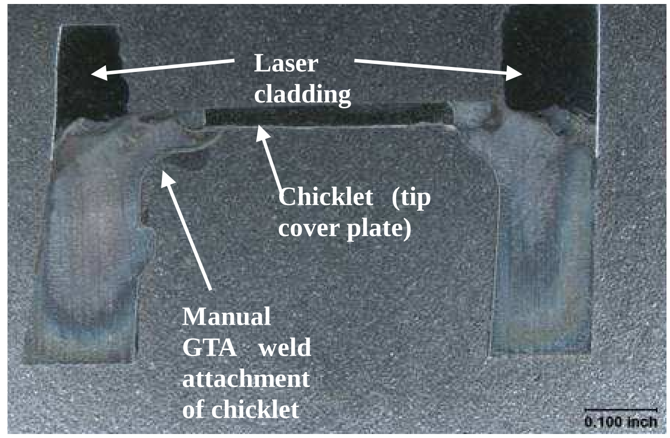

Figure 33 – Manual GTA weld attachment of the chicklet and laser cladding of the squealer tip

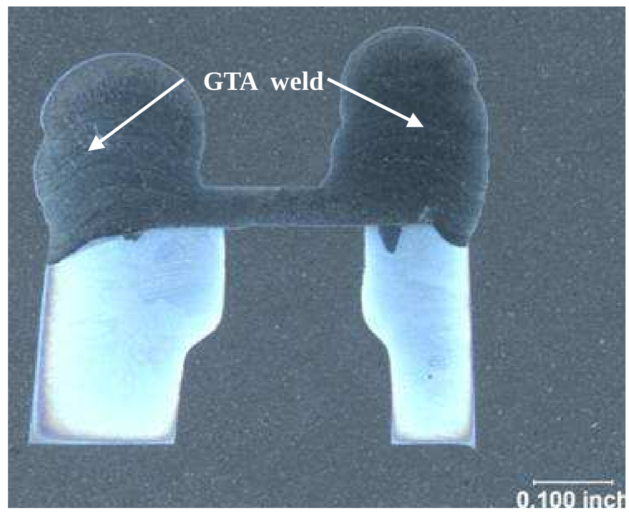

Figure 34 – Manual GTA weld attachment of the chicklet and manual GTA weld of the squealer tip

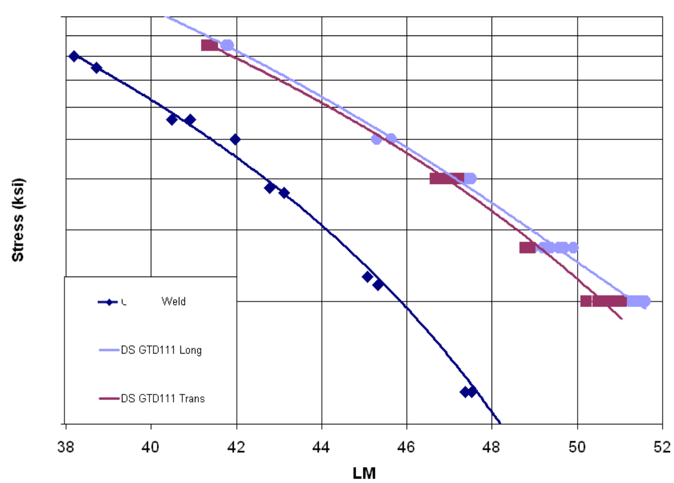

Figure 35 – Stress rupture properties of the squealer tip weld repair versus that of DS-GTD111 base metal

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Figure 36 shows non-dimensionalized data that the oxidation resistance of the squealer tip weld filler metal is superior to that of the DS-GTD111 base metal.

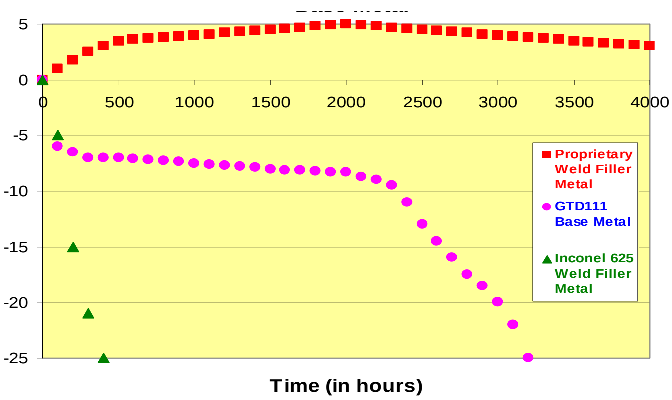

Figure 36 – Weight gain/loss of the squealer tip weld repair versus that of DS-GTD111 base metal

Rejuvenation Heat Treatment inclusive of Metallurgical Evaluation and Mechanical Property Assessment

During the metallurgical assessment of engine run buckets, it was observed that the gamma prime (γ') phase coarsened, and the formation of a γ' layer along the grain boundaries, was discovered. This condition reduces the creep strength and the ductility of the bucket material because these grain boundary films are brittle and can act as nucleation sites for creep voids (ref 7); although no evidence of creep voiding was detected in the airfoil areas.

In addition the investment casting process utilized to manufacture these bucket did not result in any large areas of shrinkage porosity. As a result HIP rejuvenation was not considered during the repair of these buckets. To precipitate a more favorable microstructure, i.e. better γ' morphology and no γ' films on the grain boundaries, a full solution heat treatment was performed on the repaired bucket after 48K hours of operation. As a reminder the standard heat treatment for GTD111 is 1121°C (2050°F) for 2 hrs, and is therefore just a partial solution heat treatment, which in turn is followed by an 843°C (1550°F) age heat treatment. The full solution heat treatment was performed at 1204°C (2200°F) for 4 hour followed by rapid cooling in a vacuum atmosphere. This took all the γ' into solution and thereafter the standard heat treatment was performed to precipitate an appropriate γ' morphology. As a result of exposing the bucket material to the 2200°F heat treatment, metallurgical evaluation was performed to verify if recrystallization (Rx) had occurred. Indeed Rx was found but the depth was within the Reconditioning specification. Figure 37 shows coarsening of the γ' phases after engine operation and the little effect the standard 1121°C (2050°F) heat treatment had in reverting the γ' phases to a more cuboidal morphology. The etchant utilized attacked the γ' phases and leaves the gamma matrix intact.

Figure 38 shows the dramatic and significant change in γ' morphology, with an ideal cuboidal shape and size forming as a result of the super-solvus rejuvenation heat treatment. Stress rupture tests were conducted to assure that the changes to the integrated heat treatment schedule did not degrade the creep rupture properties Table 2 shows that the rejuvenation heat treatment improved the stress rupture properties by a factor of 3 to 16X depending on the test temp. Although the simple short tests performed in Table 2 indicate that the specification minimum has been met, long term creep rupture tests in the order of 1000 hours have been achieved, to ensure that the rejuvenation heat treatment is successful.

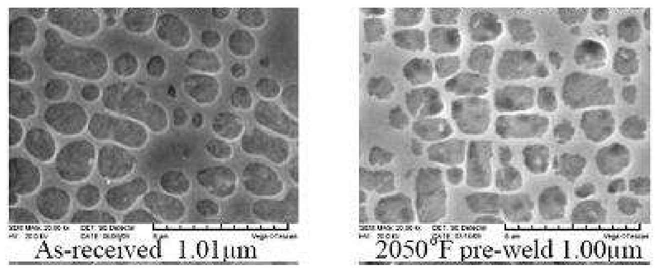

Figure 37 – Morphology of the engine run material showing significant coarsening of the γ' phases (LEFT) and little change in γ' morphology after the standard 1121°C (2050°F) heat treatment (RIGHT)

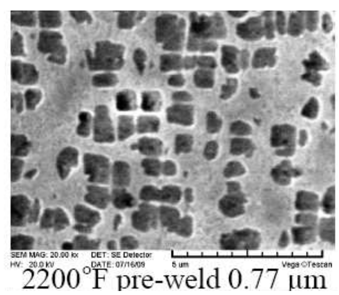

Figure 38 – Morphology of the rejuvenated material showing an ideal distribution of cuboidal γ' phases

Table 2: Mechanical Properties of engine run material given a standard partial solution HT versus a super solvus full solution HT. (HT=heat treatment)

CONDITION	LOC	TEMP °F	STRESS psi	UTS psi	0.2% YLD psi	EL %	RA %	LIFE hrs
As received	Root	70		172,400	135,800	7	11	
2050F Sol	Root	70		144,500	123,600	9	14	
2200F Sol	Root	70		148,200	126,500	9	10	
As received	Root	800		142,800	124,800	8	12	
2050F Sol	Root	800		157,800	121,200	7	11	
2200F Sol	Root	800		139,900	110,400	9	14	
As received	Airfoil	1200		161,600	124,200	6	8	
2050F Sol	Airfoil	1200		180,500	116,300	9	15	
2200F Sol	Airfoil	1200		181,200	118,600	7	12	
As received	Airfoil	1400	95,000			23	31	10
2050F Sol	Airfoil	1400	95,000			24	33	16
2200F Sol	Airfoil	1400	95,000			19	24	165
As received	Airfoil	1800	27,000			31	35	32
2050F Sol	Airfoil	1800	27,000			28	49	32
2200F Sol	Airfoil	1800	27,000			27	35	100

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Upgrades provided to the 7FA/7FA+e 1st stage bucket

Figure 39 shows the platform cooling configuration applied to buckets that arrive for repair without any platform cooling. Figure 40 shows the VCHD TBC also applied to the tip cavity. Figure 41 shows the alternative TE undercut to that supplied by the OEM, which is applied to buckets that arrive for repair that do not have any TE undercut. Figure 42 shows the modification to the shank to allow for cooling air to reach the platform and fig 43 which is not really an upgrade, is the trailing edge cut-back (scallop) applied to buckets that arrive for repair with TE cracks as seen in fig 12.

Figure 39 - Platform cooling hole upgrade

Figure 40 – Application of VCHD TBC to the bucket tip cavity

Figure 41 – Trailing edge platform undercut

Coating inclusive of Metallurgical Evaluation

The OEM applies a VPS (vacuum plasma spray) MCrAlY bond coating referred to as GT33 and a dense vertically cracked (DVC) TBC. For the reconditioning process, a high velocity oxy-fuel process is used to apply a NiCoCrAlY+Si/Hf bond coat and the air plasma spray (APS) process is utilized to apply a VCHD strain tolerant TBC coating as seen in figure 44. Porosity-free coatings with good bonding, and oxide-free interfaces were achieved. The NiCoCrAlY+Si/Hf coating has better oxidation resistance versus GT33. For the same thickness coating at 982^{o}C (1800^{o}F), the former coating system had a life of 30,000 hours versus the latter coating system that only had a life of 24,000 hours based on beta phase measurements. The strain to crack test showed that both coating systems at 427^{o}C (800^{o}F) and 538^{o}C (1000^{o}F) could reach 4% strain. Figure 45 shows the general appearance of the 7FA+e stage 1 bucket fully repaired and coated.

Figure 42 – Shank modification to allow cooling air to reach the platform

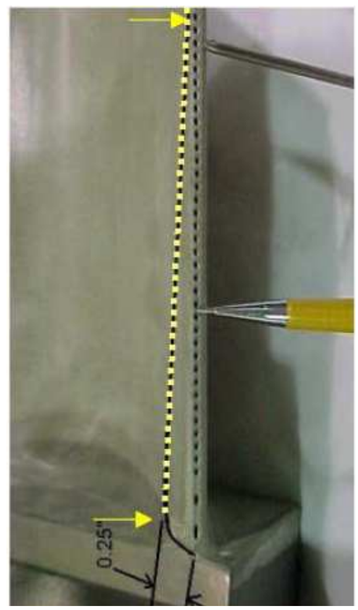

Figure 43 - TE cut-back configuration (Ref. 2)

CONCLUSIONS

With approximately 600 Frame 7FA+e units operating in a highly competitive market in North America alone, operators are looking for cost-effective, robust refurbishment techniques that will improve their assets life cycle costs. The processes and experience described in this paper show:

- The acid stripping process results in successful coating removal and acceptable IGA.

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Figure 44 – HVOF, NiCoCrAlY+Si/Hf and APS strain tolerant TBC applied to a repaired 7FA+e bucket

Figure 45 – Fully repaired and coated Frame 7FA+e, stage 1 bucket

- Platform degradation can be successfully repaired with a combination of welding and brazing. Crack-free, structurally sound weld repairs on the DS-GTD111 material, using a specially developed weld filler metal was accomplished with the high frequency GTAW process. This specially developed weld filler metal achieved the desired balance of high temperature strength and ductility.

- The removal of the original EB welded cover tip plate and GTAW 5 individual tip cover plates (chicklets) ensures no gas leakage between the internal passages and provides a more robust repair. In addition laser cladding of the squealer tip with a specially developed oxidation resistant material also provides a more robust bucket tip repair. Although the mechanical properties of the specially developed weld filler metal is not equivalent to that of the DS-GTD111 base metal, since the bucket tip is generally a lower mechanically stressed area, the reduction in mechanical properties is acceptable. Basically the bucket tip area will be somewhat strain controlled and the specially developed weld filler metal is good in terms of strain versus life; whereas the GTD111 material is better when comparing stress versus life.

- Laser cladding and laser fusion welding are high energy density processes, resulting in low heat input, producing quality precision welds, with low distortion and minimal thermal damage to the GTD111 base metal.

- The metallurgical results showed welds essentially free of defects. No microfissuring in the HAZ was seen. Neither were there any microcracks in the fusion zone.

- The rejuvenation heat treatment incorporating heating above the gamma prime solvus temperature, resulted in stress rupture properties greater than the minimum and average values for DS-GTD111 base metal.

- The reconditioning process allows for a HVOF applied NiCoCrAlY+Si/Hf bond coat and an APS applied vertically cracked high density strain tolerant TBC top coating.

- Already the newly established reconditioning process has increased the repair yields. Based on the rejuvenation heat treatment and the reconditioning process described in this paper, there is a potential of obtaining at least one additional hot gas path (HGP) inspection service interval enabling the bucket to reach 96,000 hours.

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