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HOT SECTION LIFE MANAGEMENT THROUGH IMPROVED MATERIAL PROPERTY RECOVERY

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ABSTRACT

Nickel-based superalloys are extensively used in manufacturing hot gas path components in industrial gas turbines used for power generation. Specifically, GTD-111 DS is one of the widely used alloys used in manufacturing the hot gas path rotating components. These components are subjected to extreme operating environments resulting in creep, oxidation, and fatigue of the components during operation. After continued operation, these damage modes need to be repaired and the components go through extensive repair processes, which include several heat treatments to recover the mechanical properties of the base material (GTD-111 DS) lost during operation. The heat treatments used during repair by the different repair vendors can vary widely in terms of temperature, time and the sequence as well. This study focuses on understanding the differences in the effects of the heat treatments (partial solution, full solution, HIP and full solution) to the base material in terms of microstructure-mechanical property relationships. Results indicate that HIP and full solution resulted in refined microstructures and improved mechanical properties compared to the heat treatments involving partial solution or full solution only. Microstructure-mechanical property relationships suggest that components that need to be repaired beyond OEM recommended repair intervals benefit from the HIP and full solution heat treatments.

The originality is that this study links the LCF and stress rupture properties of the GTD-111 DS of material from real life components before and after different heat treatments.

KEYWORDS

GTD-111 DS, Combustion turbine, Hot Isostatic Pressing (HIP), Repair, Solution heat treatment, Mechanical properties

LIST OF ABBREVIATIONS

AR	As Received
C	Cuboidal
°C	Degrees Celsius
C2NM	casting supplier code
C2NP	casting supplier code
CT	Combustion Turbine
DS	Directional Solidified
EDAX	Energy Dispersive Analysis X-Ray
°F	Degrees Fahrenheit
HIP	Hot Isostatic Pressing
HT	Heat Treatment
K	1000
LCF	Low Cycle Fatigue
LE	Leading Edge
MC	Mid Airfoil Transverse
MCrAlY	Coating containing a base metal (M), Chromium (Cr), Aluminum(Al) and Yttrium (Y)
ML	Mid Airfoil Longitudinal
M	C2NM, casting supplier code
OEM	Original Equipment Manufacturer
P	C2NP, casting supplier code
psi	pound per square inch
R	Rounded
RoA	Reduction of Area
RT	Root
S	Spherical
S1B	Stage 1 Bucket
SEM	Scanning Electron Microscope
TBC	Thermal Barrier Coating
TE	Trailing Edge

INTRODUCTION

Combustion turbines (CT) have become an increasingly important segment of power generation portfolios globally because of their relatively high efficiency, reduced emissions and abundant supply of natural gas. Due to the high firing temperatures and consumable component design philosophy employed by combustion turbine designers, the associated maintenance cost for CT fleet typically reaches several million dollars. These costs are related primarily to the replacement and repair of hot section parts used in the turbine engines. Hence, understanding component design life including the design intent, details of the repairs performed during its life time, and improvement of the mechanical properties during the repair is crucial for managing the reliability and maintenance costs of the combustion turbines. The overall approach used for component life extension study performed is described elsewhere [1] [2]. The component life extension includes a methodical approach including a deeper understanding of the degradation of the base material microstructure-mechanical property relationships with service, and the improvement of properties with repairs.

Another critical issue for an end-user is to understand the impact of starts-based service and hours-based service and to assess the risks (mechanical-microstructural property degradation and restoration) of swapping a set of components from a peaking operation (higher starts, lower hours) and installing the set in a baseload operation (lower starts, higher hours) and vice-versa. Maintenance guidelines published by OEMs indicate a safe operating zone for the maximum starts and maximum hours, but the operational profile of a unit can be a combination of both. A deeper understanding of the life-cycle impacts of starts-based and hours-based operation is necessary from an end-user perspective to manage the components and extract their maximum serviceable life.

Accordingly, a multi-year program was initiated by Duke Energy to understand the aforementioned risks on critical gas turbine components. One of the widely used alloys for manufacturing combustion turbine rotating components is GTD-111 DS. The repair of the components made of GTD-111 DS involves several heat treatments to bring the desired mechanical properties to the base material that were lost during operation. Some of the typical heat treatments performed during repair consists of 2050F for 2-4 hours at several stages of the process (Partial Solution), HIP at (2150F-2200F)/2 hrs, and full solution (2150F-2200F)/2 hrs, as required by the repair vendors' processes and specifications. There is no common standard or agreement as far as the sequence or the heat treatment protocol followed during repair. On the other hand, EPRI F7FA S1B repair specifications (which was developed by TEServices) recommends full and partial solution heat treatments followed by an aging cycle. The requirement of HIP prior to full solution heat treatment is based on metallurgical evaluation, operation and repair history of the buckets or customer preference. But, no further guidance on the microstructural criteria that dictates the full solution and HIP is provided. Hence, the turbine owner primarily relies on repair vendors for the heat treatments to be performed and must settle for the resulting outcome obtained from the heat treatments. This situation could be improved by developing a criteria based on the required mechanical properties, required microstructure, optimizing the microstructure-mechanical property relationships and the cost incurred during the repairs because of the heat treatments.

Literature review of the work provided some insights related to this work. Several authors studied the heat treatments and resulting microstructures from those heat treatments and concluded that the high temperature solution treatment is beneficial for improved microstructure [3] [4] [5]. Swaminathan et al. published similar work and concluded that HIP and standard solution heat treatments followed by aging resulted in restoration of the tensile and creep rupture properties in buckets after 49,000 hours of service operation [6]. An extension of this work included a higher solution treatment temperature in the repair of components from a MS5001B machine after 59,000 hours and provided similar tensile and creep rupture improvements [7]. Impact of starts-based operation or low-cycle fatigue (LCF) was not studied in this work. In addition, the operating temperatures of the components analyzed in this work is lower than that of the GE7FA machine, which might result in higher deterioration of high temperature mechanical properties during operation than observed in the study. Miglietti et al. published results from the repair of a GE Frame 7FA stage 1 bucket and concluded that a full solution at 2200F without a HIP showed a substantial improvement in short-term creep rupture tests [8]. No assessment of the starts-based operation or LCF properties was performed in this study. Shenoy et al. performed relevant work on LCF properties on GTD-111 cast plates and developed a model to characterize the material behavior in the longitudinal and transverse orientations, however this work was not compared to the crack formation on the real components.

In summary, the literature review provided an overall agreement and conclusion that high temperature solution heat treatment results in higher creep rupture properties, but the information related to the LCF and the relationship between the LCF, creep-rupture, and the microstructure for different heat treatments is missing. More importantly, the risks of operating the components in a combination of starts-hours was not addressed in the literature, and the end user was not able to make decisions based on quantitative analysis on repairability and maximum useful life of the components. Hence, this study is focused on understanding the effect of different heat treatments in terms of microstructure and mechanical properties--specifically LCF and creep rupture on GTD-111 alloy in different service conditions from the serviced buckets.

The originality is that this study links the LCF and stress rupture properties of the GTD-111 DS of material from real life components before and after different heat treatments.

SPECIMENS AND TEST CONDITIONS

The following sections cover the condition of the buckets used, heat treatments, sectioning plan, and mechanical testing parameters used in the testing in detail. The nominal composition of GTD-111 DS alloy is given in Table 1 [9].

CONDITIONS OF THE BUCKETS USED

Combustion turbine operating intervals vary according to starts- or hours-based intervals. Typically, turbine blades or buckets will be operated for 800-900 starts (1 interval-starts) and/or 24,000 hours (1 interval-hours) before they are disassembled from the machine and sent to the repair shop. After successful completion of the repair, the components will be assembled into the turbine and will be operated for another service interval as mentioned above. At that point, the parts would have accumulated 1600-1800 starts (2 intervals-starts) and/or 48,000 hours (2 intervals-hours). For the current study, reference is made to the 1 interval and 2 intervals components in the as-received and repaired condition. This study included a total of forty-two service run stage 1 buckets at varying conditions including 1 interval-as run, 2 intervals-as run, 2 intervals repaired-partial solution, 2 intervals repair-HIP plus full solution, and 2 intervals repair-full solution. (The buckets that accumulated two intervals were repaired after their first interval possibly with a partial solution heat treatment, however the exact heat treatments used during the first repair were unknown). In addition, the buckets appear to be cast from two different suppliers, which included a prefix C2NM or C2NP, which showed some differences in design attributes that resulted in varying scrap rates. Hence, the investigations focused on the two styles M and P to understand the differences in properties. The testing performed on as-run buckets was intended to quantify service degradation, and the testing performed on repaired buckets was intended to quantify the improvement obtained with heat treatments.

HEAT TREATMENTS INVESTIGATED

The heat treatments investigated are listed in Table 2.

Table 1
Nominal composition of GTD-111 DS alloy

Element	Ni	Cr	Co	Mo	Ti	Al	C	W	Ta	Cb	B
wt%	Bal	13.6	9.14	1.6	4.9	2.97	0.090	3.440	2.870	<0.01	0.010

Table 2
Heat treatments used for the study

Heat Treatment-1	Heat Treatment-2	Heat Treatment-3
Pre-weld HT 2050°F for 4 hours	Pre-weld HT 2050°F for 4 hours with slow or fast cool	HIP at 2190°F ±25°F for 4 hours with minimum 15K PSI in Argon
Post-weld HT 2050°F for 2 hours	Post-weld HT 2150°F for 2 hours	Full solution at 2175°F ±25°F for 2 hours in vacuum and argon quenched
Diffuse- MCrAlY coating 2050°F for 2 hours	Diffuse- MCrAlY coating 2050°F for 2 hours	Partial solution and age at 2050°F ±25°F for 2 hours (controlled cooling)
Diffuse TBC coating 2050°F for 2 hours	Diffuse- TBC coating 2050°F for 2 hours	Diffuse- MCrAlY coating 2050°F for 2 hours
Age 1550°F for 24 hours all in vacuum	Age 1550°F for 24 hours all in vacuum	Diffuse TBC coating HT 2050°F for 2 hours
		1550°F for 24 hours and argon quenched both in vacuum.

SECTIONING PLAN AND MECHANICAL TESTING DETAILS

The sectioning plan for microstructural investigations included five sections taken across the length of the blade as shown in Figure 1.

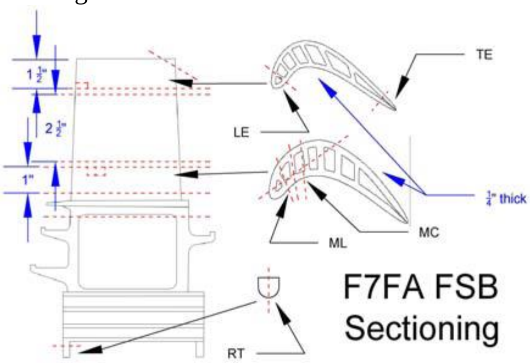


Figure 1:
Sectioning plan used for the study

The details of the sections are provided in Table 3. The root section is used for comparison of microstructure from the new manufacture, as this area is not exposed to higher temperatures. Microstructural investigations included low magnification optical microscopy to determine porosity levels, carbide structures and high magnification scanning electron microscopy to study and compare the gamma-prime morphology. Gamma prime size was measured using SEM image analysis provided with the EDAX software. Volume fraction was performed using image analysis software provided by EDAX.

Table 3
Details of sections taken for each blade

Metallurgical Section Location	Dimension (from tip of the blade)	Notation
Trailing Edge (TE)-Tip	0.25 inch (0.635 cm)	TE
Leading Edge (LE) Tip	1 inch (~2.54 cm)	LE
Mid airfoil Longitudinal	4 inches (~10.16 cm)	ML
Mid airfoil Transverse	4 inches (~10.16 cm)	MC
Root Tab	Root	RT

Mechanical property testing of the buckets focused on two locations: airfoil and platform, primarily on stress rupture properties and LCF properties. Mechanical testing included stress rupture testing at 1600°F/40 Ksi and isothermal LCF testing at 1650°F, 0.7% strain range. The specimens for mechanical testing are detailed in Figure 2. The stress rupture tests included two cylindrical stress rupture specimens from airfoil in the longitudinal direction, and one flat specimen from platform in the transverse direction, and the LCF tests included one cylindrical specimen from the airfoil in the longitudinal direction and another cylindrical specimen from the platform in the transverse direction. The locations of the specimens were obtained from the finite element models generated as a result of the studies published elsewhere [1].

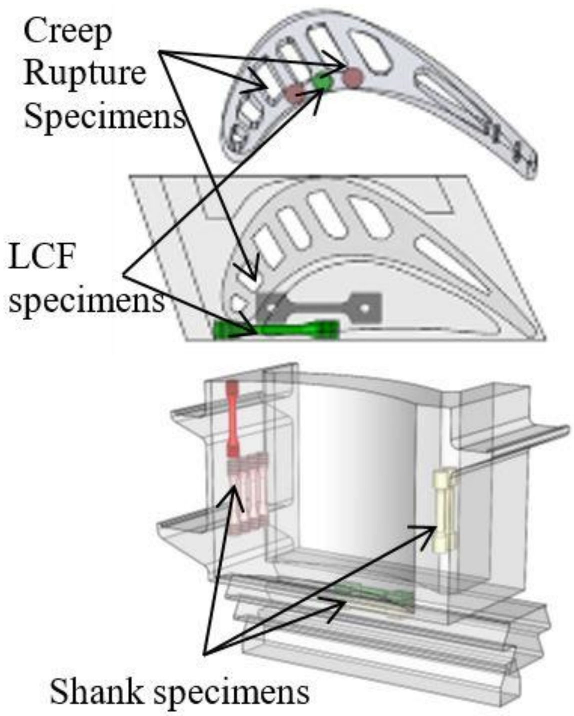


Figure 2:
Mechanical testing specimen plan used for the study

RESULTS

MICROSTRUCTURAL INVESTIGATIONS

One interval buckets: 318-899 starts and 5,243-7,298 hours (As-run condition)

Un-etched metallurgical evaluation using optical microscope in the As-Run (AR) condition showed some casting porosity in all buckets in all locations including the root. The carbide distribution was relatively small and nicely defined with a little larger carbide concentration of the P buckets compared to the M buckets. [As explained before, M and P indicated two different casting vendors.] Etched metallurgical evaluation using optical microscope showed minor differences in the dendrite and grain size for all buckets. Also, linear secondary phases were present in these sections. These secondary phases were determined to be rich in heavy elements such as tantalum, tungsten, and chromium. These phases will be discussed in detail later at the end of the current section. In most cases, casting porosity and inclusions also accompanied these secondary phases and the concern was that these phases and imperfections possibly influence the stress rupture and LCF properties.

Scanning electron microscopy of the same sections was performed to study the gamma-prime morphology and distribution. Figure 3 provides representative detail on the inter-dendritic (outside the dendrite arm) and intra-dendritic (inside the dendrite) regions for reference. Figure 4 represents the microstructure of the bucket in as-run condition. The morphology appears to be different between inter-dendritic and intra-dendritic regions. The primary gamma prime of the inter-dendritic regions appear to be smaller and more cuboidal of shape than intra-dendritic regions. The size of gamma-prime was compared across different regions and the root section was assumed to be the baseline. The primary gamma prime at the TE was rounded and had grown significantly (1.0 - 1.8 μm, spherical), and the growth was somewhat less significant at the LE (0.7 - 1.2 μm, spherical / rounded). At the mid airfoil cross and longitudinal sections, the size of the primary gamma prime (0.7 - 1.0 μm, rounded) was just a little larger than the root (0.6 - 1.0 μm, rounded /cuboidal) and maintained almost the same shape compared to the root. The secondary gamma prime was mostly not present at the TE, less present at the LE and about the same size (0.10 - 0.20 μm) and shape (spherical) at the mid airfoil and root.

Two intervals buckets, starts-based: 1,650 starts and 12,372 hours (As-run condition)

As mentioned above, the buckets that accumulated two service intervals underwent a repair after their first interval and the details of that repair are unknown. Metallurgical evaluation of the 2 intervals buckets in as-run condition showed similar microstructure as the one interval buckets except that the larger sized carbides and higher concentration of carbides were present in 2 intervals buckets compared to 1 interval buckets. The linear secondary phases associated with casting imperfections were also similar to the ones see in one-interval buckets.

Scanning electron microscopy revealed that the primary gamma prime of the inter-dendritic regions was smaller and more cuboidal of shape than the intra-dendritic regions, similar to the one interval buckets. The primary gamma prime had rounded in shape and grown significantly at the TE (1.2 – 1.8 μm - spherical) and somewhat grown less significantly at the LE (0.8 – 1.2 μm – rounded). At the mid airfoil, the primary gamma prime size (0.8 – 1.0 μm –rounded), was just a little larger than at the root (0.8 – 0.9 μm rounded) and maintained the same shape compared to the root. It needs to be noted that the relatively large size and rounded shape of the primary gamma prime at the root indicates that these buckets possibly did not receive the optimum HT's during the new manufacture or at the first repair. The secondary gamma prime was nearly not present at the TE and about the same size (0.10 - 0.20 μm) and shape (spherical) at the LE, mid airfoil and root. It needs to be noted that the volume fraction of secondary gamma prime at LE increased when compared to the first cycle buckets.

Microstructural investigations on one-interval and two-intervals buckets revealed that the size of the primary gamma-prime increased significantly in the LE and TE areas of the buckets (hottest regions of the bucket), compared to the root section.

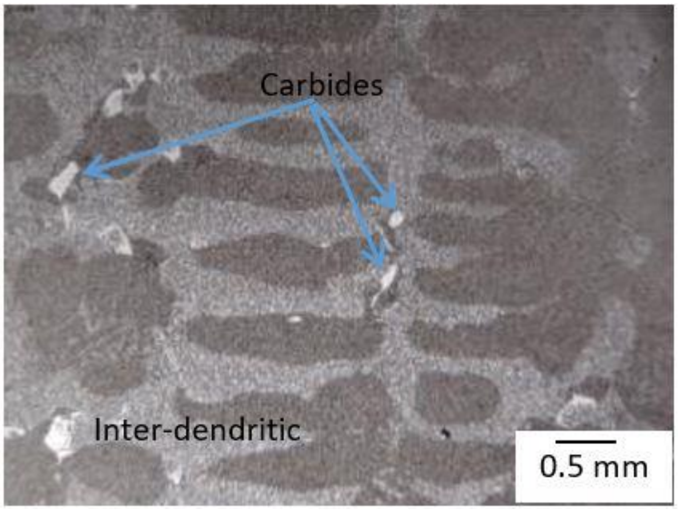
Two intervals buckets, one starts-based and one hours-based: 1,100-1200 total starts and 24,000-36,000 total hours (As-run condition)

This section refers to the evaluation of the group of buckets that accumulated two service intervals with a repair after its first cycle. The heat treatment details of that repair are unknown. The metallurgical structure of the base material (carbide and gamma prime structure) have coarsened, grain boundaries are sensitized by the presence of elongated carbides and some needle like (carbide) phases with gamma prime eutectics were observed. It appears that the metallurgical condition (carbide and gamma prime structure) has aged during operation. The primary gamma prime grown significantly at the TE (1.4 – 1.9 μm - spherical) and somewhat grown less significantly at the LE (0.6 – 0.8 μm – rounded), compared to the one interval buckets. Figure 5 represents the microstructure of the buckets that accumulated two intervals in the as-run condition.

In summary, for the as-run buckets in different conditions, microstructural investigations on one-interval and two-intervals buckets revealed that the size of the primary gamma-prime increased significantly in the TE area (hottest regions of the bucket), and less significantly in the other areas of the buckets compared to the root section.

Table 4
Gamma-prime size evaluation for 1-interval and 2-intervals buckets

		1 Interval Buckets (318-899 starts and 5,243-7,298 hrs.)		**2 Intervals Buckets, starts-based** (1,650 starts and 12,372 hours		**2 Intervals Buckets, one hours-based and one starts-based** (1,100-1200 starts and 24,000 hours)	
Location		**Primary Gamma Prime Size [µm]**	**Secondary Gamma Prime Size [µm]**	**Primary Gamma Prime Size [µm]**	**Secondary Gamma Prime Size [µm]**	**Primary Gamma Prime Size [µm]**	**Secondary Gamma Prime Size [µm]**
TE	Trailing Edge	1.0-1.8	N/A	1.2-1.3S	N/A	1.4-1.9 S	N/A
LE	Leading Edge	0.7-1.2	N/A	0.8-1.2 R	0.1-0.2	0.6-0.8 R	0.1
MC	Mid airfoil Cross section	0.7-0.9	0.15	0.9-1.0 R	0.1-0.2	0.7-0.9 R	0.1
ML	Mid airfoil Longitudinal section	0.7-0.8	0.15	0.8-0.9 R	0.1-0.2	0.8-1.0 R	0.10
RT	Root (RT)	0.6-0.9	0.15	0.8-0.9 R	0.15-0.2	0.6-0.8 R	0.05
Note: R – Rounded S - Spherical (The shape is cuboidal if no suffix is present)							



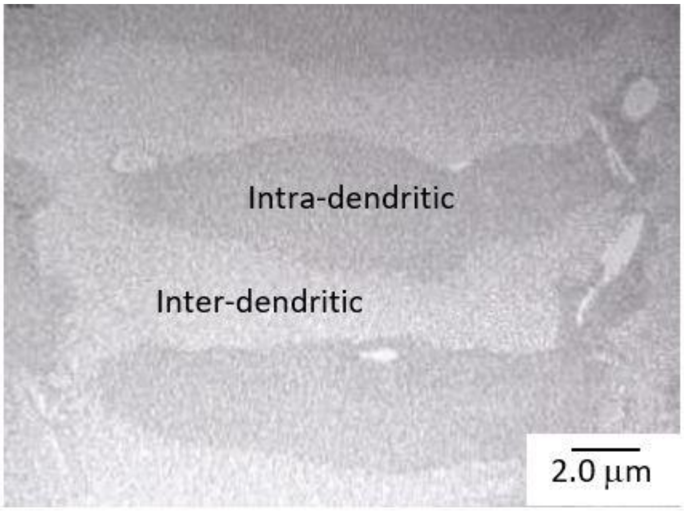


Figure 3
Representative Micrograph Showing Inter-dendritic and Intra-dendritic Regions. The picture on left shows dendritic microstructure and the one on right shows more detail on the difference in gamma-prime.

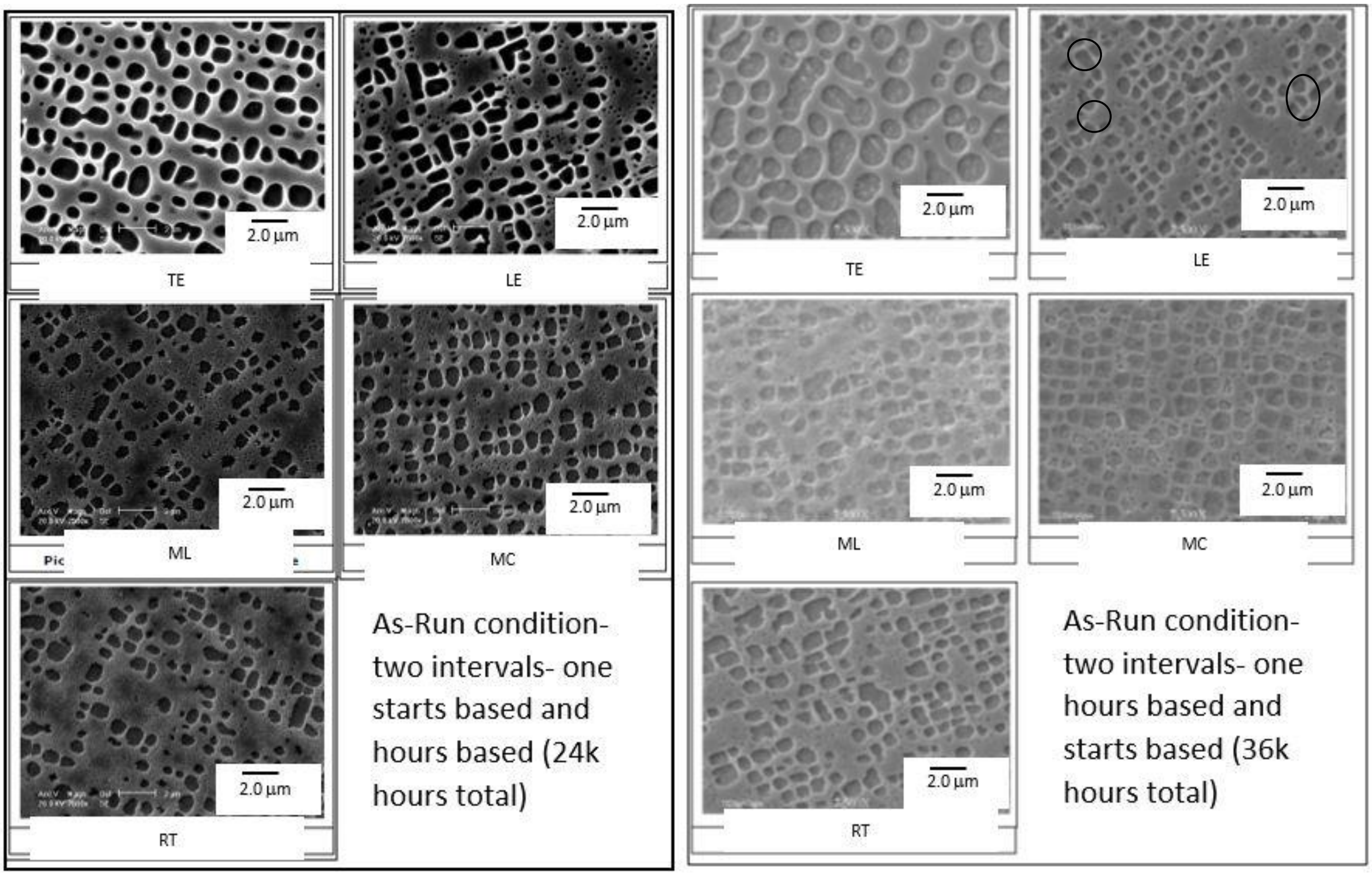


Figure 4
Microstructure of the Specimens Extracted from Buckets after Two Intervals-one starts based and on hours based in As-run Condition [buckets accumulated 24k total hours on the left and the ones accumulated 36k total hours on the right]. Details of sample locations are listed in Table 3.

Two-intervals Buckets: 1,650 starts and 12,372 hours (Repaired condition)

Repaired buckets included buckets processed in three conditions listed in Table 2. Scanning electron microscopy revealed significant differences of gamma-gamma prime morphology between different heat treatments. This can be seen in Figure 5 and Figure 6. Figure 5 represents the microstructure in buckets processed using heat treatment-1 and heat treatment-2, whereas Figure 6 represents the microstructure of the buckets processed using and heat treatment-3. It needs to be noted that the buckets from the same set were selected for as-received and different heat treatments so that accurate comparison of the microstructures with different heat treatments can be performed. Higher amounts of cuboidal primary gamma prime (0.4 – 0.5 µm) with some spherical shaped (0.10 – 0.15 µm) was observed in buckets processed using heat treatment-3 sequence. The size of gamma-prime in the non-dendritic and dendritic locations was observed to be in the range of (0.4 – 0.5 µm), and (0.8 – 1.0 µm) respectively. In contrast, in the buckets heat treated using sequence 1 and 2, large rounded primary gamma prime (0.8 - 1.2 µm) were observed.

Microstructural investigations on repaired two-intervals buckets revealed that heat treatment-3 resulted in better morphology including refined gamma-gamma prime distribution and higher volume fraction. The average gamma prime size in heat treatment-3 is in the order of 0.4-0.5 µm as opposed to 0.8-1.0 µm in the case of other heat treatments. In addition, heat treatment-3 resulted in smaller secondary gamma-prime size and lower volume fraction compared to the other heat treatments. Hence, it appears that heat treatment-3 results in an optimized microstructure similar or better than the original condition. This size distribution and the possible impact of the microstructure on mechanical properties will be discussed in the next section.

Table 5
Gamma-prime Size for the Buckets Processed using Different Heat Treatments

		Heat Treatment-1		Heat Treatment-2		Heat Treatment-3	
Location		Primary Gamma Prime Size [µm]	Secondary Gamma Prime Size [µm]	Primary Gamma Prime Size [µm]	Secondary Gamma Prime Size [µm]	Primary Gamma Prime Size [µm]	Secondary Gamma Prime Size [µm]
TE	Trailing Edge	0.8 R	0.15	1.3R /0.4C	N/A	0.4 C / 0.8 R	Few 0.2
LE	Leading Edge	0.8 R	0.15	1.5 R/ 0.4 C	N/A	0.5 C / 1.0 R	Few 0.2
MC	Mid airfoil Cross section	1.2 R	0.15	0.9 R/ 0.5 C	0.15	0.4 C / 0.9 R	Few 0.2
ML	Mid airfoil Longitudinal section	1.2 R	0.15	1.0 R /0.5 C	0.15	0.5 C / 0.9 R	Few 0.2
RT	Root	1.4 S	0.15	1.0 C /0.4C	0.15	0.4 C / 0.8 R	Few 0.1
Note: C – Cuboidal R – Rounded S - Spherical							

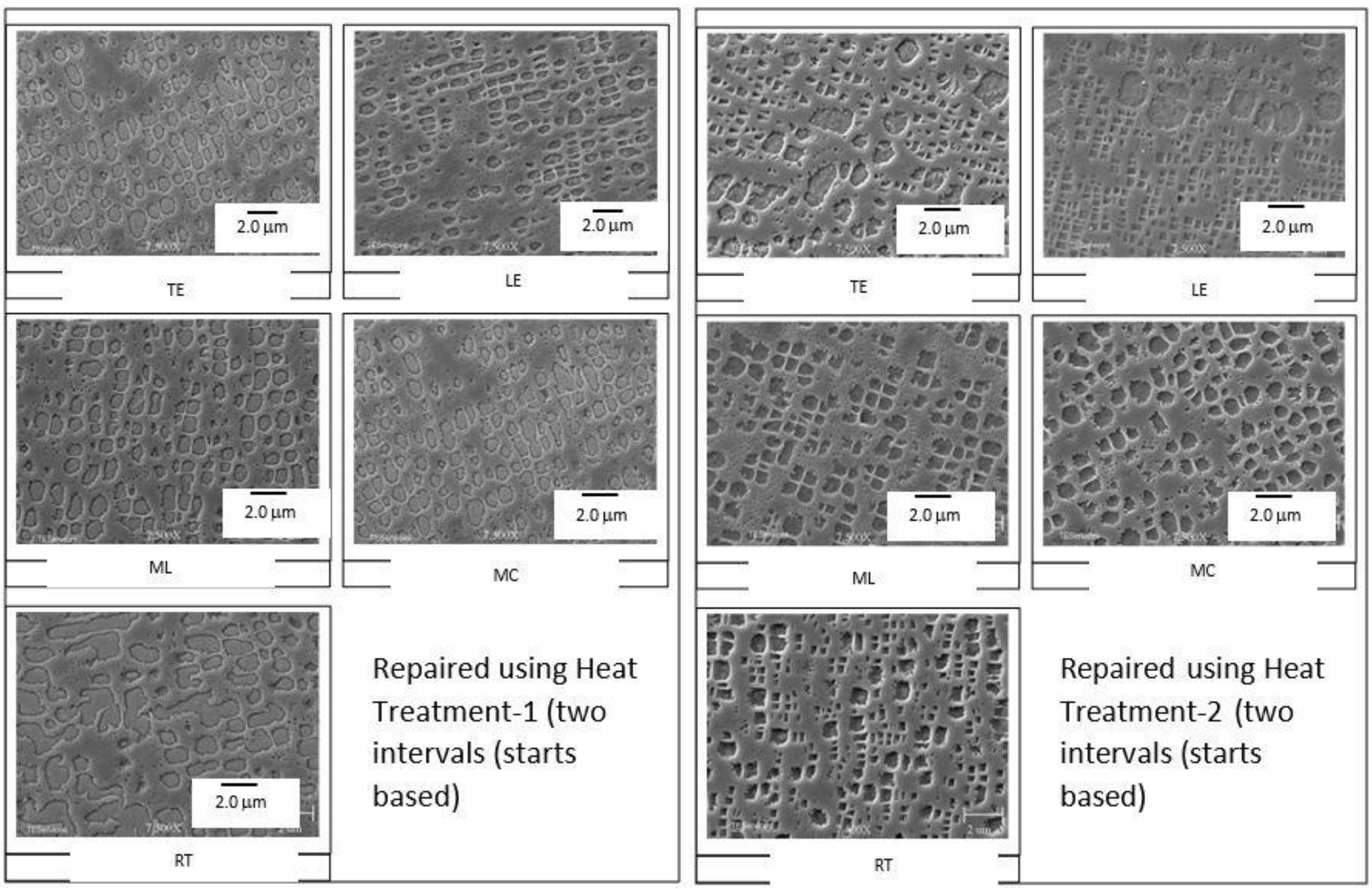


Figure 5
Microstructure of the specimens extracted from buckets after two starts based intervals and treated with heat treatment-1 (on the left) and heat treatment-2 sequence (on the right). Details of the sample locations are listed in Table 3.

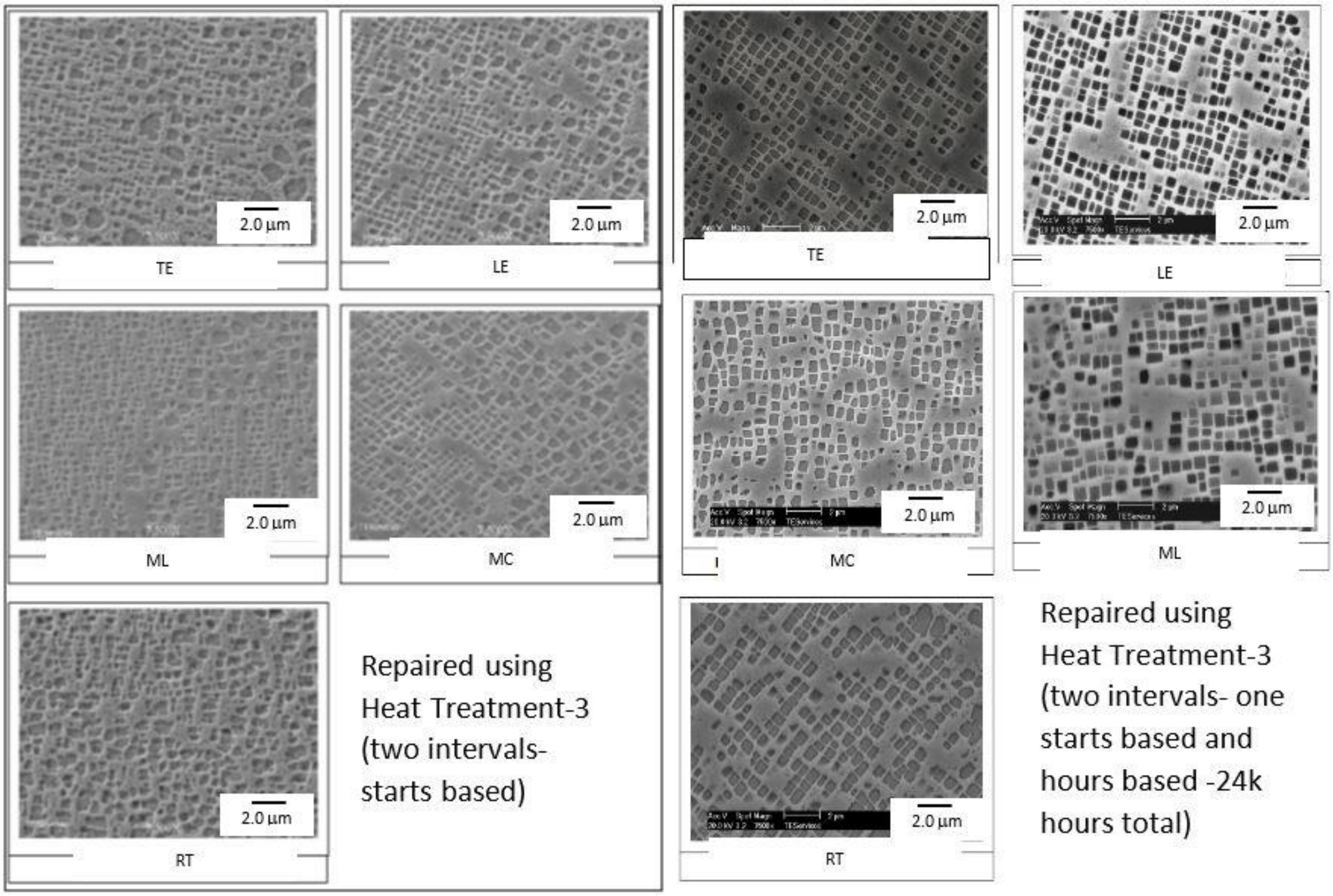


Figure 6
Microstructure of specimens extracted from buckets processed using heat treatment-2 and heat treatment-3 sequence. Details of the sequence are listed in Table 3.

MECHANICAL PROPERTIES

Specimens machined from MS7001FA blades with different intervals, cycles and hours described previously were used to determine the impact of different heat treatments on the stress rupture and Low Cycle Fatigue (LCF) properties for GTD111DS. All tests were performed in air.

AIRFOIL

The stress rupture results of the as run material from the airfoil are comparable to those of the root specimens of the same blades before heat treatment for the specimens with 800 cycles and 6000 hours. This indicates no or little degeneration of the stress rupture strength has occurred during operation.

Although test specimens taken from the root are under high stress during operating, the root is not exposed to the hot gases and has a relatively low operating temperature. Therefore, this material has relatively low or no creep and fatigue exposure and the metallurgical condition (low operating temperature), creep and fatigue properties represent the properties of the material before operating or in the as heat treated condition. For blades that have not been repaired (and only heat treated by the OEM during manufacturing) the metallurgical condition, creep and fatigue properties are considered to equal that of a new blade for material at the root.

The stress rupture testing results of the partial heat treatment specimens at 6000 hours are comparable to the As Run results. (As Run is the condition after operation without heat treatment performed). This indicates that this heat treatment does not positively or negatively change the stress rupture life, see Figure 9. The heat treatments HIP + full solution, full solution and partial solution do result in increased stress rupture lives for the 12000 hours specimens compared to As Run and even new. This indicates that the heat treatments performed at new manufacturing were not optimal.

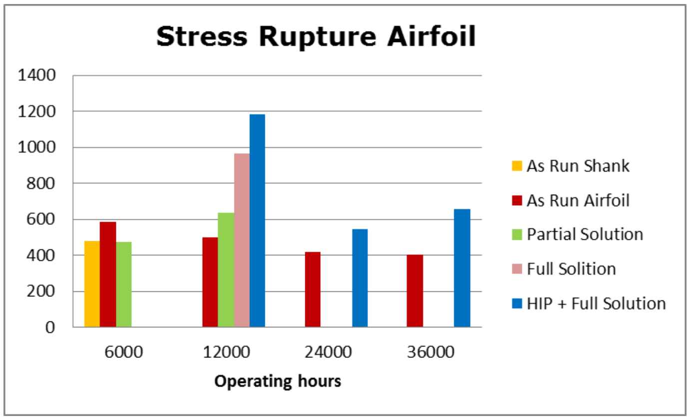


Figure 7
Average values of airfoil specimen stress rupture strength

The elongation and RoA (Reduction of Area) of the stress rupture samples are taken as a measurement of the ductility. All ductilities were between 16.8% and 24.6% and thus no significant differences for all the different operating conditions and heat treatments were observed. See Figure 10 for the elongation and Figure 11 for the RoA. An exception is the elongation for the 12000 hours specimen with the partial solution heat treatment which averaged 32% while HIP + full solution average 19%. This can be due to the heat treatment performed or just an outlier due to the low number of tests performed.

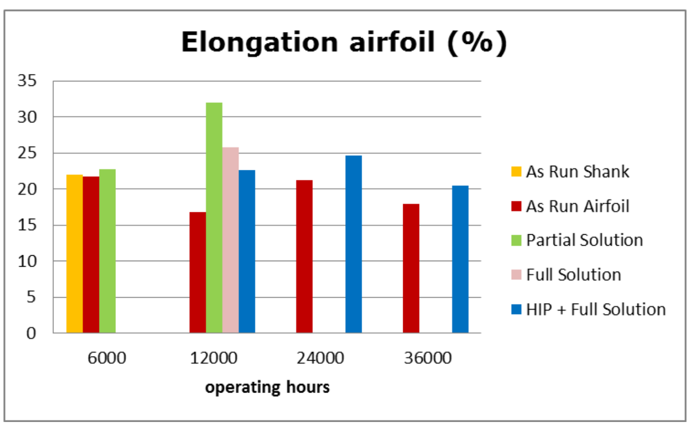


Figure 8
Average values of stress rupture elongation airfoil specimen

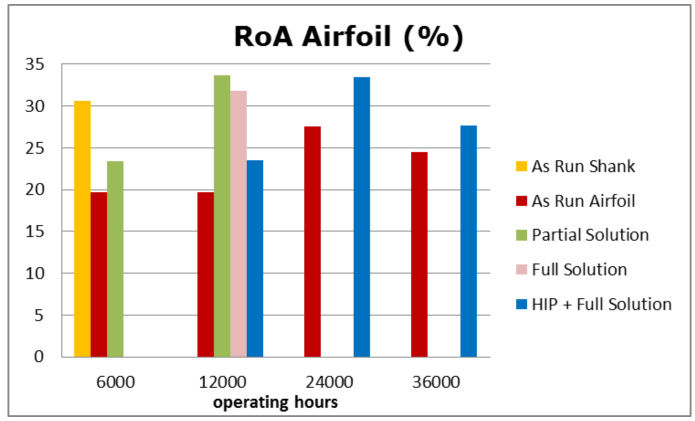


Figure 9
Average values of stress rupture RoA airfoil specimen

The 1250 cycles are specimens that have 12000 hours or 24000 operation hours, and the 1650 cycles specimens have 12000 or 36000 operation hours.

For the 1650 cycle specimens, the partial solution and the full solution heat treatment results in a lower LCF life (although higher than was measured for 1250 cycle As Run), while the HIP + full solution heat treatment increased the LCF life, see Figure 12.

Note: The number of specimens used for the LCF tests was limited and for partial and full solution data only two data points were available for each. More tests should be performed to reduce the scatter and improve the reliability of the data.

The root specimen (new) LCF lives of the one interval (800 cycles with 6000 hours) are lower than the airfoil specimens of the as run material (exposed). This was not observed in the stress rupture testing where the result for the root and airfoil were comparable. The differences in LCF can be due to the casting differences in the root (direction grains).

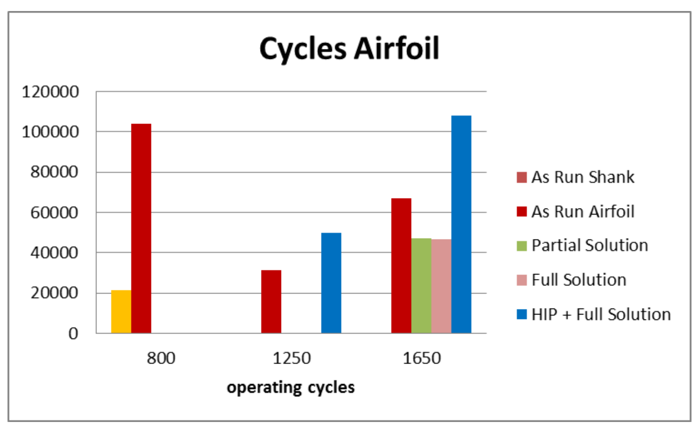


Figure 10
Average LCF life of airfoil specimens

PLATFORM

The stress rupture life of the as run specimen from the shank (no repairs and considered new material) cut in the transverse direction perpendicular to the Directionally Solidified (DS) structure is more than double, 481 hours for the root specimen versus 191 for the as run specimen of the airfoil cut in the same direction as the root specimen (the specimens have 800 cycles and 6000 hours).

Note: The grain structure in the platform is created during casting and the grain growth during solidification is from root to tip (DS). At the platform the DS structure is lost and results in a poor equiaxed structure with a large grain in the middle of the platform.

The heat treatments for the 12000 hours specimens show an improvement of the stress rupture results even with the partial solution heat treatment.

The stress rupture life of the material at the platform was rejuvenated with all the performed heat treatments, especially for the 24000 and 36000 hours specimens that underwent HIP + solution heat treatment, see Figure 13. This suggests again that the standard heat treatments performed at new manufacturing on the blade from which the specimens were taken were not optimal.

There are no substantial differences between the ductility for full solution and HIP + full solution heat treatments for the platform specimens which were between 10.3% and 17.4% for elongation and 10.2% and 19.5% for RoA, see Figure 15 for the elongation and Figure 15 for the RoA. The partial solution heat treatment has a ductility about twice (average 27.2% versus 11.7%) that of the full solution heat treatment for the specimens that have ran for 12000 hours. This high ductility cannot be observed for the RoA.

The specimens for the as run condition after 6000 hours from the root have a lower ductility than those of the airfoil in the as run condition. Note: The grain size structure is equiaxed with large grains.

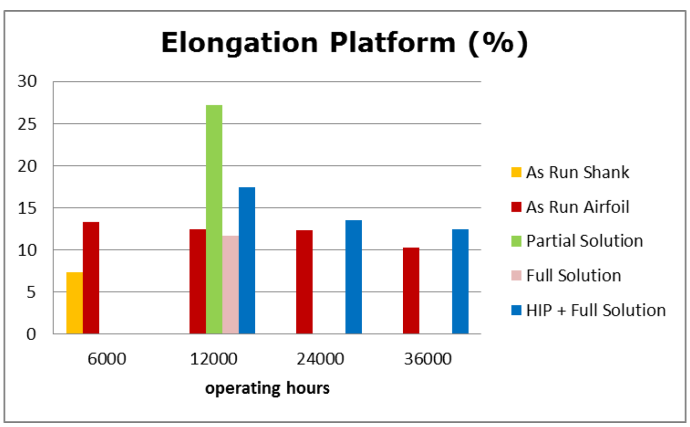


Figure 11
Average values of elongation of stress rupture tests platform specimens

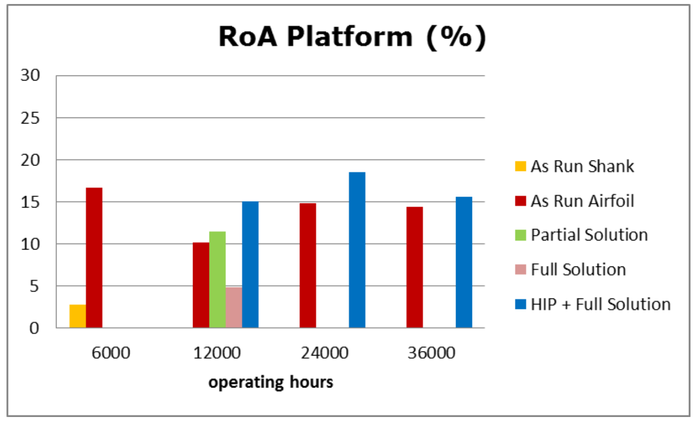


Figure 12
Average values of elongation of ROA of stress rupture tests platform specimens

For the 1650 cycles platform specimens, full solution heat treatment gave the best LCF life, followed by the HIP + full solution heat treatment and the partial solution heat treatment, see Figure 16. Note: The partial solution heat treatment results were lower than the As Run LCF tests. The number of test specimens was limited and the LCF data also showed a significant scatter and therefore more LCF testing is required to substantiate above observations.

Note: The data for 1250 cycles are for specimens that have ran 12000 hours or 24000 hours and the 1650 cycles are specimens that have ran 12000 or 36000 hours in the machine.

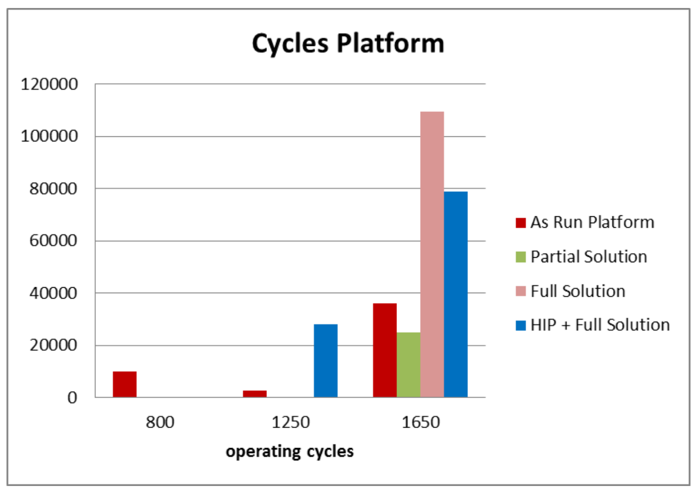


Figure 13
Average LCF life of specimens extracted from the platform

The 6000 hour exposed material has a comparable stress rupture life for both the specimens taken from the root (new) and the airfoil and the platform (exposed). The heat treatments for the 12000 hour specimens did improve the stress rupture life. This suggests that the initial heat treatment after the manufacturing of the blades from which the specimens were taken was not optimal.

For airfoil operated for 12000 hours, the stress rupture lives with the HIP + full solution had the highest number of hours, followed by the full solution and then partial solution and heat treatment, see Table 6.

For the platform specimens operated for 12000 hours the full solution heat treatment gives the higher values, followed by the HIP + full solution heat treatment and the partial solution heat treatment.

DISCUSSION

Heat treatments can rejuvenate the stress rupture and the LCF properties of the material although the effect for partial solution heat treatment was minimal.

Ductility improvement can be observed of the elongation for partial solution heat treatment. This is the case for both the airfoil and platform specimens.

Table 6
Ranking of the different heat treatments for 12000 hours airfoil and platform stress rupture results

12000 hours Airfoil and Platform				
Heat Treatment		Partial Solution	Full Solution	HIP + Full Solution
Stress Rupture Airfoil	hours	3	2	1
	elongation (%)	1	2	3
	RoA (%)	1	2	3
Stress Rupture Platform	hours	3	1	2
	elongation (%)	1	2	3
	RoA (%)	3	2	1
Ranking		1	2	3

The ductility for the specimens taken from the root in the transverse direction of the DS was in the same range as those of the airfoil specimens (in DS direction). The specimens taken from the platform were the equiaxed grain structure with large grains and the ductility was lower.

For the LCF results the ranking for the airfoil specimens ran for 1650 cycles show the HIP + full solution heat treatment with the best result and the partial solution with the lowest values, see Table 7.

For the LCF results the ranking for the platform specimens ran for 1650 cycles show the full solution heat treatment with the best result and the partial solution again with the lowest values.

Table 7
Ranking of the different heat treatments for the 1650 cycles airfoil and platform LCF results

1650 cycles Airfoil and Platform			
Heat Treatment	Partial Solution	Full Solution	HIP + Full Solution
LCF Cycles Airfoil	3	2	1
LCF Cycles Platform	3	1	2
Ranking	1	2	3

For the platform samples the number of cycles for the HIP + full solution treatment is about twice the value of the next heat treatments, the partial solution and full solution heat treatments (108062 cycles versus respectively 47354 and 46544 cycles).

STRESS RUPTURE, LCF, MICRO-HARDNESS AND GAMMA PRIME

The mechanical properties of the material are determined by size and shape of the gamma prime phase in the material. Table 8 shows an overview of the gamma prime and the mechanical properties of a limited number of samples.

The average gamma prime sizes for the specimen:

- For the As Run shank specimens (new material) the gamma prime sizes were between 1.2 µm (LE) with a spherical shape and 0.6 µm (root) with a rounded cuboidal shape.
- Partial solution heat treatment gave gamma prime sizes between 0.3 µm (TE) and 1.5 µm (LE) both with a rounded cuboidal shape.
- For the full solution heat treatment the gamma prime particles were between 1.0 µm (LE) with a rounded off shape and 0.4 µm (root) cuboidal in shape
- The gamma prime particles for HIP + full solution heat treatment are 0.8 µm (ML) and 0.4 µm (root). For one repair vendor all the gamma prime particles are 0.4 µm and cuboidal in shape.

Note: The castings are from different casting houses.

The best stress rupture life is obtained for the HIP + full solution heat treatment, with an average of 1556 hours with an outlier of 2144 hours for one repair vendor heat treatment (the same as for the 0.4 cuboidal gamma prime size). The full solution heat treatment gives a lower stress rupture life of 967 hours. The partial solution heat treatment has the lowest result, 475 hours, however this is still within the specification for GTD 111.

The elongation of the creep rupture specimens of the HIP + full solution heat treatment has the highest value, followed by the HIP + full solution and the partial solution heat treated specimens. The full solution heat treatment has the lowest value for elongation.

For the LCF lives (1650 operation cycles) the HIP + full solutioned specimens give the best results followed by the full solution heat treated specimens. The specimens with the partial solution heat treatment have the lowest result.

The hardness increases with the other mechanical properties from 405 Hv500gr for the partially solutioned specimens to 435 Hv500gr for the HIP + fully solutioned specimens. It should however be taken into consideration that all three values are within the bandwidth for the material.

Table 8
Overview of the metallurgical data and the mechanical properties for the heat treated airfoil specimens run for 1650 cycles

Heat Treat		As Run	Partial Solution	Full Solution	HIP + Full Solution
Gamma Prime	TE	1.0S/1.2S	0.3R/0.4C	0.4C/0.8R	0.4C
	LE	0.9R/0.7R	1.5R/0.4C	0.5C/1.0R	0.4C
	ML	0.7C/0.8R	0.9R/0.5C	0.4R/0.9R	0.3C
	MC	0.7R	1.0R/0.5C	0.5C/0.9R	0.4C
	Root	0.7R/0.6C	1.0C/0.4C	0.4C/0.8R	0.4C
Stress Rupture	hours	582	475	1011	1556
	Elong (%)	22	22.7	15.8	23.1
	ROA (%)	30.8	23.4	19.5	28.3
LCF	Nf (cycles)	22618	34947	81914	106911
Hardness	Hv_{500g}	425	405	426	435

Ranking shows that based overall the HIP + full solution heat treatment is the optimal heat treatment, see Table 9.

Table 9
Ranking of the different heat treatments for airfoil specimens run for 1650 cycles

Heat Treatment		As Run	Partial Solution	Full Solution	HIP + Full Solution
Gamma Prime	µm	4	3	2	1
Stress Rupture	hours	3	4	2	1
	ductility (%)	3	2	4	1
	ROA (%)	1	3	4	2
LCF	Nf (cycles)	4	3	2	1
Hardness	Hv_{500g}				
Ranking		1	2	3	Neutral

The stress rupture and LCF properties show that there is a relationship between the metallurgical properties and the stress rupture data. This confirms the results from the previous tests and evaluations performed by TEServices that show that the best creep rupture results are obtained with sizes between around 0.4 - 0.6 µm with cuboidal shapes.

For the relation between hardness and gamma prime and mechanical properties no conclusions can be drawn. The data is all within the bandwidth of the measurements (±5%).

CONCLUSIONS

1. Heat treatments can rejuvenate the stress rupture and the LCF properties of the material, although the effect for partial solution heat treatments was minimal.
2. The results of the stress rupture and LCF lives show that the optimal results are for a HIP + full solution heat treatment.
3. Based on limited LCF testing, the intrinsic nature of LCF testing and the scatter observed, no relationship could be determined between ductility (elongation and ROA) and LCF however limited data indicates that higher ductility does not relate to higher LCF values. More testing is required to confirm this.
4. The properties after (repairs) HIP + full solution and full solution heat treatments are better than new material which indicates that the heat treatments performed during new manufacturing were not optimal.

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