Hot Section Life Management Through Improved Material Property Recovery

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Study Objectives

- Quantify the effect of different heat treatments on microstructure and mechanical properties of GTD-111 DS in different service conditions
- Fill knowledge gaps from prior work
  - Explore relationship between low cycle fatigue, creep-rupture and microstructure for different heat treatments
  - Address risks of operating the components in a combination of starts and hours
- Establish microstructure-mechanical property relationships as a function of heat treatment

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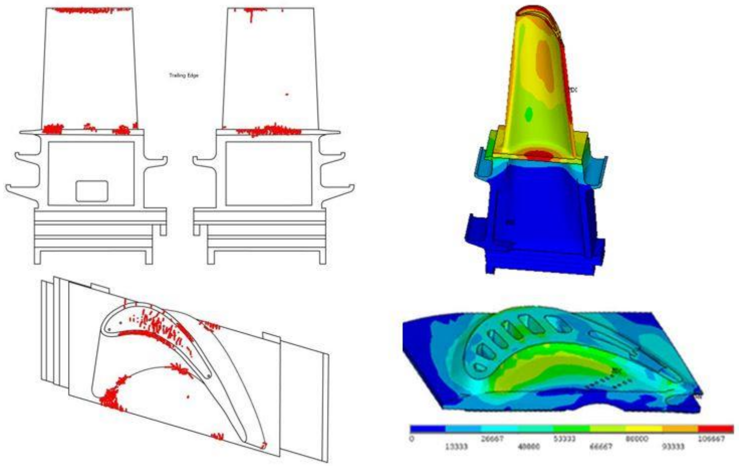
Components and Heat Treatment Methods Evaluated

Components

- GE Frame 7FA stage 1 buckets
  - 42 service run buckets at varying conditions
    - 1 interval, As-Run
    - 2 intervals, As-Run
    - 2 intervals, Repaired - Partial Solution
    - 2 intervals, Repaired - Full Solution
    - 2 intervals, Repaired - HIP + Full Solution



Heat Treatment Methods

Heat Treatment-1 (Partial Solution)	Heat Treatment-2 (Full Solution)	Heat Treatment-3 (HIP + Full Solution)
Pre-weld HT 2050°F (1121°C) for 4 hours	Pre-weld HT 2050°F (1121°C) for 4 hours with slow or fast cool	HIP at 2190°F (1199°C) ±25°F (±14°C) for 4 hours with minimum 15K PSI (103.4 MPa) in Argon
Post-weld HT 2050°F (1121°C) for 2 hours	Post-weld HT 2150°F (1177°C) for 2 hours	Full solution at 2175°F (1191°C) ±25°F (±14°C) for 2 hours in vacuum and argon quenched
Diffuse- MCrAlY coating 2050°F (1121°C) for 2 hours	Diffuse- MCrAlY coating 2050°F (1121°C) for 2 hours	Partial solution and age at 2050°F (1121°C) ±25°F (±14°C) for 2 hours (controlled cooling)
Diffuse TBC coating 2050°F (1121°C) for 2 hours	Diffuse- TBC coating 2050°F (1121°C) for 2 hours	Diffuse- MCrAlY coating 2050°F (1121°C) for 2 hours
Age 1550°F (843°C) for 24 hours all in vacuum	Age 1550°F (843°C) for 24 hours all in vacuum	Diffuse TBC coating HT 2050°F (1121°C) for 2 hours
		1550°F (843°C) for 24 hours and argon quenched both in vacuum.

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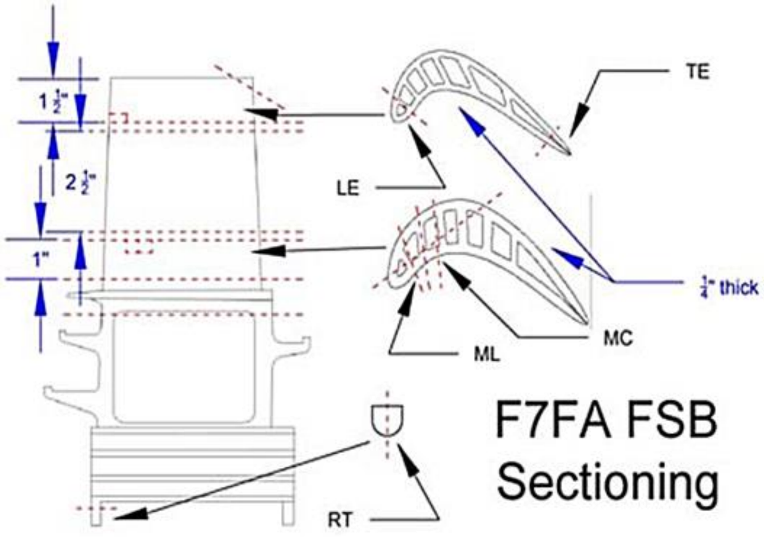
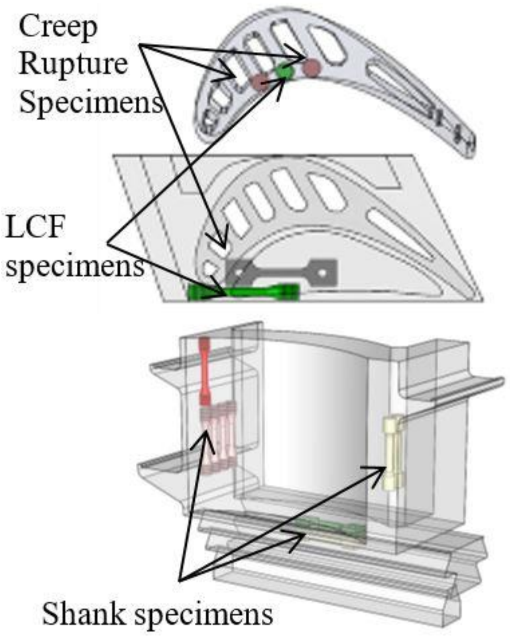
Investigations

- **Microstructural Investigations**
  - Low magnification microscopy
    - Porosity
    - Carbide structures
  - High magnification microscopy
    - Gamma prime morphology



Metallurgical Section Location	Dimension (from tip of the blade)	Location
Trailing Edge Tip	0.25 inch (0.635 cm)	TE
Leading Edge 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 Properties**
  - Primary focus on:
    - Stress rupture testing at 1600°F/40 ksi (871°C/275.8 Mpa)
      - 2 cylindrical specimens from airfoil in longitudinal direction
      - 1 flat specimen from platform in transverse direction
    - Low cycle fatigue testing (1650°F [899°C] / 0.7% strain range)
      - 1 cylindrical specimen from airfoil in longitudinal direction
      - 1 cylindrical specimen from platform in transverse direction



Results of Microstructural Investigations

Microstructural Investigations

Gamma Prime Size Evaluation

Location		1 Interval Buckets (318-899 starts and 5,243-7,298 hours)		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)	
		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	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)

For the As-Run buckets under different conditions, generally the size of the primary gamma prime increased significantly in the inter-dendritic regions at the trailing edge area and less significantly in the other areas compared to the root section.

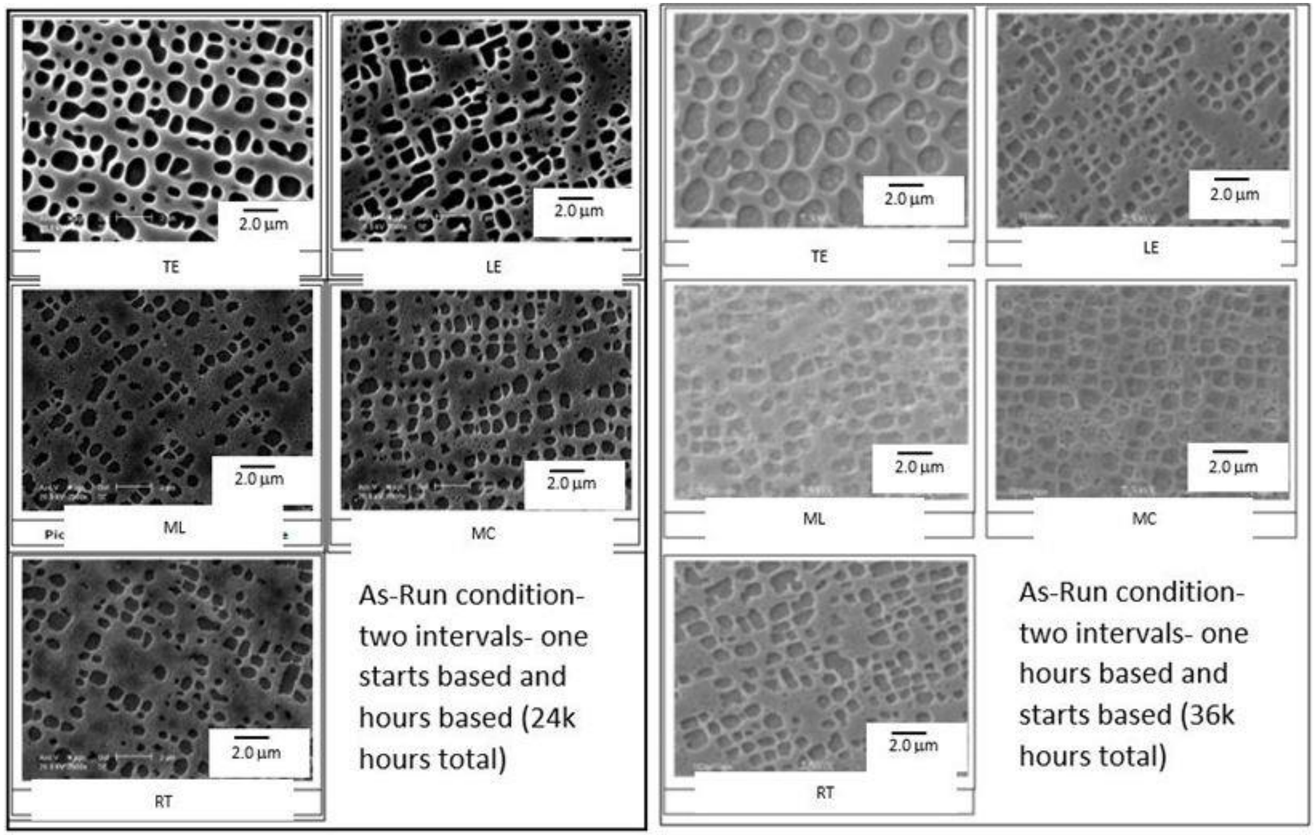
For the repaired '2 Intervals Buckets, starts-based', HIP + Full Solution resulted in better morphology with microstructure similar to original condition.

Location		Heat Treatment-1		Full Solution Heat Treatment		HIP + Full Solution	
		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	0.4 C / 1.3 R	N/A	0.4 C / 0.8 R	Few 0.2
LE	Leading Edge	0.8 R	0.15	0.4 C / 1.5 R	N/A	0.5 C / 1.0 R	Few 0.2
MC	Mid airfoil Cross section	1.2 R	0.15	0.5 C / 0.9 R	0.15	0.4 C / 0.9 R	Few 0.2
ML	Mid airfoil Longitudinal section	1.2 R	0.15	0.5 C / 1.0 R	0.15	0.5 C / 0.9 R	Few 0.2
RT	Root	1.4 S	0.15	0.4 C / 1.0 R	0.15	0.4 C / 0.8 R	Few 0.1

Note: C – Cuboidal R – Rounded S - Spherical

Microstructural Investigations

Microstructure of Specimens – As Run Condition

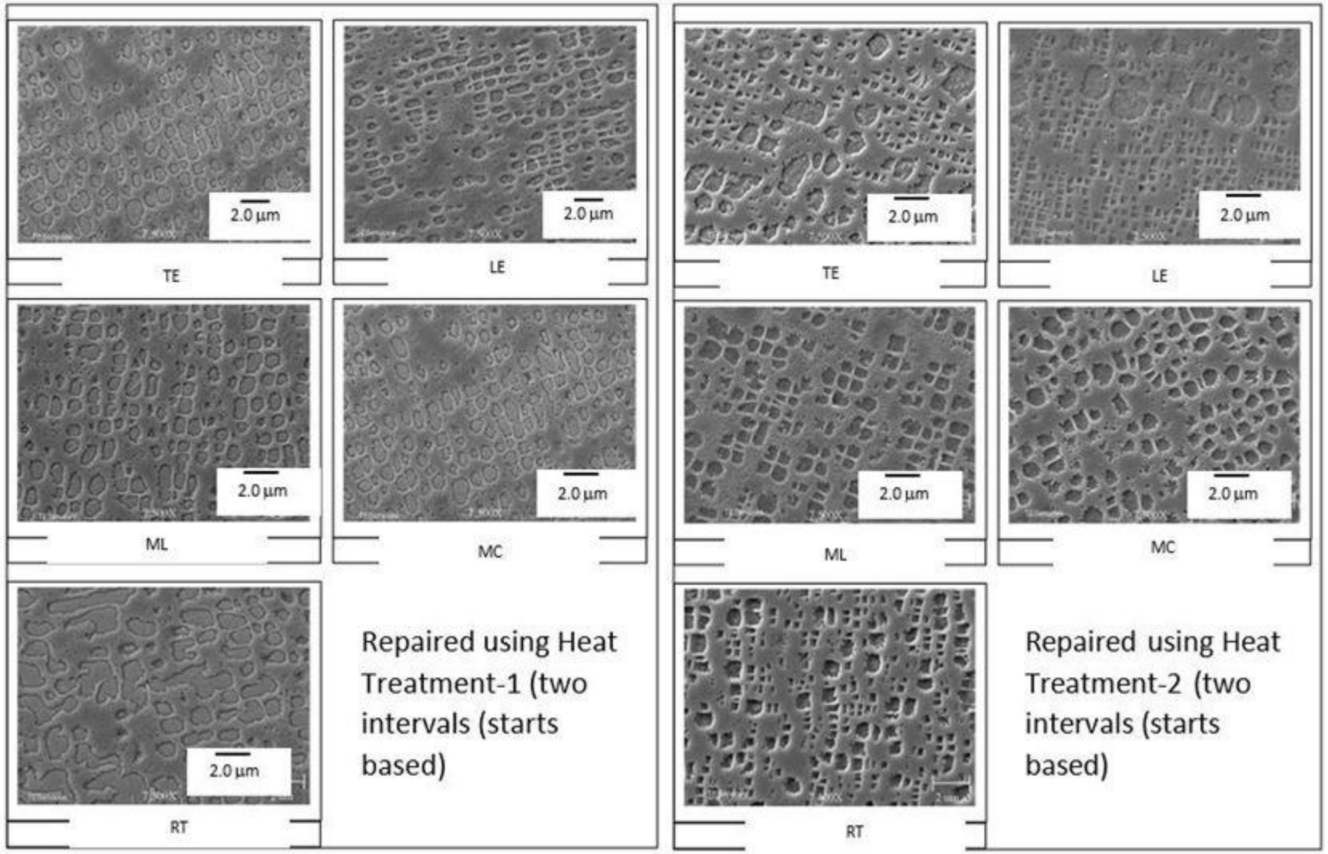


Comments:

- Microstructures are of two intervals buckets with an unknown repair after its first cycle
- Metallurgical structure of base material (carbide and gamma prime) have coarsened, grain boundaries sensitized by presence of elongated carbides, and needle-like phases with gamma prime eutectics were observed
- Primary gamma prime had grown significantly at the inter-dendritic regions of the TE and less significantly at LE

Microstructural Investigations

Microstructure of Specimens – Repaired Condition (Partial and Full Solution)

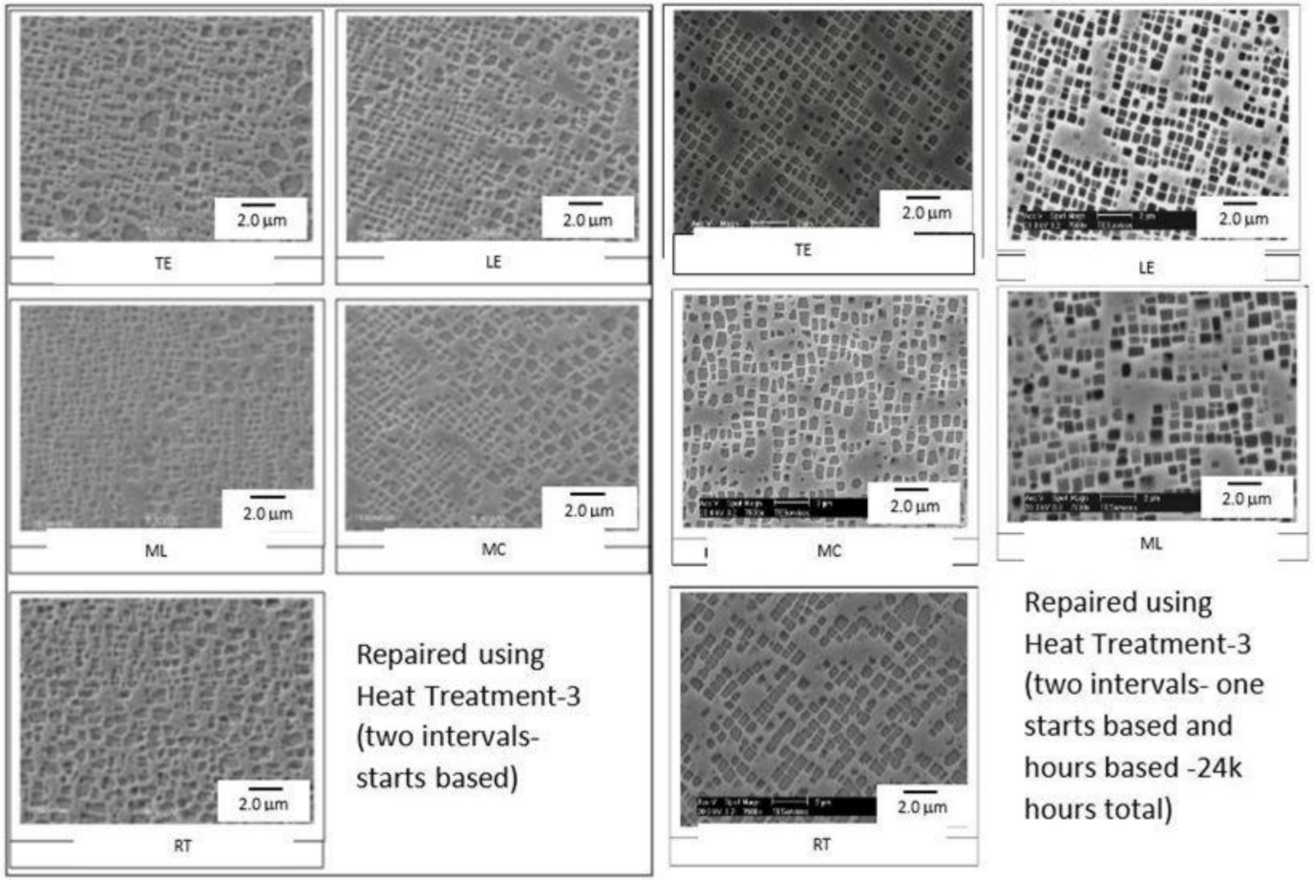


Comments:

- Microstructures are of two intervals buckets (starts-based) repaired with partial solution (left) and full solution (right) heat treatments
- Buckets from the same set were selected for As Run and different heat treatments, so an accurate comparison of microstructures for different heat treatments can be performed
- Large rounded primary gamma prime (0.8-1.2 µm) were observed in inter-dendritic regions.

Microstructural Investigations

Microstructure of Specimens – Repaired Condition (HIP + Full Solution)



Comments:

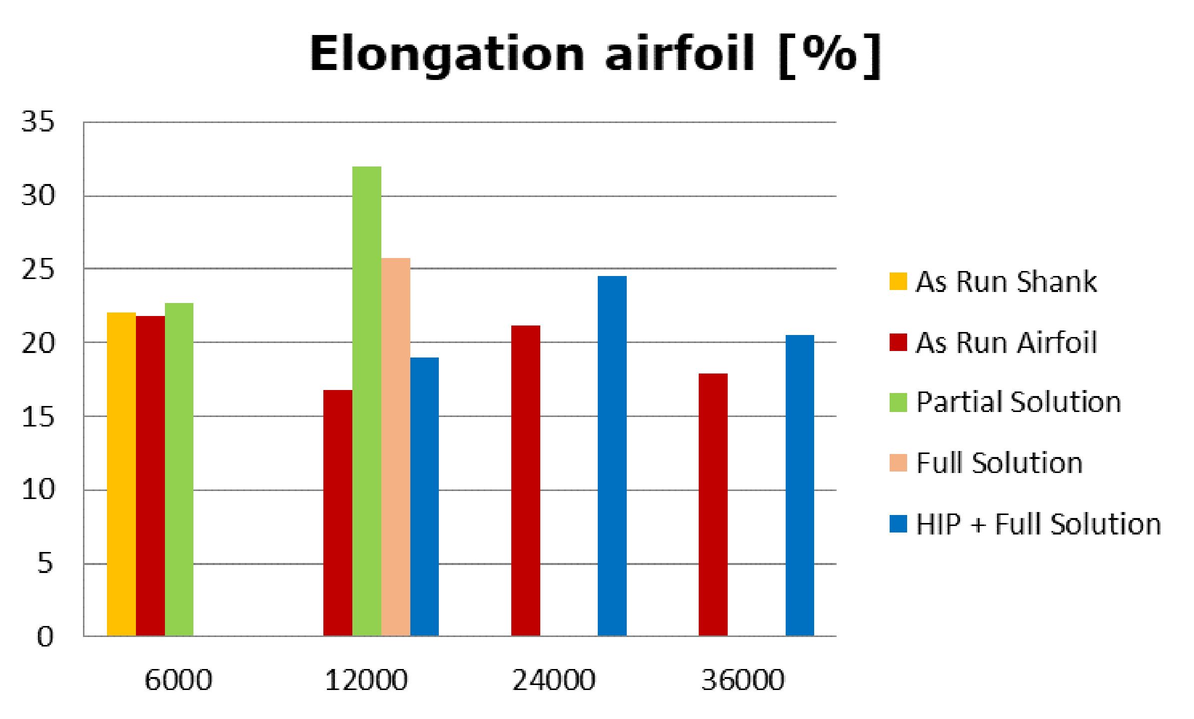
- Microstructures are of two intervals buckets repaired with HIP + full solution for starts-based (left) and one starts-based and one hours-based 24k total hours (right)
- Higher amounts of cuboidal primary gamma prime (0.4-0.5 µm) with some spherical shaped (0.10-0.15 µm) were observed
- The size of gamma prime in the inter-dendritic and dendritic locations was observed to be in the range of 0.4-0.5 µm and 0.8-1.0 µm, respectively

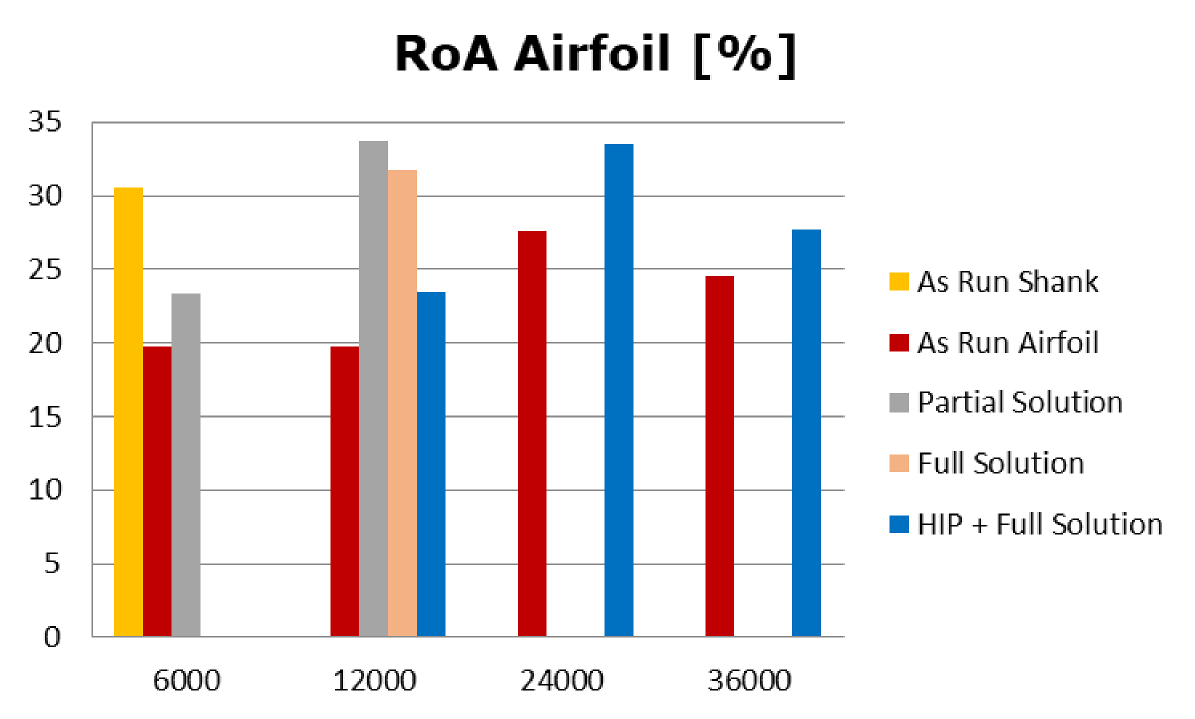
HIP + full solution heat treatment followed by full solution heat treatment resulted in an optimized microstructure similar to or better than original condition

Results of Mechanical Properties Evaluation

Mechanical Properties – Airfoil

Average Elongation and Reduction of Area

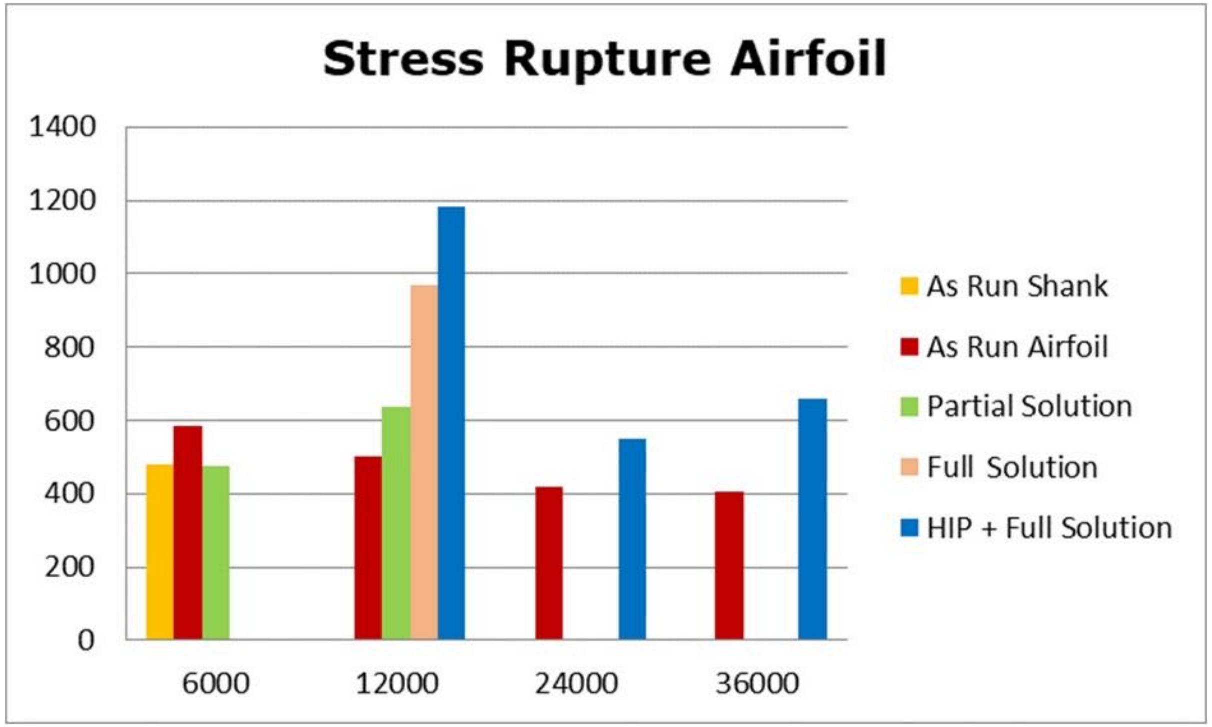


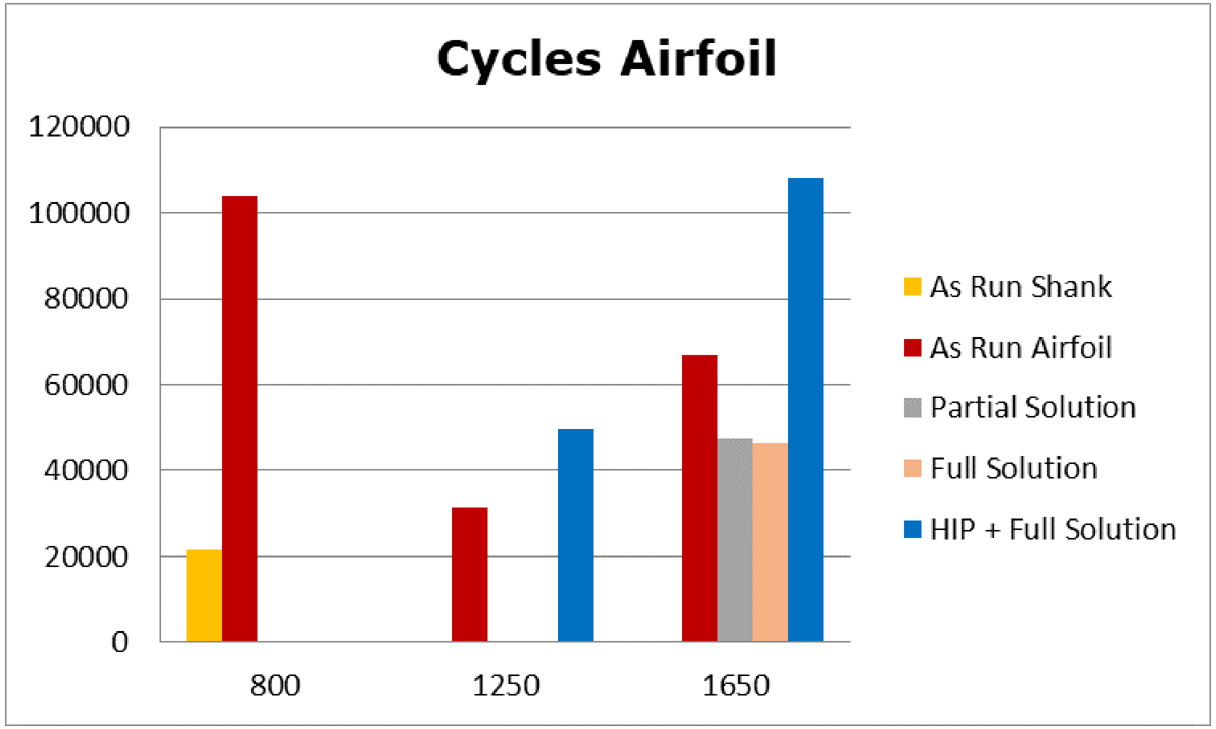


- Elongation and Reduction of Area are measures of ductility
- In general, no significant differences were observed
- The Partial Solution at 12000 hours may be an exception but may also be an outlier due to low number of tests performed

Mechanical Properties – Airfoil

Average Stress Rupture Life and Low Cycle Fatigue Life



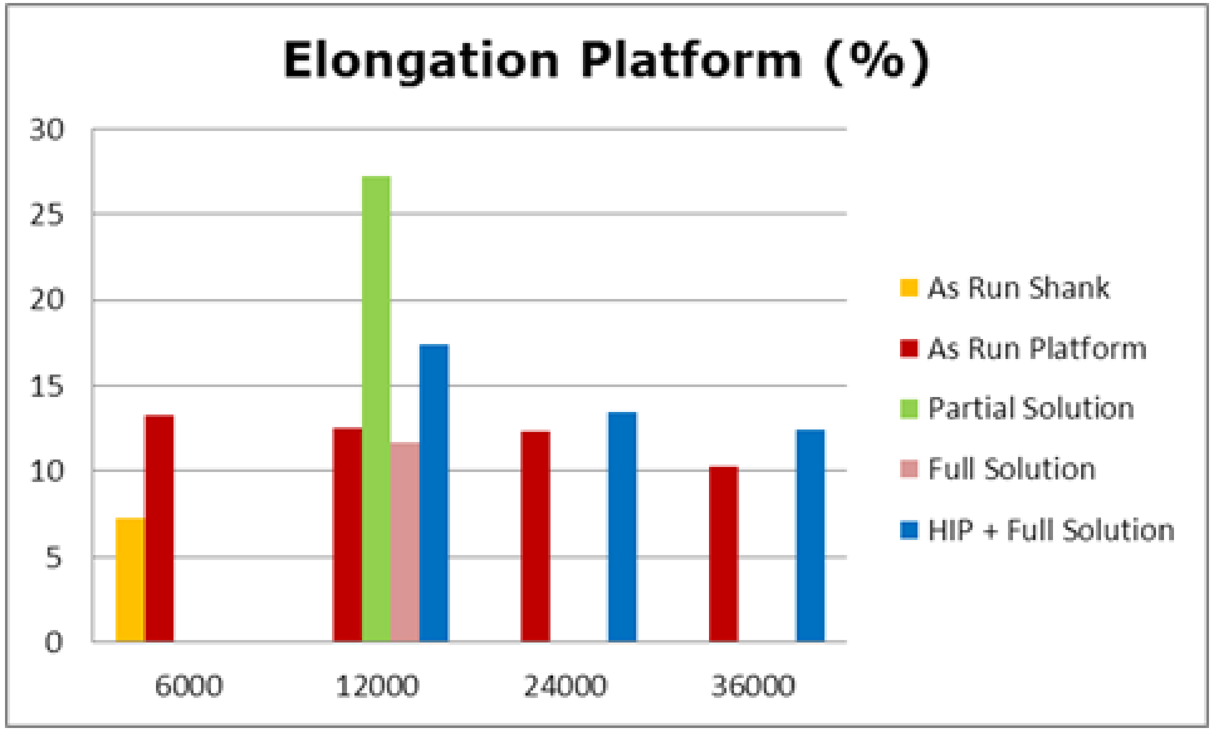


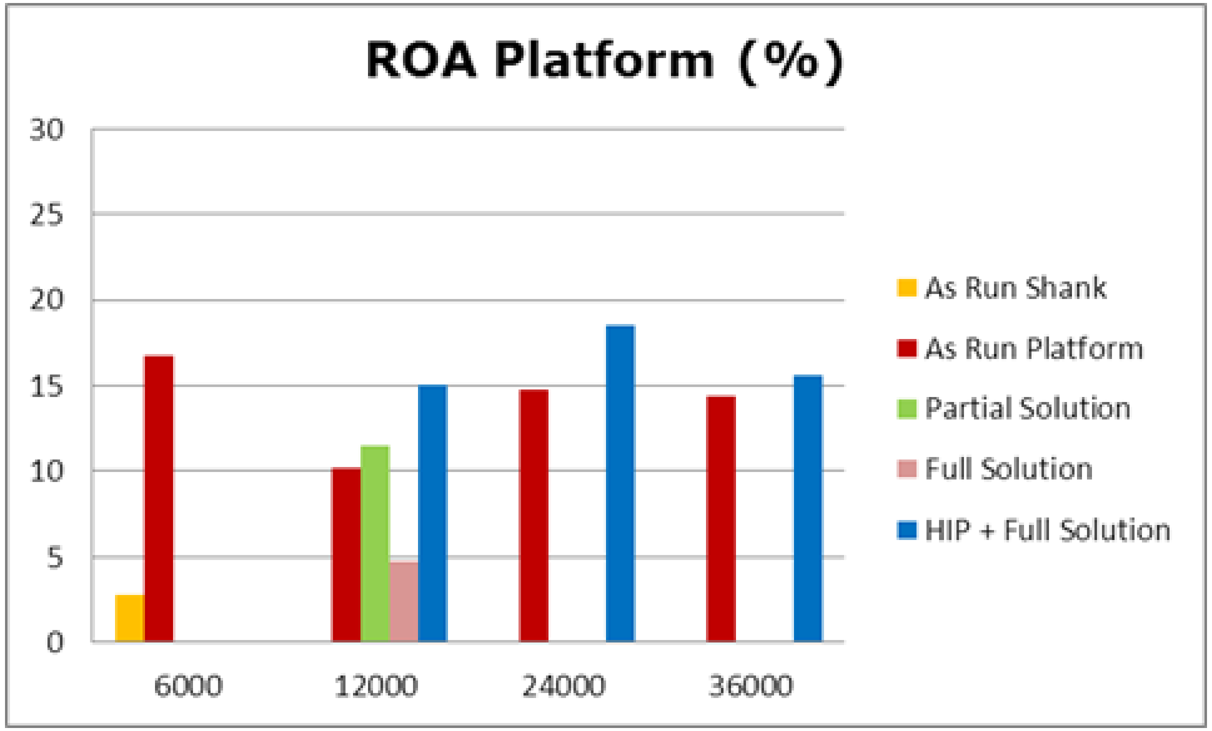
- At 6000 hours, stress rupture of As Run Airfoil is comparable to As Run Shank, indicating minimal degradation of strength during operation. Also, partial solution heat treatment had minimum effect.
- At 12000 hours, all three heat treatments resulted in increased stress rupture lives

- Results based on limited number of specimens
- For 800 cycle specimens, low LCF life of root compared to airfoil may be due to casting differences in root
- For 1650 cycle specimens, the partial and full solution heat treatments result in lower LCF life, while HIP + full solution increased LCF life

Mechanical Properties – Platform

Average Elongation and Reduction of Area

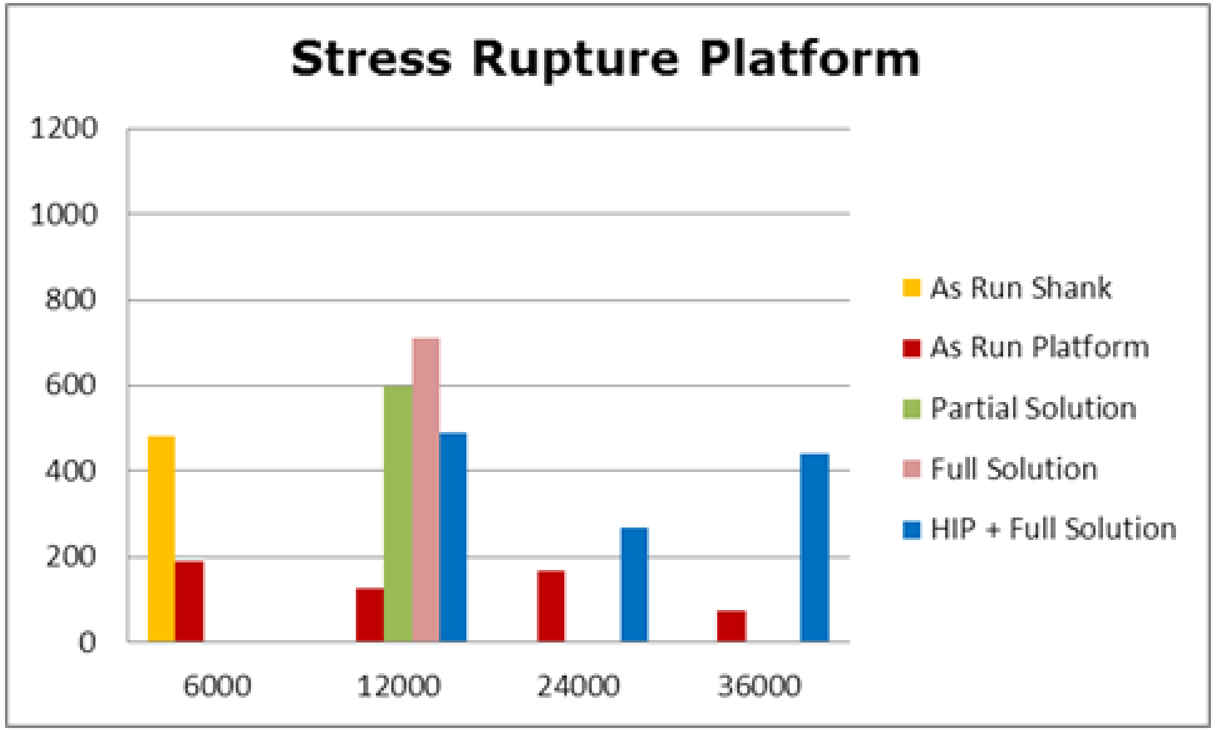


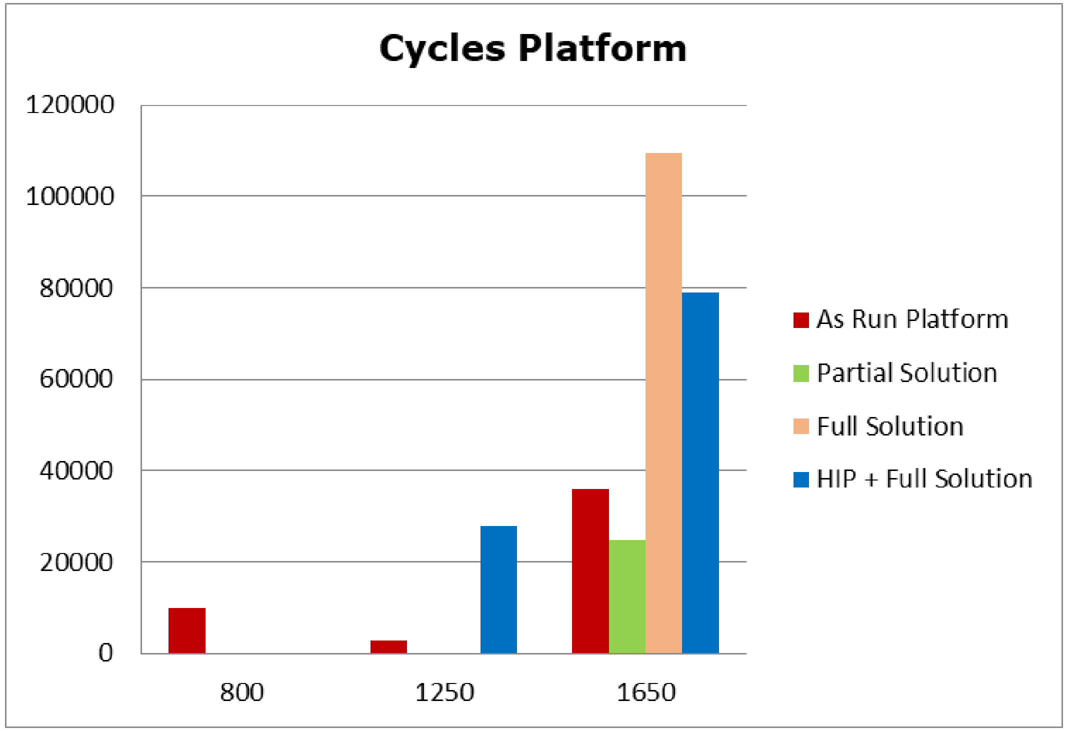


- For As Run condition at 6000 hours, ductility of root is lower than platform (with equiaxed grain structure)
- No substantial differences in ductility for HIP + Full Solution and Full Solution
- High ductility (elongation) at 12000 hours with Partial Solution not observed in Reduction of Area at 12000 hours

Mechanical Properties – Platform

Average Stress Rupture Life and Low Cycle Fatigue Life





- At 6000 hours, low stress rupture life of platform likely due to grain structure (equiaxed with large grain in middle)
- At 12000 hours, specimens showed improved stress rupture with all heat treatments
- At 24k and 36k hours, HIP + full solution improved stress rupture

- For the 1650 cycles specimens, Full Solution resulted in the highest LCF life.

  Note Partial Solution results were lower than As Run (likely due to limited number of test specimens and significant data scatter)

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Mechanical Properties – Airfoil

Gamma Prime, Stress Rupture, LCF and Micro-hardness

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

Heat Treat		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	4	Neutral

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Conclusions

- Heat treatments can rejuvenate the stress rupture and the LCF properties of the material, although the effect for partial solution heat treatments was minimal
- The results of the stress rupture and LCF lives show that the optimal results are for a HIP + full solution heat treatment
- Limited data indicates that higher ductility does not relate to higher LCF values; more testing is required to verify the relationship
- The partial solution heat treatment provides limited improvement of stress rupture life and LCF life
- The properties of the material after repairs/heat treatments are better than new material, which indicates that the heat treatments performed during new manufacturing were not optimal
- Due to the intrinsic nature of LCF testing and the scatter observed in the limited tests, more tests are required to confirm the conclusions

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