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ALTERNATE MATERIAL FOR ELEVATED TEMPERATURE TURBINE COOLING PLATE APPLICATIONS

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Abstract

Extrude+ isoforged Ni-base powder alloy René104 was initially developed for critical rotating applications subject to elevated temperature for extended periods. The excellent dwell fatigue behavior and metallurgical stability makes this a viable candidate for material upgrade to improve the durability of non-critical turbine engine components that encounter severe operating conditions. This program was performed to address distress and metallurgical changes observed after field service of rotor cooling plates in aircraft turbine engines. Temperature capability is a key factor affecting hardware durability as commercial engine design temperatures and take-off cycle severity continues to climb.

Full-scale forgings were processed for manufacture of finished parts for engine test and destructive evaluation to determine behavior for conditions specific to rotor cooling plates. Material behavior in the 700-870°C range was emphasized. The advantages of René104 were quantified relative to the current As-HIP René95 product using fatigue cycling with a super-imposed dwell at maximum load, simulated mission fatigue cycling, and tensile test of specimens after stressed pre-exposure. Dwell fatigue capability was improved by ~110°C with a nominal life advantage ranging from 10-100X, increasing with test temperature. Fatigue life advantage was nominally 4X when continuously cycled to simulate mission profiles.

A series of oversize creep-rupture tests were performed to provide material for tensile test following a stressed thermal exposure at 760-815°C. Significant degradation of room temperature and 650°C tensile behavior due to pre-exposure was not encountered, although microstructural changes were observed. Metallurgical stability by this measure was clearly superior to that of As-HIP René95. Changes in René104 microstructural features and hardness with time at temperature are also presented.

Introduction

Turbine engine cooling plates and blade retainers are frequently subjected to an extreme thermal environment that contributes to non-catastrophic distress (Figure 1) discovered upon engine teardown. Analyses of field-returned hardware provide evidence of fracture via dwell-related fatigue, a performance metric also of growing criticality for disk, shaft, and seal components. Microstructural features of field returned hardware provide evidence of thermal excursions approaching 870°C. Upgrade to an alloy with greater thermal capability was considered an opportunity to improve turbine component durability and increase rotor maintenance intervals.

As a result of uncertainties regarding this dynamic environment, a matrix of conventional and mission simulation testing was required to quantify the performance benefit to substantiate engine test of finished hardware. Alloy René104, an extrude+ isoforged Ni-base powder alloy partially developed under NASA-Enabling Propulsion Materials programs (1,2) was considered for a drop-in performance improvement versus fine grain As-HIP René95 (3). Nominal compositions are provided for reference.

Table I
Alloy Composition in Weight %, Balance Ni

Alloy Wt%	Co	Cr	Mo	W	Nb	Al	Ti	Ta	C
Rene′104(4)	14-23	11-15	2.7-5	0.5-3	0.25-3	2-5	3-6	0.5-4	0.015-0.1
As-HIP Rene′95(5)	8	13	3.5	3.5	3.5	3.5	2.5	na	0.06
Rene′88DT(5)	13	16	4	4	0.7	2.2	3.8	na	0.05

Improved metallurgical stability is desired to ensure mechanical capability during service under severe thermal and stress conditions. Microstructural stability is expected to benefit the dwell fatigue resistance of the alloy system. Quantification of mechanical property retention against proven alloy systems is necessary to abate risk of embrittlement encountered on earlier Ni-base alloy systems.

Figure 1 Finished René104 cooling plate representing non-critical rotor components that show distress related to extreme thermal conditions. Nominal outer diameter is 50cm.

Experimental Procedure

Materials

Powder metal René104 isothermal forgings were processed from billet similar to the René88DT methods described in reference 6, with the exception of size and a moderate cooling rate from super-solvus solution heat treat. Following quench, forgings were subjected to an intermediate stabilization and final age cycle to a schedule similar to that of Waspaloy[7,8]. Finished components were nominally 55 cm in diameter with an ID of 35 cm and 6 cm thick. As-HIP René95 specimens were excised from production cooling plate stock of similar dimension, but solutioned below the γ'-solvus temperature, quenched and aged [5].

Test Methods

Sustained-peak LCF (SPLCF) behavior was determined for proposed René104 and current As-HIP René95 alloys. Notched specimens (Kt 2.7) were cycled in load-control using a trapezoidal waveform with 90-second dwell at maximum load (Figure 2A). Data were compared to average LCF behavior developed with a triangular waveform at 20cpm (Figure 2B).

Simulated mission fatigue (SMF) tests were performed to quantify impact of a material upgrade on the life limiting location. A simplified fatigue test was derived to represent the complexity of an engine mission. Notched specimens (Kt 1.8) were performed in load control with an induction coil programmed to vary temperature out-of-phase with stress (Figure 2C). No intentional dwell period was imposed as in isothermal SPLCF testing described above. The initial SMF test condition ranged from 427°C, 20MPa tensile to 760°C, 14.5MPa compressive stress. Thermal ramp was in excess of 650°C/minute during the temperature increase, and slightly over 300°C/minute during the cool to 427°C with linear ramps. A second series of SMF testing ranged from 427 to 815°C, also out-of phase, to reflect a more severe hot gas ingestion event.

Metallurgical stability was measured by tensile and hardness retention after extended exposure to high temperature. As initially described in reference 9, threaded ends of over-size René 104 creep bars were used as input stock for tensile test bar manufacture following completion of creep tests at 760-815°C for various times. Upon creep-rupture test completion, tensile specimens were manufactured from either end of the geometry indicated in Figure 3. Specimens removed from the 'A' end were subsequently tested at room temperature, the 'B' end was tested at 650°C. Results were compared to unexposed data from the same forging for evidence of overage or embrittlement by this measure. René104 tensile property retention was also compared to that of As-HIP René95 following an unstressed pre-exposure. Macrohardness, HRc, was determined on the shoulder of bars prior to room temperature test. One creep 870°C creep specimen was also hardness tested and evaluated metallographically; no tensile data were generated for this condition.

Microscopy

Optical and field emission scanning electron microscopy techniques were performed on the as-manufactured and pre-exposed René104 conditions to determine microstructural evolution to mechanical behavior. Test gages of the over-size René 104 creep specimens were prepared mechanically on a plane normal to the applied stress axis, and immersion etched to reveal grain structure. Following removal from the mount media, each was re-prepared electrolytically in a solution of 300ml ethylene glycol+80ml Perchloric+500ml Methanol. The following parameters were applied in the presence of a platinum cathode. Nominal specimen area was 3.cm^2. Preparation and optical microscopy were performed by GEAE, field emission SEM was provided by The Ohio State University.

	Voltage	Time
Electropolish	28	15 seconds
Electro-etch	5	3-6 seconds

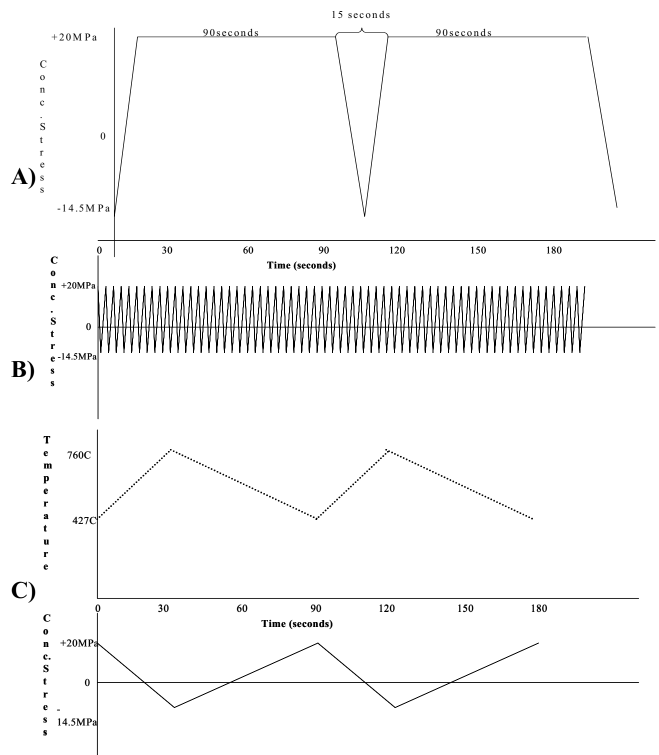


Figure 2 **Fatigue cycle profiles performed for A) Sustained-peak LCF, B) continuous cycle LCF and C) simulated mission fatigue. The latter mission was also performed to a maximum temperature of 815°C.**

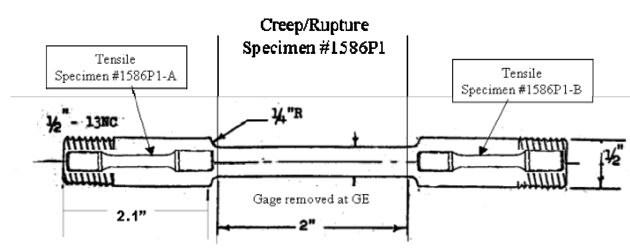


Figure 3 **Oversize creep specimen used to evaluate the metallurgical stability of René104. Sub-size tensile bars were excised from either end. Gage section was subjected to microstructural evaluation.**

Results and Discussion

Microstructure of as-heat treated René104 evaluated in this study are presented in Figure 4. Average grain size throughout the cross-section ranged from ASTM 6 to 7.5. The As-HIP René95 product measured an average ASTM 11.5.

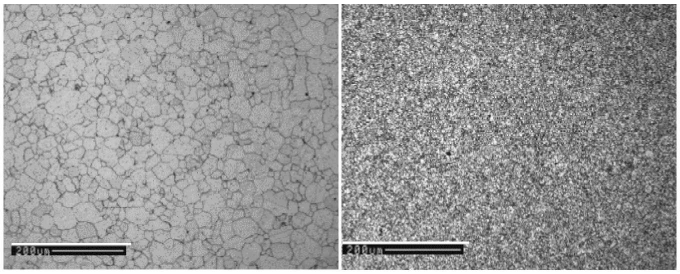


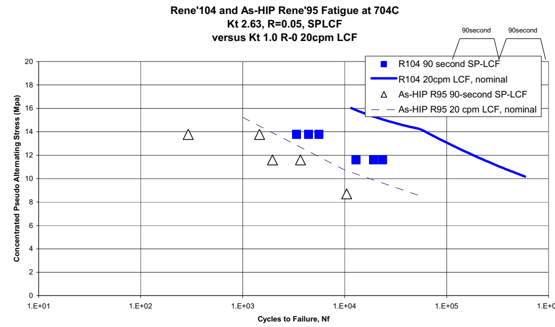
Figure 4 Equiax grain structure of A) René104 and B) As-HIP René95 representing material condition prior to thermal exposure.

<u>Dwell Fatigue</u>

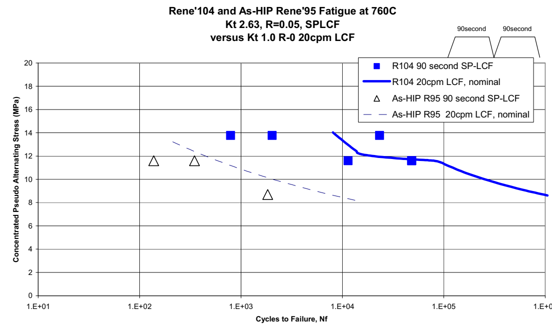
Sustained-peak LCF results are provided in Table II and Figures 5A through 5C, relative to the continuous cycling LCF behavior of each alloy. These figures illustrate the life debit encountered with a dwell at maximum load when cycled at elevated temperatures. Isothermal comparisons indicate René104 has a nominal 10x life benefit at 704°C, 100x at 760 and 815°C when cycled under these dwell conditions (Figure 6). For a given stress range, The René 104 forging showed a nominal 110°C benefit over the As-HIP René95 behavior.

Table II
Sustained-peak LCF
Kt 2.63, R=0, 90-second dwell at max, Load-control

Alloy	Temp C	Max Conc. MPa	Measured notch radius, mm	Max Net MPa	Failure Cycles	Conc. PsAlt Mpa
Rene104	704	24.4	0.35	9.3	12,936	11.6
Rene104	704	24.4	0.32	9.3	19,278	11.6
Rene104	704	24.4	0.35	9.3	23,684	11.6
Rene104	704	29.0	0.35	11.0	4,435	13.8
Rene104	704	29.0	0.33	11.0	3,390	13.8
Rene104	704	29.0	0.35	11.0	5,601	13.8
Rene104	760	24.4	0.34	9.3	48,422	11.6
Rene104	760	24.4	0.35	9.3	48,056	11.6
Rene104	760	24.4	0.35	9.3	11,390	11.6
Rene104	760	29.0	0.36	11.0	791	13.8
Rene104	760	29.0	0.35	11.0	2,030	13.8
Rene104	760	29.0	0.35	11.0	23,343	13.8
Rene104	816	18.3	0.35	7.0	8,113	8.7
Rene104	816	21.4	3.48	8.1	2,634	10.1
Rene104	816	21.4	0.34	8.1	1,162	10.1
Rene104	816	21.4	3.40	8.1	1,351	10.1
Rene104	816	24.4	0.36	9.3	4,996	11.6
Rene104	816	24.4	0.35	9.3	3,726	11.6
Rene104	816	29.0	0.36	11.0	937	13.8
Rene104	816	29.0	0.35	11.0	675	13.8
Rene104	871	18.3	0.37	7.0	1,814	8.7
Rene104	871	18.3	0.34	7.0	2,183	8.7
Rene104	871	24.4	0.35	9.3	235	11.6
Rene104	871	24.4	0.34	9.3	341	11.6
AS-HIP R95	704	18.3	0.34	7.0	10,479	8.7
AS-HIP R95	704	24.4	0.34	9.3	1,963	11.6
AS-HIP R95	704	24.4	0.33	9.3	3,697	11.6
AS-HIP R95	704	29.0	0.35	11.0	1,466	13.8
AS-HIP R95	704	29.0	0.33	11.0	293	13.8
AS-HIP R95	760	18.3	0.34	7.0	1,836	8.7
AS-HIP R95	760	24.4	0.34	9.3	348	11.6
AS-HIP R95	760	24.4	0.34	9.3	138	11.6
AS-HIP R95	816	24.4	0.34	9.3	26	11.6



A)



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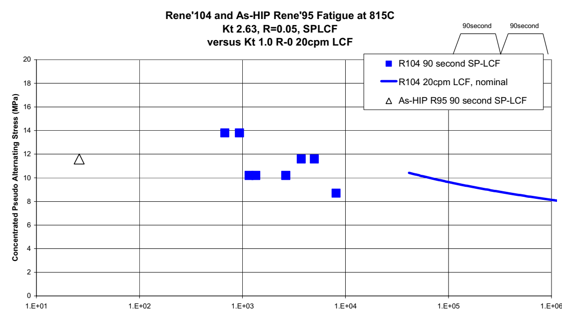

C)

Figure 5 SPLCF data versus continuous-cycled LCF behavior. René104 shows a nominal 10X benefit at 704°C and 100X at 760 and 815°C versus As-HIP René95.

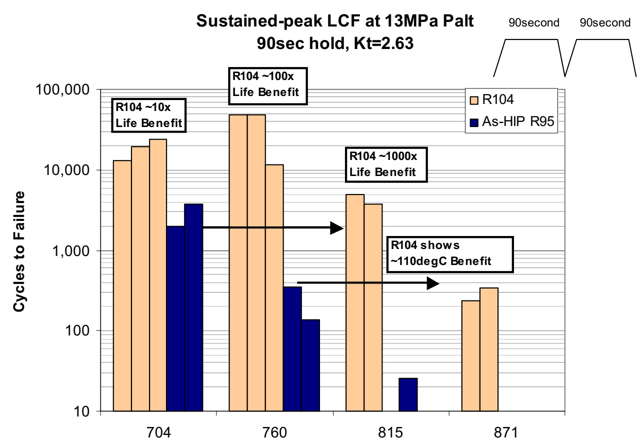

Figure 6 Behavior at this pseudostress condition shows a nominal 110°C advantage in capability over As-HIP René95.

Simulated Mission Fatigue

Simulated mission test cycles to failure for each alloy and condition are listed in Table III and presented in Figure 7. The René 104 advantage in cycles to failure to this profile was 3.1X and 4.7X that measured for As-HIP René95 for 427-760°C and 427-815°C°F mission cycles, respectively. Data were instrumental in substantiating René104 hardware for factory and field engine tests.

Table III
Simulated Mission Fatigue

ID	ALLOY	MISSION	Nf
1586-S35	R104	760 to 427C -14.5 to +20MPa	6335
1582-S9	R104	760 to 427C -14.5 to +20MPa	4430
1586-S25	R104	760 to 427C -14.5 to +20MPa	5618
R95-SMF1	As-HIP R95	760 to 427C -14.5 to +20MPa	1951
R95-SMF3	As-HIP R95	760 to 427C -14.5 to +20MPa	1548
1582-S13	R104	815 to 427C -14.5 to +20MPa	3456
1586-S28	R104	815 to 427C -14.5 to +20MPa	3317
R95-SMF4	As-HIP R95	815 to 427C -14.5 to +20MPa	793
R95-SMF5	As-HIP R95	815 to 427C -14.5 to +20MPa	642

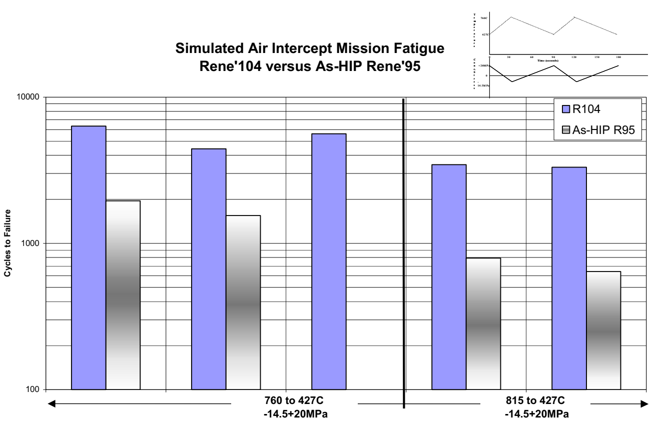

Figure 7 **Mission simulation data for the profile represented by Figure 2C) indicate a René104 life advantage of 3.1X that of As-HIP René95 when cycled out-of-phase with stress between 427 and 760°C, and 4.7X cycling from 427 and 815°C.**

Metallurgical Stability

Tensile properties of each alloy in the as-heat treated and thermal pre-exposure conditions are provided in Table IV and Figure 8. The 650°C tensile behavior after 25 hours at 760 and 815°C showed little impact on Rene′ while As-HIP Rene′95 exhibits an 8-15% loss of strengths and 18-37% lower ductility.

Table IV
25-hour Exposure on 650°C Tensile Retention

Normalized Behavior	R104 760C, 25 Hrs	R104 815C, 25 Hrs	R95 760C, 25 Hrs	R95 815C, 25 Hrs
Ultimate Strength	0.98	0.98	0.92	0.94
0.2% Yield	1.02	0.98	0.87	0.90
%Elongation	0.99	1.07	0.65	0.63
%Red of Area	0.98	0.97	0.82	0.66

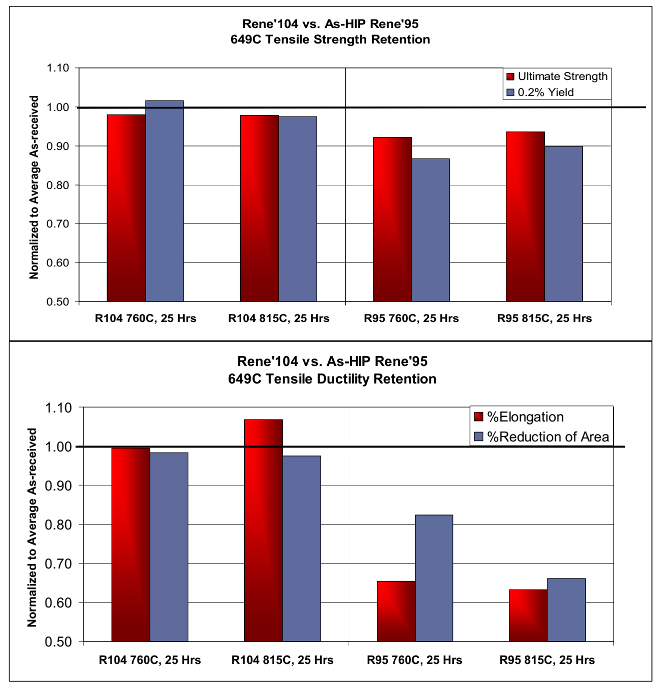

Figure 8 **Influence of thermal pre-exposure on retention of René104 and As-HIP René95 tensile properties following 25-hour pre-exposures. René 104 exposures were performed with minor stress.**

Additional tensile data versus thermal exposure are presented as a function of Larson Miller parameter:

$$LMP(1000)=(T°F+460)(25+\log(t, Hrs))$$

As-heat treated properties are arbitrarily assigned an LMP of 41,500 for plotting purposes. Data include the conditions of Table IV and extend to 870°C, 430 hours. Curve fits are provided only to show general trends, assignment of the initial LMP affects any derived model.

Room temperature tensile response showed stability throughout the temperature and times evaluated (Figure 9). Similar results were obtained from a cooperative GE Global Research program to evaluate René104 exposed to 732 and 738°C exposures through 1,000 hours [10]. These data confirmed that stress during thermal exposure does not affect over-age by this measure. This conclusion can also be reached for alloy 718 by comparing data presented in references 9 and 11. Room temperature behavior of René104 was nearly constant through the evaluated range of thermal exposures.

At the relatively sensitive 650°C tensile condition, the onset of strength decay was significantly delayed relative to that recorded in an earlier study of As-HIP René95 following unstressed thermal exposure(12). The tensile strength advantage of the fine grain As-HIP René95 is nearly eliminated following thermal exposure (Figure 10, LMP 49,000). René104 tests showed loss of strength only after exceeding an LMP value of approximately 53,000 and clearly superior to that of the As-HIP René95 product. Similar to room temperature results, René104 ductility response showed no pre-exposure effect; indicating that René 104 does not, within the limits of processing and composition evaluated, suffer any evidence of gross embrittlement.

A similar Larson Miller profile of average hardness presents as-heat treated and thermal exposed conditions (Figure 11). Hardness increased slightly prior to overage. An increase of 2 HRc is followed by decay to below the initial value at LMP beyond 56,000. Hardness response is not considered a sensitive indicator of age condition in γ'-strengthened Ni-base Superalloys. Readings below HRc 40 would indicate a severely over-aged condition.

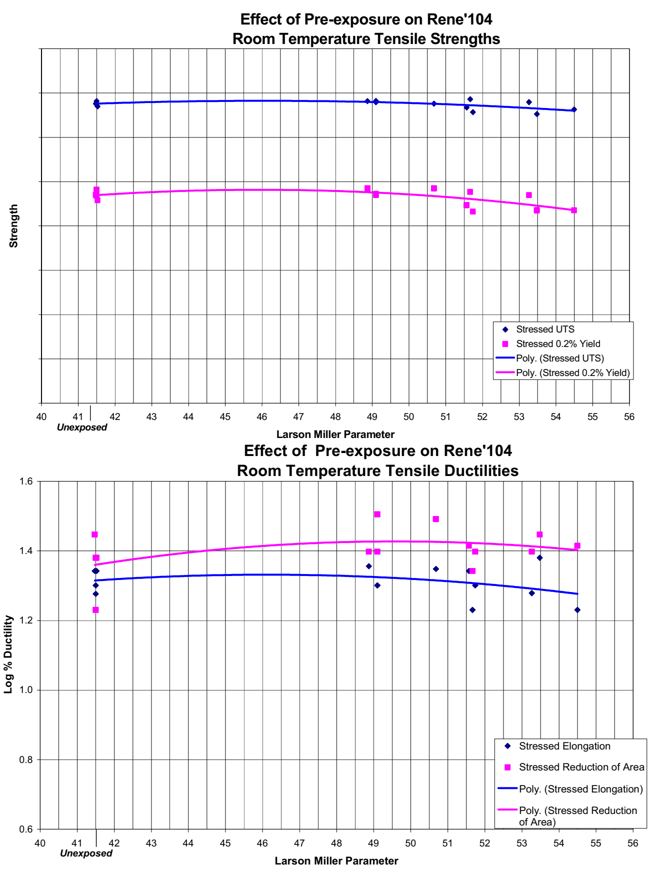

Figure 9 **Influence of thermal pre-exposure on room temperature tensile retention of René104. Tensile behavior is not affected by these conditions.**

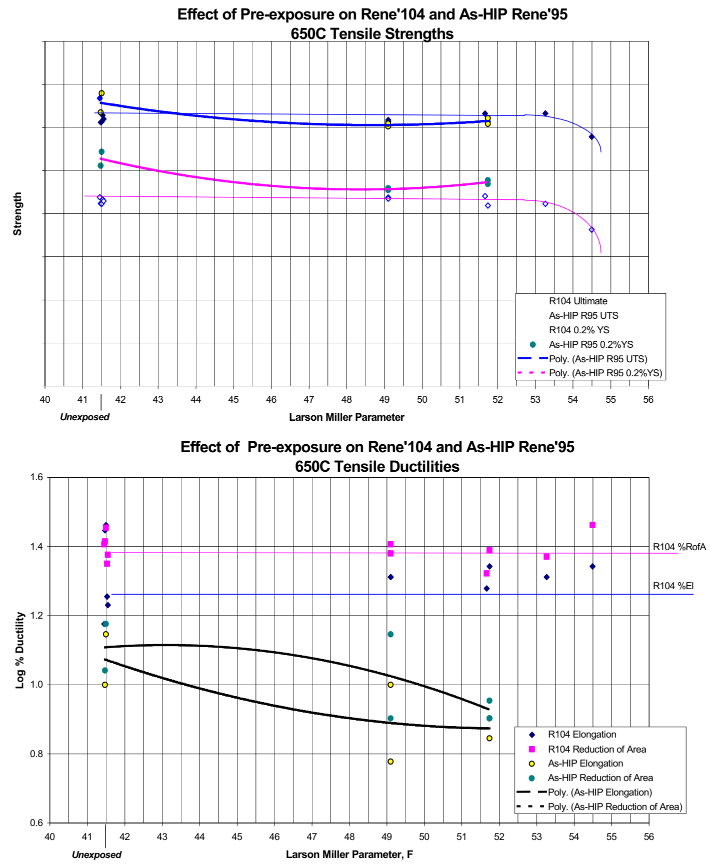

Figure 10 **Influence of thermal pre-exposure on René104 tensile retention shows improved stability versus As-HIP René95 when tested at 650°C.**

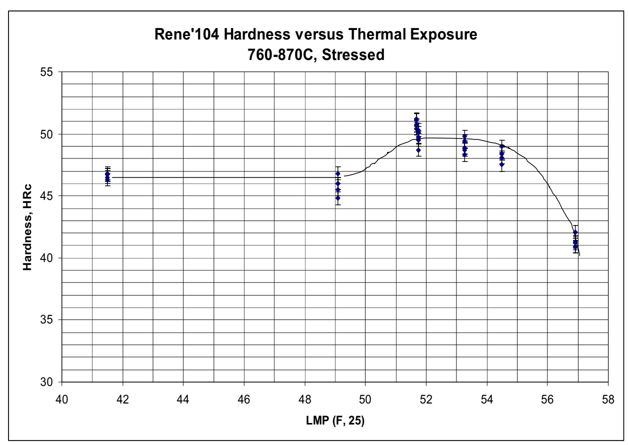

Figure 11 **René104 hardness representing as-heat treated and stressed thermal pre-exposure conditions.**

Microstructural Stability

The electron images representing René104 microstructure without pre-exposure show a duplex γ' size distribution consisting of secondary precipitation (~0.35μm) during quench from super-solvus solution, plus a tertiary precipitate (<0.09μm) formed and/or coarsened during subsequent stabilization and aging cycles (Figure 12). Primary γ' associated with fine grain processing is absent due to solutioning above the solvus temperature to enable grain growth to a more damage tolerant grain structure similar to that of René88DT [13,14]. Intragranular borides and primary carbides are also present in these micrographs and stable throughout the evaluated range of temperature-time. Secondary carbides are not evident in these images, but extraction work was not performed.

Quench models show the specimen pre-exposed to 760°C/25 hour was cooled with an average cooling rate of ~20°C/minute[7]. Although a nearly identical rate to the as-heat treated condition, Figure 13 presents a dendritic cooling γ' measuring ~0.45μm., evidence of slow cool through the γ'-solvus. Prior René 104 cooling rate studies show this morphology precipitates at single-slope average cooling rates of <15°C/minute or "2-slope quench" associated with locations internal to the heat-treated shape[15]. Tensile response was not reduced by this microstructure. Coarsening of the fine γ' precipitate is implied in these micrographs. Common to As-HIP René95, secondary carbides are observed at the imaged grain boundary for this pre-exposure. Grain boundary precipitates were assumed Cr-rich $M_{23}C_6$ and borides, as reported for René88DT exposed at 732°C for 10,000 hours (LMP 52,500, F, 25, ref. 14).

The balance of pre-exposed René104 Cooling Plate specimens were modeled to a similar average cooling rate and reflect the quench rate and path reflected by the baseline condition (Figures 14-17 versus Figure 12). Progressive growth and coalescence of cooling γ' occurs in situ with dissolution of the fine γ' precipitates. Aging γ' is dissolved between 150 and 636 hours at 815°C and is not present in the 870°C/430 hour condition. The latter condition shows evidence coalescence of cooling γ', particularly along grain boundaries (Figure 17).

A semi-continuous, secondary precipitate was present at grain boundaries after 760°C/599 hours. This phase remains discontinuous after 636 hours at 815°C. A continuous grain boundary film and was present after 430 hours of creep at 870°C (Figure 17); no tensile response was generated for this condition.

No evidence of acicular, topologically close-packed phases, reported previously for select Ni-base alloys[12-13, 16-17], was observed in the current study. Improved metallurgical stability likely provides a significant contribution to the superior dwell fatigue (sustained-peak LCF) behavior demonstrated for this alloy.

Summary

The high temperature behavior and metallurgical stability of René104 were developed for conditions and applications beyond the original intent for this alloy system. The advantages over As-HIP René95 were quantified for the targeted cooling plate application. The benefit relative to the fine grain product, and even René88DT with a comparable microstructure, increases with application temperature-time severity. While some changes in microstructure and performance were observed, the relative stability and fatigue capability provides an alloy and processing option that provides a significant improvement in durability for extreme conditions.

Conclusions

- René104 showed a nominal 110°C advantage over As-HIP René95 in sustained-peak LCF capability. Evaluated isothermally, René 104 life advantage was 10X at 704°C and 100X at 760 and 815°C.
- René104 also showed a nominal 4X nominal life benefit when tested to a simulated mission with temperature cycled out of phase with applied stress.
- Based on tensile response, no evidence of embrittlement was noted for René104 after stressed thermal pre-exposures. Tensile ductility was unaffected by the temperature-time range evaluated as opposed to reductions measured for As-HIP René95 at these extreme conditions.
- René104 room temperature tensile strength was also unaffected by pre-exposure. The 650°C ultimate and yield strength retention was far superior to that of As-HIP René95 over the evaluated range.
- Hardness was confirmed a poor measure of age condition for René104. A slight hardness increase was followed by decay at an extreme 870°C condition.
- Thermal exposure above the age temperature coarsens both cooling and aging γ' of René104. Extreme conditions dissolve age γ' as cooling γ' precipitates begins to coalesce.
- Additional grain boundary phases precipitate in a discontinuous manner through 815°C and 636 hours. A grain boundary film was formed after extended time at 870°C.
- René104 showed no evidence of acicular TCP phases over conditions ranging to 870°C and 640 hours.

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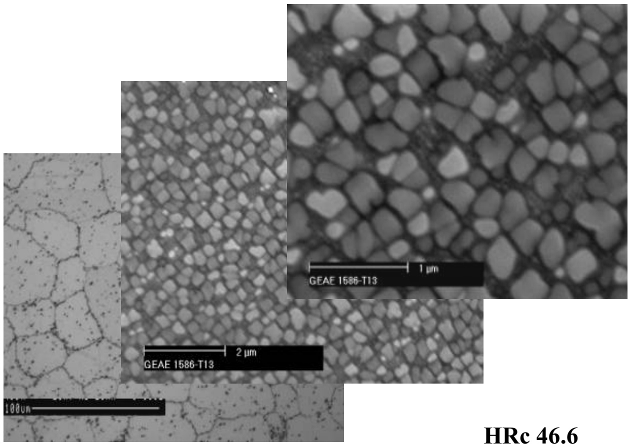
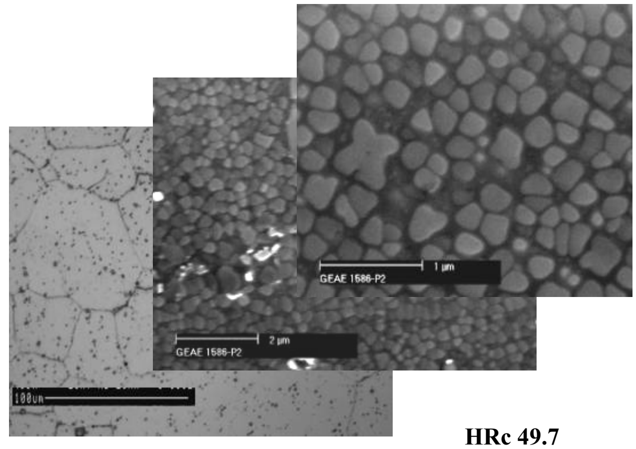


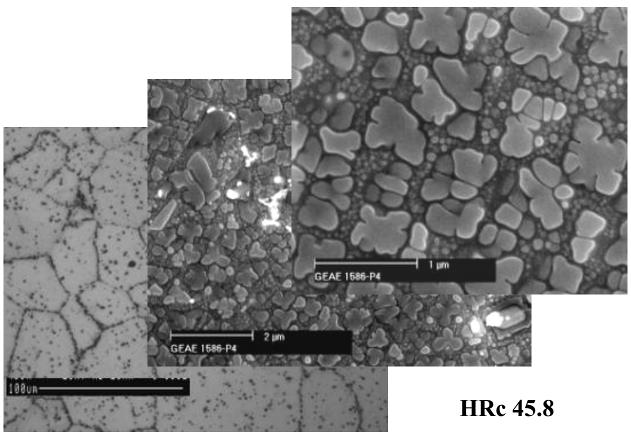
HRc 46.6

Figure 12 As-heat treated René104 microstructure images provide initial cooling and age γ' distribution.



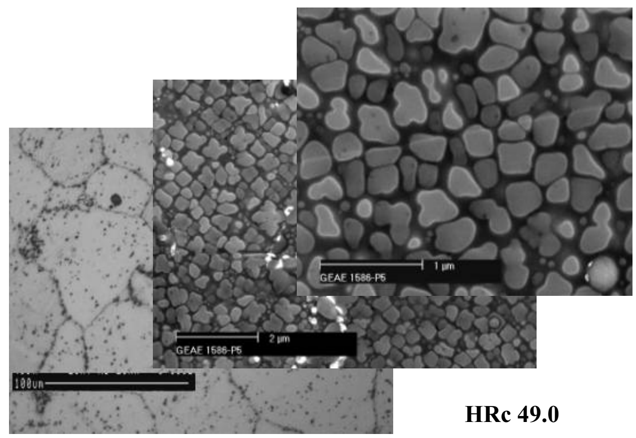
HRc 49.7

Figure 15 René104 shows grain boundary precipitates and cooling + age γ' after 25 hours, 815°C exposure.



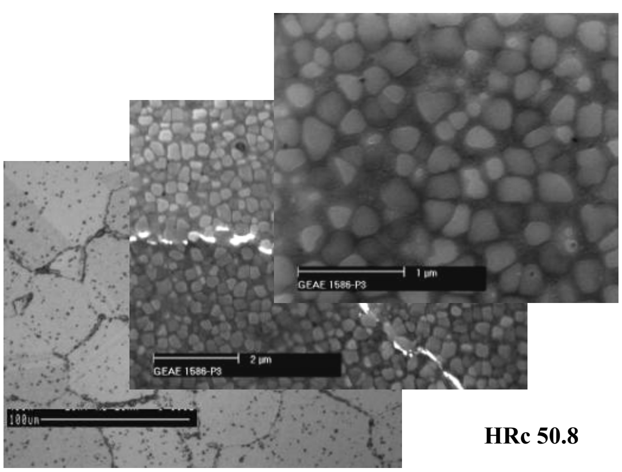
HRc 45.8

Figure 13 Dual slope cooling rate of the bar used for the 760°C/25 hour exposure is indicated by dendritic cooling γ' of the specimen exposed to 760°C/25 hours. Age γ' precipitates are more easily resolved due to slight coarsening.



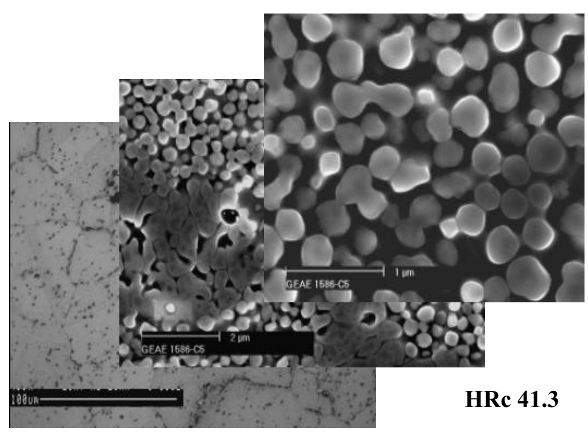
HRc 49.0

Figure 16 René104 shows grain boundary precipitates and coarsened cooling γ' and very low fraction age γ' after 150 hours, 815°C exposure. Age γ' was dissolved by 636 hours at this condition (48.3 HRc).



HRc 50.8

Figure 14 After 599 hours at 760°C, additional grain boundary precipitation and partial dissolution are evident.



HRc 41.3

Figure 17 René104 shows extensive grain boundary precipitates plus age +cooling γ' coarsening after 430 hours, 870°C exposure.

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