

Creep Property Characterization of Potential Brayton Cycle Impeller and Duct Materials

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Abstract. Cast superalloys have potential applications in space as impellers within closed-loop Brayton cycle nuclear power generation systems. Likewise wrought superalloys are good candidates for ducts and heat exchangers transporting the inert working gas in a Brayton-based power plant. Two cast superalloys, Mar-M247LC and IN792, and a NASA GRC powder metallurgy superalloy, LSHR, have been screened to compare their respective capabilities for impeller applications. Mar-M247LC has been selected for additional long term evaluations. Initial tests in helium indicate this inert environment may debit long term creep resistance of this alloy. Several wrought superalloys including Hastelloy® X, Inconel® 617, Inconel® 740, Nimonic® 263, Incoloy® MA956, and Haynes 230 are also being screened to compare their capabilities for duct applications. Haynes 230 has been selected for additional long term evaluations. Initial tests in helium are just underway for this alloy. These proposed applications would require sufficient strength and creep resistance for long term service at temperatures up to 1200 K, with service times to 100,000 h or more. Therefore, long term microstructural stability is also being screened.

Keywords: Superalloy, creep.

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INTRODUCTION

Certain space operations require an electric power source that is not dependent on the sun and can perform for long time periods. A promising concept (Mason, 2005) fulfilling these requirements uses a nuclear reactor to heat an inert He-Xe working gas, which is expanded in a closed-loop Brayton cycle to power a turbo-generator for electricity production. There are multiple combinations of reactor and heat exchanger design that can be used (Barrett, 2005), but in each scenario power conversion efficiency increases with higher turbine temperature. Also space power systems may be required to operate for very long service times. In the Jupiter Icy Moons Orbiter (JIMO) vehicle concept, the turbo-generator would require an impeller (radial turbine wheel) which can operate with sustained centrifugal loads for times extending to 100,000 hours and maximum temperatures approaching 1200 K. Cast superalloys such as Mar-M247LC and IN792 could potentially be used for these impellers, provided creep and alloy phase stability are sufficient.

Ducts subjected to pressure and thermal loads at similar temperatures will be needed to route and cool the working gas. The associated materials will need to be shaped, brazed, and welded into duct and turbine housing components. Solid solution strengthened wrought superalloys such as Hastelloy® X, and Inconel® 617 could be readily fabricated in these ways. However, their high temperature creep resistance may be insufficient. Precipitation hardened wrought superalloys such as Nimonic® 263 and Inconel® 740 have improved creep resistance, but could be harder to shape, join, and subsequently precipitation heat treat. Mechanically alloyed, precipitation hardened wrought superalloys such as Incoloy® MA956 can have even higher creep resistance at high temperatures near 1200K, but are very difficult to shape and join. Long term creep tests are therefore needed at realistic stresses and temperatures to compare these alloys at simulated the service conditions. Ducts subjected to pressure and thermal loads at similar temperatures will be needed to route and cool the working gas. The associated materials will need to be shaped, brazed, and welded into duct and turbine housing components. Solid solution strengthened wrought superalloys such as Hastelloy® X, and Inconel® 617 could be readily fabricated in these ways. However, their high temperature creep resistance may be insufficient. Precipitation hardened wrought

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The objective of this work is to evaluate the creep properties of these materials for potential space applications. Potential impeller alloys Mar-M247LC, IN792, and LSHR, and potential duct alloys Hastelloy X, Inconel 617, Haynes 230, Inconel 740, Nimonic 263, Incoloy MA956 were screened with selective tensile and creep testing. Typical material databases do not include creep tests beyond about 10,000 hours or consider such long term exposure in inert gases (Ammon, Eisenstatt, and Yatsko, 1981). Based on the long durations envisioned in some of these space applications, short term creep tests are being run in order to enable selection of allowable creep stresses and temperatures conducive to such long durations. Tests at the prospective application stresses and temperatures are now getting underway. Some key tests are ongoing, but results generated to date will be reviewed.

MATERIALS AND PROCEDURES

Mar-M247LC (Cannon-Muskegon Corp., 2006) bars were cast in a mold of 18 bars using standard foundry practices. Additional bars were cast using the Microcast® process to produce finer grain size. The bars had diameters about 1.9 cm and lengths of about 15 cm. These bars were subsequently hot isostatically pressed at 1458 K using a pressure of 172 MPa for 4 h. The bars were then solution heat treated in a vacuum furnace at 1494 K / 2 h/Argon quench, and aged at 1352 K / 4 h /Argon quench + 1144 K / 20 h / Air quench. An auxiliary power unit impeller made of the superalloy IN792 (Sims, Stoloff, and Hagel, 1987) was provided by Sundstrand Aerospace. The IN792 impeller had been cast using the Grainex® process, another fine grain casting process, at Howmet. After casting the impeller was hot isostatically pressed and heat treated using proprietary processes. Powder of LSHR superalloy (Gabb, et al, 2005) was atomized by Special Metals Corp. in argon and passed through screens of -270 mesh to give powder particle diameters of no more than about 55 μm . The powder was then sealed in a stainless steel container, hot compacted, and extruded at a reduction ratio of 6:1. Segments of the extrusion billet were machined into sections 15 cm in diameter and 20 cm long, then isothermally forged into a flat disk about 30 cm in diameter and 4 cm thick by Wyman-Gordon Forgings. The disk was solution heat treated at about 1444 K for 2.5 h, then transferred in 2 minutes for a quench in air by fans on each side of the disk. The disk was then given an aging heat treatment of 1128 K / 8 h.

The wrought alloys were supplied by Special Metals Corp and Haynes International. Hot rolled plates of Hastelloy X (Haynes International, Inc., 1997; Special Metals Corp., 2003), Inconel 617 (Special Metals Corp., 2005), and Incoloy MA956 (Special Metals Corp., 2003) of about 0.64 cm in thickness were supplied. These plates were tested in the solution anneal condition. A hot rolled plate of Haynes 230 (Haynes International, Inc., 2005) was subsequently obtained for testing. A hot rolled plate of Inconel 740 (Special Metals Corp., 2004; Smith, and Shoemaker, 2004) plate of 1.6 cm thickness and a Nimonic 263 (Special Metals Corp., 2004) section of 4 cm thickness were also supplied in solution annealed and air quenched form. Unlike the other wrought duct materials, Inconel 740 and Nimonic 263 require an aging heat treatment in order to precipitate strengthening γ' precipitates and thus were subjected to an aging heat treatment of 1073 K / 8 h before testing.

Specimens with a gage diameter of 0.63 cm and gage length of 3.8 cm were machined from the candidate impeller materials. Smaller creep specimens with a gage diameter of 0.32 cm and gage length of 0.76 cm were machined from the plate materials. Most tests are being performed in conventional uniaxial lever arm constant load creep frames using resistance heating furnaces and shoulder-mounted extensometers at Metcut and GRC. However, several tests are being run in specialized creep testing machines at GRC, with the specimens sealed within environmental chambers containing inert helium gas of 99.999% purity held slightly above atmospheric pressure. All creep tests are being performed according to ASTM E139.

RESULTS AND DISCUSSION

The actual chemistries in weight percent of all tested alloys are listed in Table 1. Typical grain microstructures in optical images of etched metallographic sections of impeller materials are shown in Fig. 1. Grain width was approximated using grain linear intercept distance according to ASTM E112. LSHR had a fine, uniform grain microstructure, with an average linear intercept distance of about 29 μm , equivalent to a grain size of 7.0. Conventionally cast Mar-M247LC had more irregular, very coarse grains of near 700 μm width and near 800-12000 μm length, with grains often longer in the direction of primary dendrite growth. However, Microcast Mar-M247LC had a more uniform grain microstructure, with smaller grains of about 96 μm width (grain size = 3.5). IN792 had intermediate grain uniformity and size compared to the two versions of Mar-M247LC, with grain about 320 μm in width (grain size = 0). All the impeller alloys had microstructures predominated by 55-70% γ' precipitates in a γ matrix. MC and M_{23}C_6 carbides were also present. LSHR microstructure was predominated by about 55 volume per cent γ' precipitates in a γ matrix, but also contained minor MC and M_{23}C_6 carbides, M_3B_2 borides, and very fine oxides. Cooling γ' precipitate size was uniformly about 0.2 μm . Mar-M247LC and IN792 microstructure was predominated by about 65-70 volume per cent γ' precipitates in a γ matrix, with minor MC carbides. γ' precipitate sizes varied widely in these cast alloys, between about 0.4 and 3.0 μm , due to dendritic growth within grains.

Typical microstructures for plate materials are shown in Fig. 2. Hastelloy X, Inconel 617, Inconel 740, and Nimonic 263 had comparable grain sizes, but MA956 had much coarser grains. Hastelloy X, Inconel 617, and Haynes 230 had fairly uniform grain structures with mean grain sizes of about 69, 75 and 33 μm (grain sizes of 4.4, 4.2, and 6.5, respectively). They were predominantly made up of γ phase, with minor contents of carbides. Inconel 617 also had about 2 volume percent of γ' precipitates. However, these precipitates were very large at 1-10 μm diameter, and would not be expected to provide significant strengthening. Inconel 740 and Nimonic 263 had similar grain sizes of about 69 and 62 μm (grain sizes of 4.4 and 4.7, respectively). They both were predominantly made up of γ phase strengthened by about 20-25 volume per cent γ' precipitates, along with minor contents of carbides. The γ' precipitates were smaller in Inconel 740 than for Nimonic 263. Incoloy MA956 had a much coarser grain structure than the other duct alloys, with grains of flattened aspect ratio in the plane of the plate. Grains were typically 100-200 μm thick, but 300-1500 μm wide in the plane of the plate. This microstructure was predominantly made up of BCC ferrite phase, with minor contents of fine carbides and $\text{Y}_2\text{O}_3 - \text{Al}_2\text{O}_3$ dispersion strengthening particles. These chemistries and microstructures were typical of those reported in the manufacturers' references.

TABLE 1. Alloy Chemistries.

Wt. %	LSHR	MM247LC Conv. Cast	MM247LC Microcast	IN792	HX	Inconel 617	Haynes 230	Inconel 740	Nimonic 263	MA956
Al	3.46	5.60	5.52	3.45	0.19	0.99	0.29	0.93	0.45	4.56
B	0.028	0.015	0.002	0.002			0.002			
C	0.029	0.090	0.086	0.084	0.086	0.095	0.110	0.031	0.061	0.017
Co	20.70	9.40	9.31	8.95	1.01	11.64	0.22	19.95	19.30	
Cr	12.5	8.3	8.52	12.64	21.44	22.65	21.86	24.24	20.45	19.7
Cu					0.24	0.05	0.04	0.04	0.02	0.01
Fe	0.07		0.04	0.01	19.49	0.91	1.12	0.45	0.38	Bal.
Hf		1.4	1.46	0.02						
Mn		0.02			0.53	0.04	0.49	0.25	0.33	0.09
Mo	2.73	0.50	0.51	1.83	8.50	9.45	1.29	0.51	5.80	0.01
Ni	Bal.	Bal.	Bal.	Bal.	Bal.	Bal.	Bal.	Bal.	Bal.	0.13
Nb	1.45				0.115	0.12		1.96	0.05	0.005
O										0.20
Si	0.03	0.01	0.05	0.03	0.31	0.16	0.39	0.53	0.13	0.08
Ta	1.60	3.20	3.15	3.98	0.01	0.01			0.01	
Ti	3.50	0.70	0.75	3.84	0.02	0.36		1.71	2.19	0.37
V					0.03	0.01				0.03
W	4.33	9.50	9.47	4.08	0.46	0.04	13.87	0.01	0.01	0.01
Y										0.29
Zr	0.05	0.01	0.011	0.015			0.011	0.011		
La							0.19			

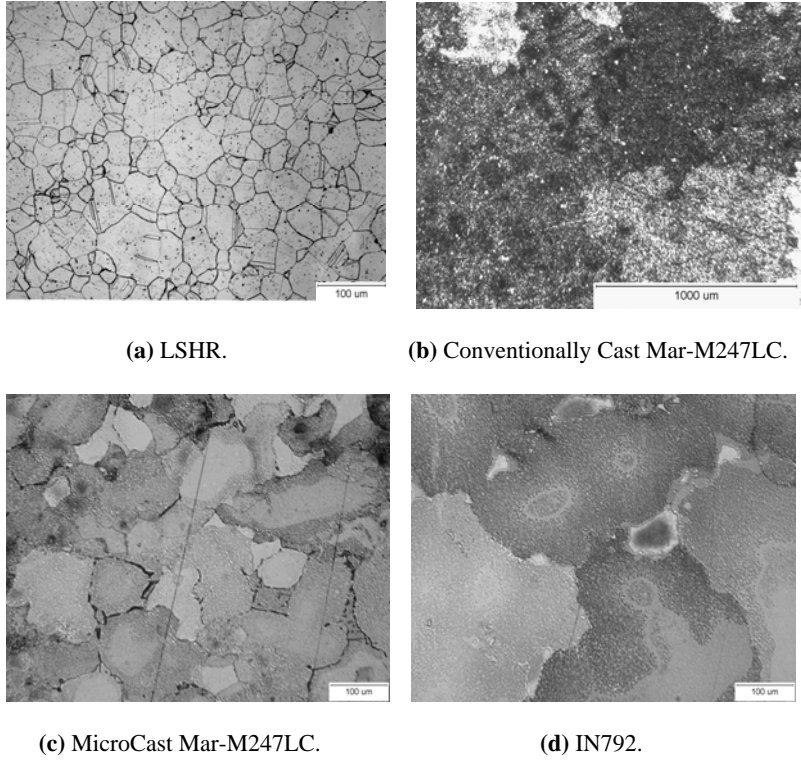


FIGURE 1. Typical Impeller Alloy Microstructures.

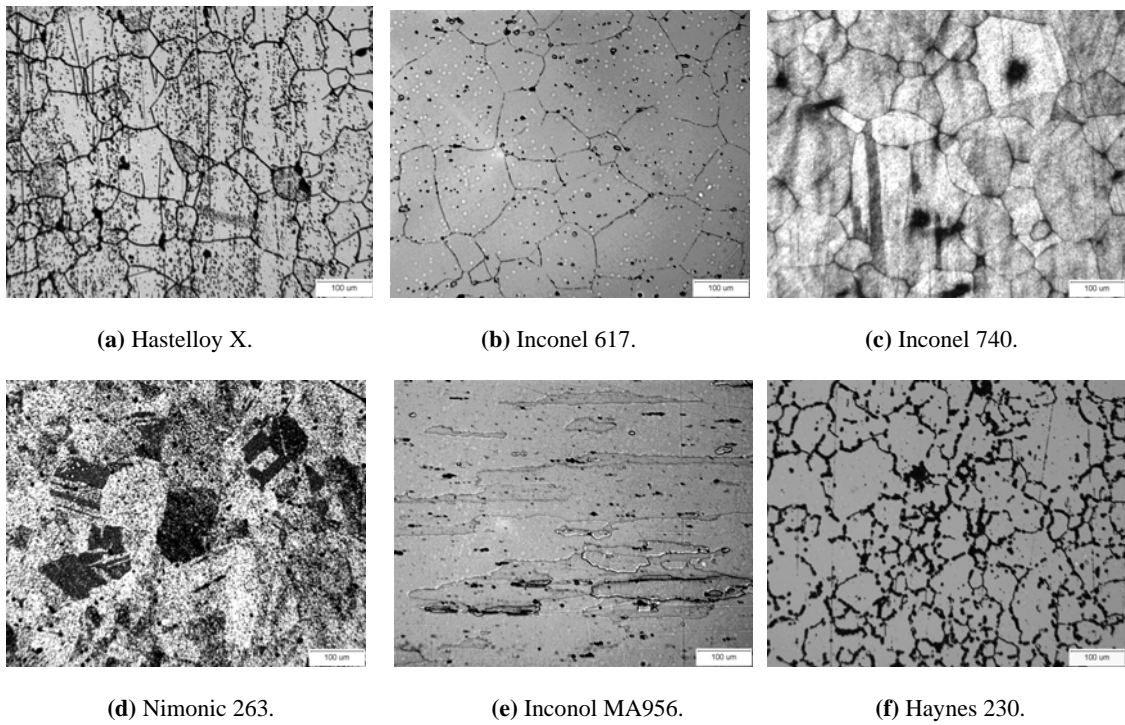


FIGURE 2. Typical Microstructures for Plate Materials.

Creep Response of Impeller Materials

Creep tests of impeller materials were designed to first screen the materials at temperatures of 978, 1090, and 1200 K. Subsequent tests were designed to ultimately determine allowable creep stresses for each material and temperature that would give 1% creep strain in 10 years of service, a goal projected for JIMO applications. This service goal represented a target strain rate of 0.1% per year, or 1.1×10^{-5} %/h. Therefore, tests were performed to determine the allowable stress that would produce this strain rate at each of the test temperatures. Creep results of all tests for impeller materials were used to generate conventional Larson-Miller curves of stress versus Larson-Miller parameter (LMP) using temperature (T) and time (t) in the equation (Larson and Miller, 1952):

$$\text{LMP} = (T)(20 + \log t)/1000 \quad (1)$$

This parameter has a direct dependence with temperature, but a weaker logarithmic dependence of time. The resulting plot is shown in Fig. 3. Simple regression equations are included for estimating creep response at intermediate conditions. However, it is not advisable to use these equations to estimate creep response in excess of ten times that of the input data. The input data extended up to 7,295 hours. LMP curves in Fig. 3 indicate consistently higher creep resistance for LSHR at combinations of high stress and low temperatures, but higher response for Mar-M247LC at combinations of low stress and high temperatures. This could be related in part to the much coarser grain size in Mar-M247LC compared to LSHR. The conventionally cast Mar-M247LC had a larger typical grain size than LSHR, as shown in Fig. 1. Increasing grain size has often been demonstrated to strongly improve superalloy creep resistance in these alloys (Sims, Stoloff, and Hagel, 1987). However, Mar-M247LC also has a different chemistry containing more aluminum and titanium to produce a content of γ' precipitates near 70%, compared to that of LSHR containing about 55-60% of γ' . Mar-M247LC also has higher levels of the refractory elements tungsten, tantalum, niobium, and hafnium than does LSHR, which can all improve creep resistance of superalloys (Cannon-Muskegon Corp., 2006). Limited tests of IN792 indicated intermediate response.

In order to examine the effects of only grain size on creep resistance, specimens from a bar of Mar-M247LC cast using the Microcast® process were obtained, containing finer grains compared to conventionally cast material, Fig. 1. Limited comparison tests indicate the Microcast specimens had 2x-10x lower creep life than conventionally cast Mar-M247LC, Fig. 4. The initial tests of IN792 are also included for comparison, as its content of γ' and microstructure were similar to Mar-M247LC. IN792 material was cast using a proprietary Grainex process that also produced a finer grain size than conventionally cast Mar-M247LC. It also had lower creep resistance, comparable to Microcast Mar-M247LC. This illustrated the strong effect of increasing grain size on creep resistance at high temperatures, and should be kept in mind when selecting processing paths for both impeller and duct alloys. This grain size difference more strongly affected creep resistance than strength for this alloy.

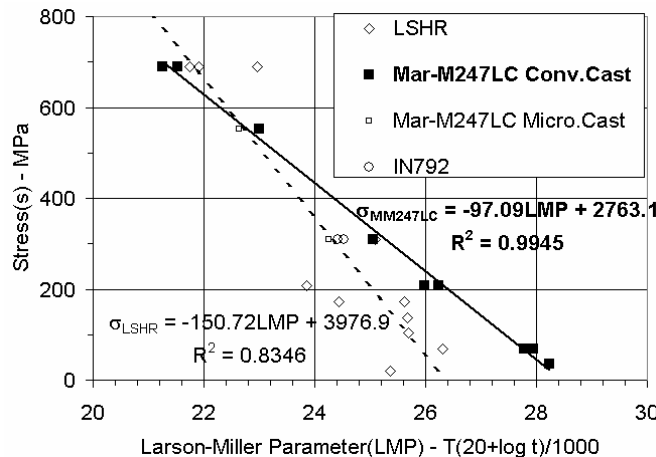


FIGURE 3. Larson-Miller-Parameter Creep Comparisons of Impeller Alloys.

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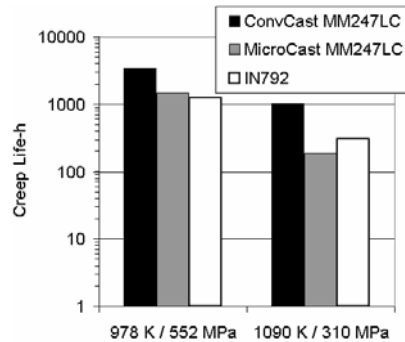


FIGURE 4. Comparison of Creep Resistance for Mar-M247LC and IN792.

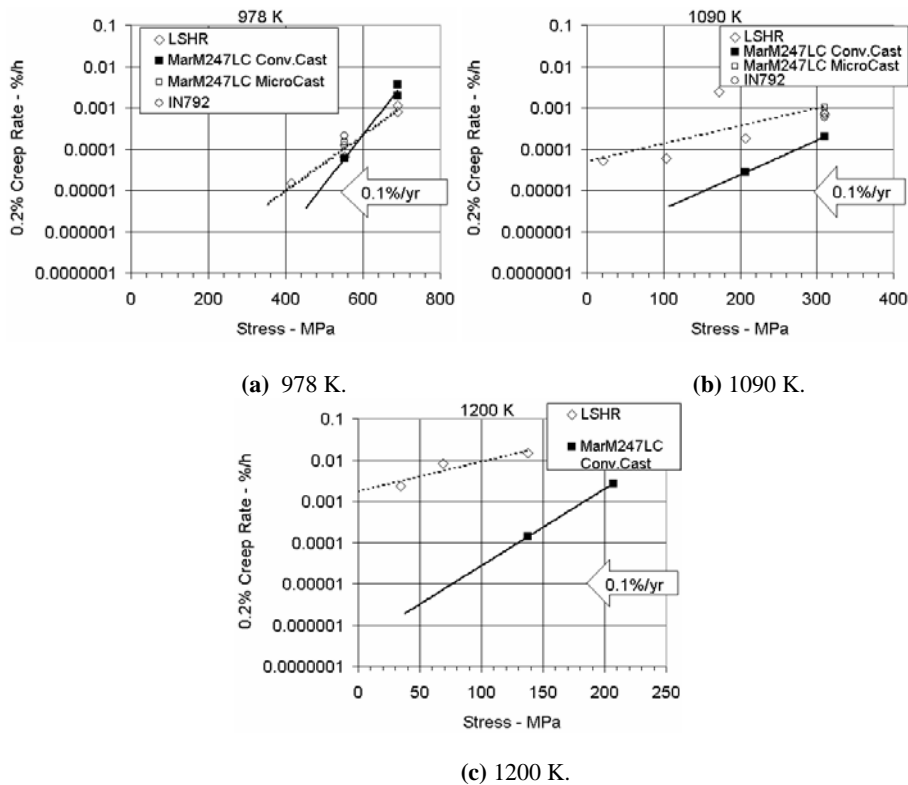
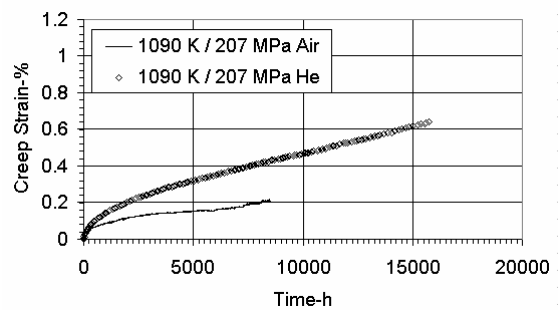


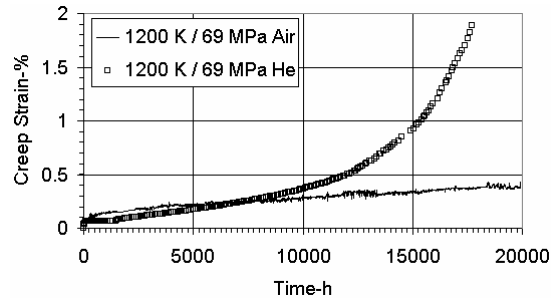
FIGURE 5. Creep Rate Versus Stress for Impeller Alloys at 978 K, 1090 K, 1200 K.

Average creep strain rate to 0.2% strain is shown versus stress in Fig. 5. This plot allowed initial estimation of allowable stresses for achieving the target strain rate of 0.1%/yr, or 1.1×10^{-5} %/h. At 978 K, an applied stress of 450 MPa should result in about 0.1% strain per year for both LSHR and Mar-M247LC. However, at higher temperature the superior creep resistance of Mar-M247LC compared to LSHR was clearly reflected in the estimated stresses. An applied stress of 180 MPa was estimated to produce the target strain rate in Mar-M247LC at 1090 K. At 1200 K, a stress of 60 MPa was estimated to produce the target strain rate in Mar-M247LC. The creep resistance of the LSHR samples was sufficiently low at 1090 K and 1200 K that an applied stress for the desired strain rate could not be estimated. Verification creep tests and analyses are necessary, but the preliminary creep analysis using current test results indicates quite good potential for an impeller fabricated of Mar-M247LC to meet Brayton cycle requirements, for maximum temperatures up to 1200 K (Gayda and Gabb, 2005).

Tests to estimate the effects of air vs. inert environments on creep resistance were also initiated, using conventionally cast Mar-M247LC. The results of single tests in air at one atmosphere pressure and in helium slightly above one atmosphere at 1089 and 1200 K are compared in Fig. 6. Creep deformation appears to be progressing faster in helium than that for air in these on-going tests at 1089 K and 1200 K. More tests are needed as well as post-test examination for confirmation, but this appears to show a reduction in creep resistance due to the inert environment. A previous study that compared creep for superalloys in helium and air environments (Ammon, et al, 1981) found very modest effects. Additionally, other creep testing on LSHR has conclusively shown that creep loading in air encourages cracks to initiate at oxidized surfaces, initiating failure (Gabb, et al, 2005). Therefore, a helium environment had been expected to potentially improve creep life. So these results indicating a reduction in creep resistance were unexpected and need to be explored further.



(a) 1090 K.



(b) 1200 K.

FIGURE 6. Comparison of creep response of conventionally cast Mar-M247LC in helium and air at 1090 K, 1200 K.

Creep Response of Duct Materials

The literature contained appreciable information on the creep resistance of candidate duct materials for temperatures near 977K, but had little data at higher temperatures. Therefore, creep tests of duct/heat exchanger materials were designed to screen the materials at higher temperatures of 1090 and 1200 K. Subsequent tests designed to determine

allowable stresses for each alloy based on service goals have not yet been started, due to the variety of duct and heat exchanger applications possible here, as well as recent changes in program goals.

Typical comparisons of time to 0.1, 0.2, and 0.3% creep of these materials at 1089 K are shown in Fig. 7, for duplicate tests at a stress of 103 MPa. Of the solid solution strengthened superalloys, Inconel 617 had about 10x better creep resistance than Hastelloy X. However, the γ' precipitate strengthened superalloys Inconel 740 and Nimonic 263 had about 20x improved creep resistance over Inconel 617. These results indicate Inconel 617, Inconel 740, and Nimonic 263 had good creep resistance for potential applications at 1089 K, while Hastelloy X would be at a definite disadvantage. Additional testing would be necessary to determine allowable stresses for each alloy. Creep tests of another solid solution strengthened superalloy, Haynes 230, are on-going, but it is estimated based on the literature that Haynes 230 could have creep resistance similar to that of Inconel 617.

Typical comparisons of time to 0.1 and 0.2% creep of the duct materials at 1200 K are shown in Fig. 7, for single tests at a very low stress of 14 MPa. The materials had much lower creep resistance at this temperature. Of the solid solution strengthened superalloys, Inconel 617 had 2-3x better creep resistance than Hastelloy X. However, the γ' precipitate strengthened superalloys Inconel 740 and Nimonic 263 had mixed response. Nimonic 263 had comparable creep resistance to Inconel 617, while Inconel 740 had lower creep resistance than Hastelloy X as well as Inconel 617. This could be related to the potential for precipitation of harmful phases in Inconel 740 and Nimonic 263 at this temperature (Smith and Shoemaker, 2004). Incoloy MA956 had much better creep resistance than the other materials at 1200 K, but does have many component processing issues. It would therefore be expected that Inconel 617 and Nimonic 263 have potential for 1200K applications, though at very low stresses. Incoloy MA956 could have potential for application for higher stresses, but would require an extensive process development program in order to form and join duct components from this alloy.

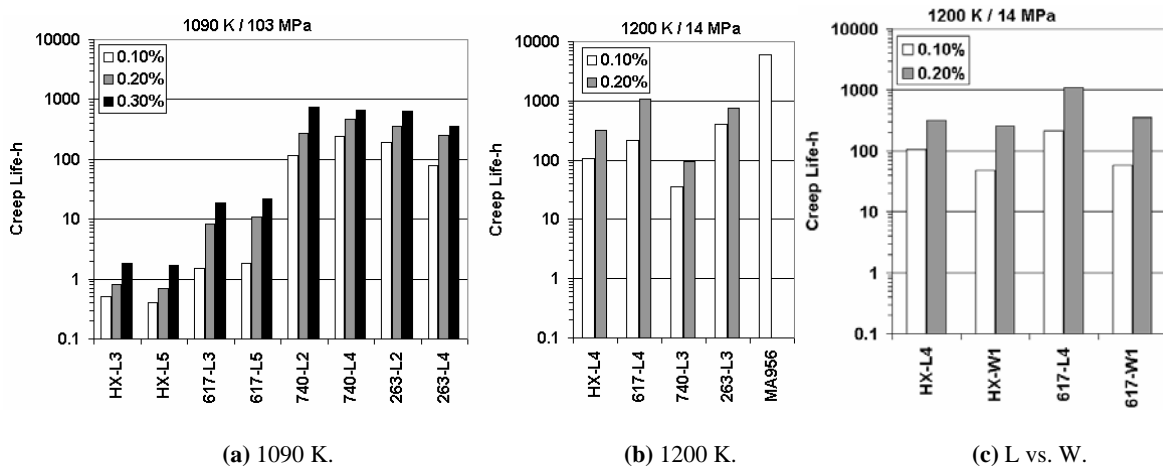


FIGURE 7. Comparison of Creep Resistances for Duct Alloys at 1090 K and 1200K, and comparison of Longitudinal (L) vs. Width (W) effects.

Several creep tests were performed at 1200 K to compare the relative creep resistance of Hastelloy X and Inconel 617 in the plate longitudinal and width directions. Specimens in the plate longitudinal direction had superior response for both alloys, as shown in Fig. 7. While the differences were only 2 - 3X, this direction dependence could be an important consideration in duct design, where internal pressure-induced stresses for tubes rolled from flat plates are often highest in the hoop direction.

Average creep strain rate to 0.2% strain is shown versus stress for duct alloy tests in Fig. 8. Inconel 617 could potentially attain the target strain rate of 0.1%/yr, or 1.1×10^{-5} %/h at a stress of about 48 MPa at 1090 K, while Haynes 230 was projected to achieve the rate at a stress of about 15 MPa. The only duct alloy with any potential for achieving this rate at 1200 K is MA956.

Alloy Stability

Microstructural stability is crucial to the mechanical properties of superalloy because these alloys rely on complex microstructure for strength. Literature surveys indicated alloy stability could be an issue for 5-10 year service times at the temperatures of interest to this program. Therefore a companion alloy stability analysis is being performed along with creep testing. Samples are being isothermally exposed for extended times at 1090K and 1200K. Some of the results to date are shown in Fig. 9. The baseline duct alloys, Hastelloy X, Inconel 617, Inconel 740, Nimonic 263 showed enhanced precipitation of carbide and topological close pack phases when aged at 1090 K for 1000 h, generally consistent with previous literature for aging at lower temperatures. These phases could potentially affect long term ductility (Klarstrom, 2004), as well as other properties such as creep rupture.

The predictive results of microstructure modeling software package JMatPro_Ni-4.0 (Saunders and Guo, 2004) are being compared to the experimentally determined phase formation as functions of time and temperature. Typical predictive results likewise are shown in Fig. 10. The experimentally observed enhanced precipitation of carbide and topological close pack phases in Hastelloy X aged at 1090 K for 1000 h was predicted by JMatPro. A search of superalloys indicated the solid solution strengthened superalloy Haynes 230 could have improved phase stability in comparison to initially screened duct superalloys, as illustrated in the JMatPro predictions of Fig. 10. Literature indicates that short term creep resistance of this alloy appears similar to Inconel 617. Haynes 230 has therefore been selected for further evaluations through both creep and aging experiments.

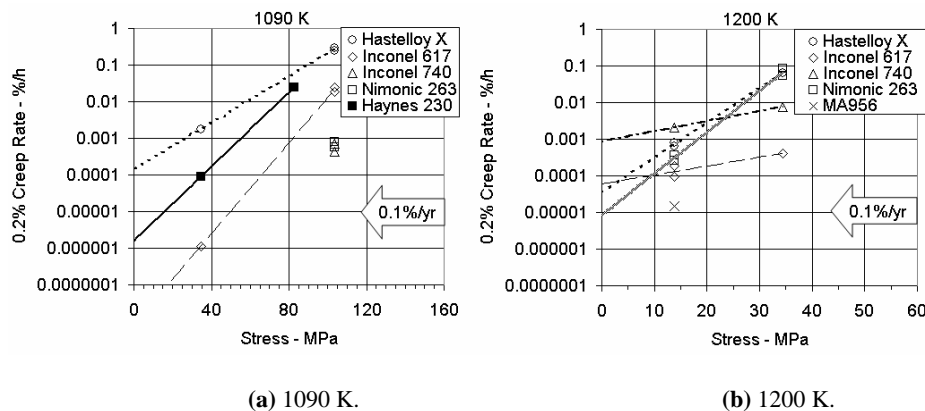


FIGURE 8. Average Creep Strain Rate vs. Stress for Duct Alloys Tested at 1090 K and 1200 K.

Material Selections

For impeller applications having maximum temperatures of 1090 K and higher, conventionally cast Mar-M247LC was chosen for further study. The conventionally cast Mar-M247LC had far superior creep response and comparable tensile strength to the microcast Mar-M247LC, LSHR and IN792 evaluated in this program. This was related in part to the coarse grain size of the conventionally cast Mar-M247LC bars. Indeed, the differences in response between Mar-M247LC and IN792 may be largely due to the different casting processes of the samples evaluated. Inspection of Table 1 indicates that Mar-M247LC and IN792 have very similar compositions with respect to total content of γ' stabilizing elements (Al+Ti+Ta+Nb+Hf), although hafnium is absent in IN792. Yet IN792 samples were taken from an actual impeller casting using a common fine grain casting process, while the Mar-M247LC samples were conventionally cast as simple bars. The IN792 properties may therefore reflect those to be expected in Mar-M247LC, if the latter alloy were cast into an impeller using typical production casting practices (Delgado and Halford, 2004). Terrestrial impeller are designed for applications with greater emphasis on fatigue (start/stop) and impact (foreign object damage). Space power impellers design for maximum creep life may need different casting processes to take advantage of grain size optimized for creep life in highly stressed regions.

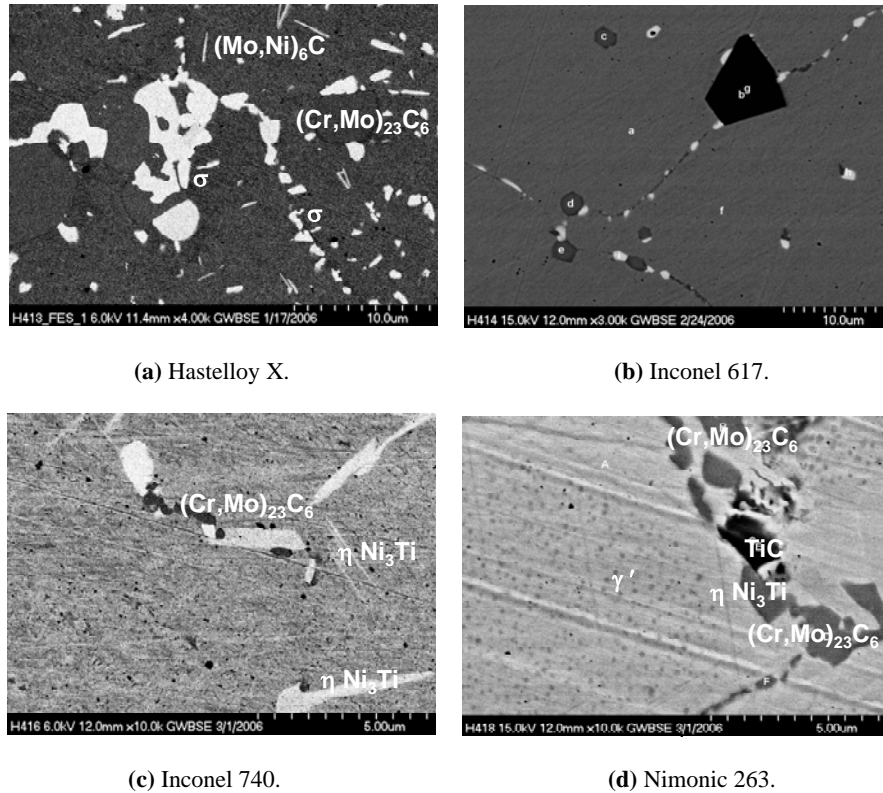


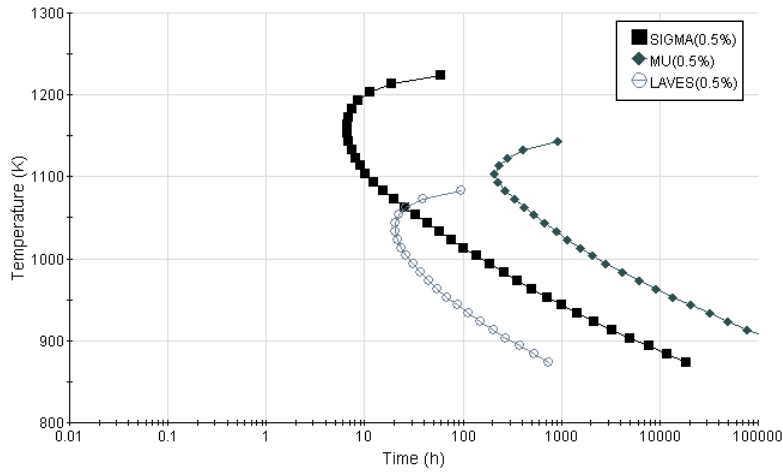
FIGURE 9. Duct Alloy Microstructures After Aging at 1090 K for 1000 h.

For duct applications having maximum temperatures of 978 - 1089 K, current results indicate Inconel 617 would be preferable over Hastelloy X, due to superior creep resistance. However, alloy stability predictions suggested that both alloys have potential microstructural instabilities in exposures over 10,000 hours. Literature and modeling indicates Haynes 230 should have improved microstructural stability, with comparable creep resistance. Haynes 230 has therefore been chosen for further study. This alloy would be relatively easy to fabricate into duct components. The precipitation strengthened alloys Inconel 740 and Nimonic 263 offer further improvements in creep resistance. However, significant additional process development efforts would be necessary to shape, join, and heat treat duct components for these alloys. For applications having maximum temperatures of 1200K, none of the tested duct alloys looked promising. Inconel 617 could be the preferable selection, albeit at low creep stresses. Inconel 740 and Nimonic 263 offered no evident improvements in creep resistance, and would again have the processing development issues and also phase stability questions. Incoloy MA956 might offer improvements in creep resistance, but would have extensive processing issues to be addressed.

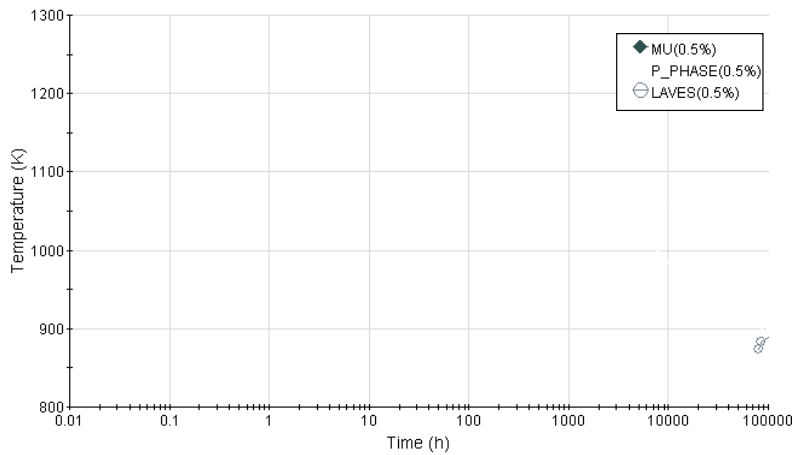
SUMMARY AND CONCLUSIONS

The creep responses of several superalloys were screened for potential applications as impellers and ducts in a Brayton cycle power generation system. It can be concluded from these evaluations that Mar-M247LC should be further evaluated for Brayton cycle impeller applications. The effects of helium environment do not appear to be benign in initial tests, and the potential debits need to be quantified for proper design considerations. The solid solution strengthened superalloy Haynes 230 should be evaluated for duct applications at maximum temperatures up to 1089K. Tests in helium are just underway on this alloy, and potential He-environment effects need to be fully quantified for this alloy also. Long term aging effects on alloy stability also need to be considered for both alloys, and samples are currently in isothermal exposure. For both impeller and duct materials, the material processing and fabrication procedures necessary to produce these components will also eventually need to be considered and screened, in order to assess material potentials and properties as real components. For Mar-M247LC, this will require screening of casting effects for an impeller shape, potentially using both conventional casting and state-of-

the-art microcast processing. For Haynes 230, this will require screening of plate orientation effects, as well as the effects of different joining processes on creep resistance.



(a) Hastelloy X.



(b) Haynes 230.

FIGURE 10. Predictions of Long Term Phase Stability for Hastelloy X and Haynes 230.

NOMENCLATURE

- T = temperature (K)
- t = time (h)
- LMP = Larson-Miller Parameter

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