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AN ADVANCED CAST-AND-WROUGHT SUPERALLOY (TMW-4M3) FOR TURBINE DISK APPLICATIONS BEYOND 700°C

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Abstract

A new cast & wrought (C&W) superalloy, designated as TMW-4M3, has been developed on the basis of our innovative concept for applications of turbine disks and other components beyond 700°C. TMW-4M3 contains 25 wt% Co and 6.2 wt% Ti, which are higher than that of commercial disk alloys. Full-scale pancakes with 400 mm in diameter and 50 mm in thickness were manufactured from TMW-4M3 alloy via a process route of triple-melting, billet making and disk forging. The investigations on the microstructure and the mechanical properties including tensile strength, creep resistance, fatigue strength and resistance to crack propagation of TMW-4M3 indicate that the alloy provides a 100MPa advantage in 0.2% yield strength at 750°C and a 76°C temperature advantage in 0.2%-strain creep performance loaded under 630MPa over Alloy 720Li (U720Li). The alloy maintains its γ/γ′ two-phase structure exposed at 750 °C for up to 5000 hours. The increment of strength at high temperatures is attributed to the precipitation hardening caused by higher volume fraction of the secondary γ′ precipitates and twin boundary strengthening as a result of high density of annealing twins.

Introduction

To meet high requirements of mechanical properties in turbine components of advanced engines, a new kind of cast and wrought (C&W) Ni-Co base superalloys (registered as TMW® alloy) has been designed recently for the applications of turbine disk and high-pressure compressor beyond 700°C [1-4]. TMW alloy normally has a Co content of 22 to 31 wt.%, a Ti content of 5.4 to 7.4 wt. % and a gamma prime (γ′, $L1_2$) weight volume fraction of 0.4 to 0.5.

Preliminary results indicate that TMW-4 alloy has the strongest creep resistance among TMW alloys and provides a 32°C temperature advantage in strain-rupture performance over Alloy 720Li [1]. However, small amount of eta (η, Ni_3Ti) phase, a topologically close packed (TCP) phase, exists in the TMW-4 alloy after homogenization at 1220°C and then aging at temperatures ranging from 1000°C to 1175°C for hours [5]. Normally, the existence of η phase has deleterious effects on the alloy's ductility and its notched stress rupture strength. It is reported that high Ti content, especially high Ti/Al composition ratio, may promote the phase transition from γ′ to η in alloys, while high Cr level may also promote the formation of TCP phase.

In comparison with TMW-4 alloy, TMW-2 alloy shows superior workability and phase stability (no η phase), but less creep resistance and weaker in other mechanical properties [2]. Therefore, a new TMW alloy, TMW-4M3, has been designed by decreasing Cr content slightly while keeping the Ti+Al content and the Ti/Al composition ratio of TMW-2 alloy for the purpose of maintaining its good phase stability and the workability. Furthermore, the contents of Co, W and Mo were increased slight for improving its mechanical properties (Table I).

This paper examines the phase equilibria and the mechanical properties of TMW-4M3 and Alloy 720Li processed and heat treated under same conditions. The results indicate that TMW-4M3 is a promising C&W superalloy for the applications of turbine components beyond 700°C.

Materials and Experimental Procedure

Chemical compositions of TMW-2, TMW-4M3 and Alloy U720 Li are listed in Table I.

Materials for this study were melted and processed by Mitsubishi Materials Corporation, Japan. Ingots were produced through primary vacuum induction melting (VIM), electro-slag re-melting (ESR) and vacuum arc re-melting (VAR). Each of VAR ingots was 500 mm in diameter and weights about 1.7 ton. The surfaces of the VAR ingots were checked carefully and no evidence of instability during the re-melting process and defects such as

Table I. Nominal Compositions of Tested Alloys (weight percent)

Alloy	Co	Cr	W	Mo	Ti	Al	Zr	C	B	Ni
TMW-2	21.8	14.4	1.1	2.7	6.2	2.3	0.03	0.02	0.02	Bal.
TMW-4M3	25.0	13.5	1.2	2.8	6.2	2.3	0.03	0.02	0.02	Bal.
U720Li	15.0	16.0	1.3	3.0	5.0	2.5	0.03	0.02	0.02	Bal

cracks, pores or heavy segregations were observed. Chemical analysis showed that most of the elemental compositions were well controlled to the nominal values, although Al and Ti contents slightly varied within the VAR ingots, which might be caused by the ESR process. The VAR ingots homogenized below the γ' solvus temperature were forged successfully and the final billets of 200 mm diameter were obtained without surface cracks. The microstructure was fine and homogeneous enough for further processing. Several pancake disks of tested alloys were forged at the same deformation condition under 1100°C, which are 400 mm diameter and 50 mm thickness as shown in Figure 1.

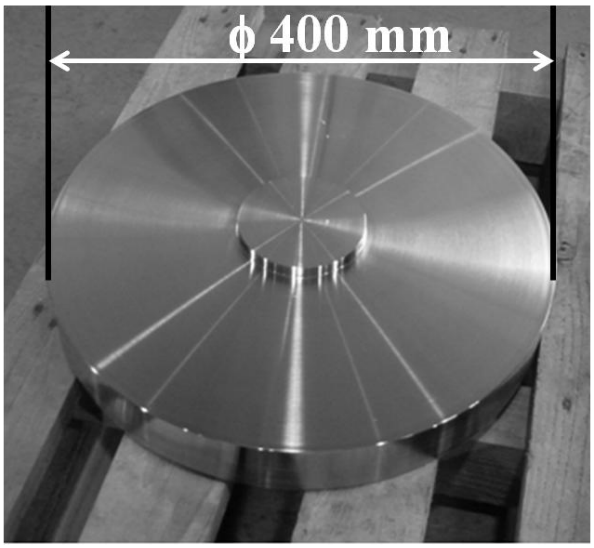

Figure 1. Pancake forged from TMW-4M3 alloy

All specimens were cut from the pancakes. The samples of Alloy 720Li were treated with its standard heat-treatment condition while the samples of TMW-4M3 were treated under two conditions as indicated in Table II.

Table II. Heat Treatment Schedules of the Tested Alloys

Alloy	Heat Treatment Conditions
Alloy 720Li	1100°C/4h/OQ + 650°C/24h/AC + 760°C/16h/AC
TMW-4M3-1	1100°C/4h/OQ + 650°C/24h/AC + 760°C/16h/AC
TMW-4M3-2	1120°C/4h/OQ + 650°C/24h/AC + 760°C/16h/AC

Note: AC — Air Cooling, OQ — Oil Quench

The phase constitution and the microstructure evolution caused by heat treatment and thermal exposure were observed by optical microscopy, X-ray diffraction, scanning electron microscopy (SEM) and transmission electron microscopy (TEM). The specimens were prepared by metallographic polishing followed by etching in a solution of Marble reagent (10 g $CuSO_4$ + 50 ml HCl + 50 ml H_2O). TEM samples were electrochemically polished with a twin jet polisher using a solution of 83% ethanol, 7% glycerol and 10% perchloric acid at -25°C.

Mechanical testings were performed according to ASTM E8/E21, ASTM E139, ASTM E606 and ASTM E647 standard test methods for tensile, creep, low-cycle fatigue (LCF) and fatigue crack growth rate (FCGR), respectively,

Results and Discussion

Microstructure and Microstructural Stability

The equilibrium phases of the TMW-4M3 at 760 °C were analyzed by using the Thermo-Calc program (Version N) and Ni-RUMN database (Thermo-Calc Software, Sweden) as shown in Figure 2. Several key thermodynamic data are listed in Table III.

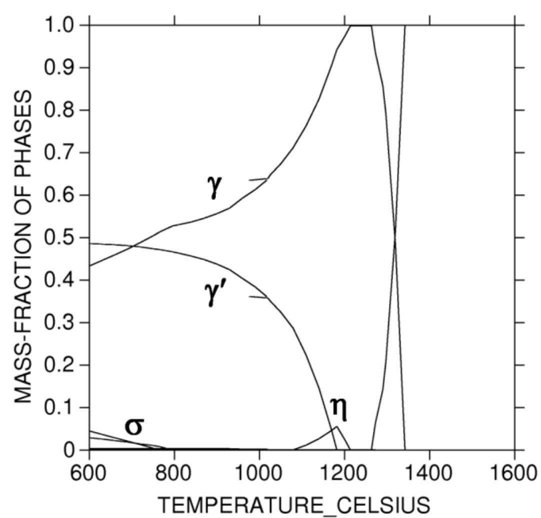

Figure 2. Calculated phase fraction *vs* temperature diagram of TMW-4M3.

Table III. Key Thermodynamic Data of TMW-4M3 Alloy

Alloy	Liquid °C	Solidus °C	σ Region °C	η Region °C	γ' solvus °C	γ' wt.% at 750°C
TMW-4M3	1343	1273	570—752	1083—1218°C	1183	49.4%

TMW-4M3 was predicted to contain γ, γ′, η (from 1083°C to 1218 °C), sigma (σ) (existed from 570°C to 752 °C), and some minor phases such as carbide and boride.

However, no η and σ phases were found in the sample treated at 1200°C/1h and then cooled to 760°C with a cooling rate of 0.5°C/h (Figure 3), which passed the η phase forming region in the Thermo-Calc result and TMW-4 alloy [5]. Furthermore, η and σ phases did not existed in the samples treated at 1200°C/1h/WQ and then exposed at 850°C, 750°C and 650°C for 5000 hours, which indicates that TMW-4M3 alloy has better microstructural thermal stability than that of TMW-4 alloy.

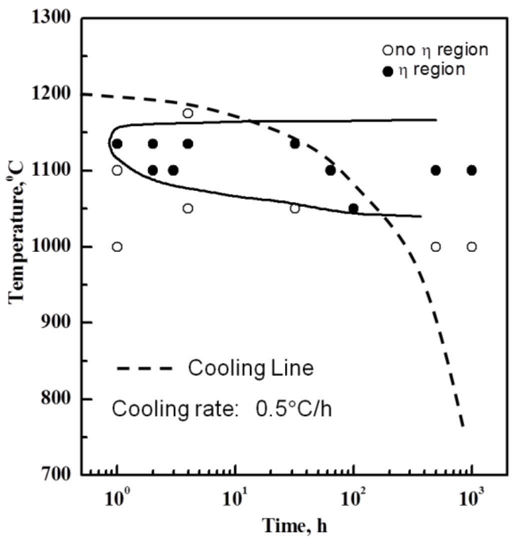

Figure 3. TTT curve of the η phase forming region in TMW-4 [5] and cooling line in TMW-4M3.

Microstructural features of each heat treated alloys are shown in Figure 4. The grain size and other characters are listed in Table IV. It is noted that the grain size for TMW-4M3-2 treated at 1120°C/4h is 10.6 μm, which is almost the same as that of Alloy 720Li treated at its standard heat-treatment condition. Meanwhile, high density annealing twins were found in the heat treated TMW-4M3 alloy. The total twin length in an area of 150×150 μm was 2.45, 5.03 and 5.15 mm in Alloy U720Li, TMW-4M3-1 and TMW-4M3-2, respectively (Figure 4b). High twin formability may be caused by low stacking fault energy (SFE) in TMW-4M3 alloy [6].

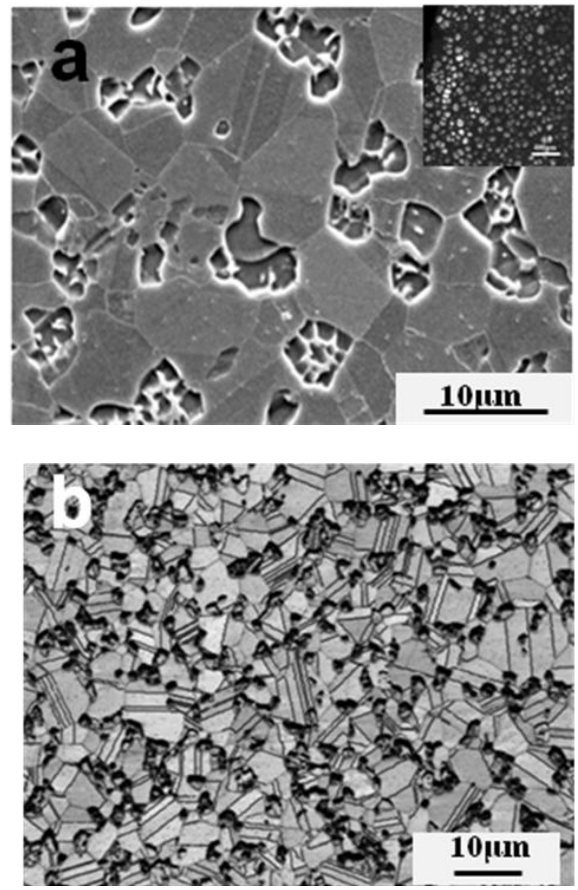

Figure 4. Typical microstructures after heat treatment: (a) Alloy 720Li; (b)TMW-4M3-2.

Table IV. Microstructural Characteristics of Tested Alloys

Alloy	Grain Size (μm)	Primary γ′		Secondary γ′		Tertiary γ′		Annealing Twins Length (mm) (in150×150 μm²)
		Fraction (vol.%)	Size (μm)	Fraction (vol.%)	Size (nm)	Fraction (vol.%)	Size (nm)	
4M3-1	8.7	16.9	< 2.5	30.0	60	~2.1	10	5.03
4M3-2	10.6	14.5	< 2.5	31.5	70	~3.0	10	5.15
U720Li	10.2	13.1	< 2.5	29.4	90	~2.5	10	2.45

Table V. Tensile Properties of Tested Alloys

Alloy	20°C				650°C				750°C			
	YS (MPa)	UTS (MPa)	EL %	R.A. %	YS (MPa)	UTS (MPa)	EL %	R.A. %	YS (MPa)	UTS (MPa)	EL %	R.A. %
U720Li	1175	1584	22.5	23.0	1052	1319	34.0	33.0	915	1045	20.4	23.5
TMW-4M3-1	1185	1638	14.0	13.6	1074	1334	14.4	12.4	1007	1122	9.9	10.5
TMW-4M3-2	1165	1615	13.5	13.7	1049	1422	14.3	14.6	1008	1131	9.5	9.8

Tensile Strength and Creep Properties

The tensile tests were conducted at room temperature (20°C), 650°C and 750°C, respectively. 0.2% yield strength (YS), ultimate tensile strength (UTS), elongation (EL) and reduction of area (RA) are given in Table V. Below 650°C, all tested alloys had comparable tensile YS while the YS strength of TMW-4M3 decreased by about 2% with the increase of the solution temperature. At 750 °C, YS and UTS of TMW-4M3 treated under two conditions had almost the same strength level and were about 100 MPa higher than that of Alloy 720Li.

Stress-rupture tests were conducted in air under loads ranging from 480MPa to 840 MPa in temperatures ranging from 650 °C to 760 °C. TMW-4M3 alloy treated under two conditions exhibited a great improvement in the creep resistance compared with Alloy U720Li at all tested temperatures and stresses (Table VI). By comparison of the life to 0.2% strain at the stress level of 630MPa,

Table VI. Tensile Creep Properties of Tested Alloys

Prop. \ Alloy \ Stress/MPa \ Temp.		650°C	725°C			760°C
		840	480	630	840	480
Life to 0.2% crept strain, (hour)	720Li	8.4	10.5	1.2	0.09	1
	4M3-1	458	229	74	1	18
	4M3-2	298	304	48	0.8	21
Rupture life (hour)	720Li	183	203	36	2.8	29
	4M3-1	820*	870	258	10	112
	4M3-2	1107*	936*	293	14	188
Elongation (%)	720Li	14	40	31	19.5	37
	4M3-1	0.35*	36	14.1	5	28
	4M3-2	0.55*	1.8*	18	5.3	21
Reduction in area (%)	720Li	13	64	39	23	60
	4M3-1	0.5*	63	25	10	56
	4M3-2	1*	2*	25	8	28

*** The test was interrupted.**

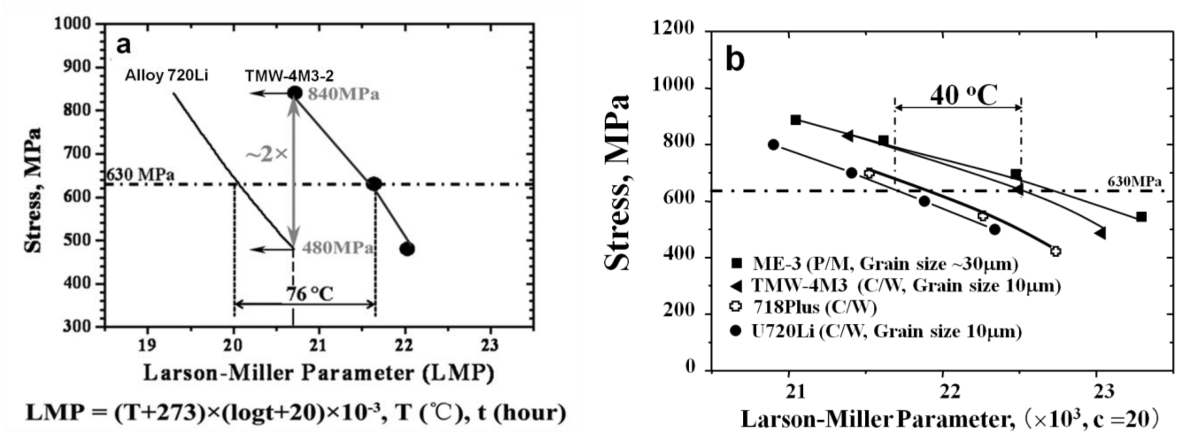

Figure 5. Larson-Miller stress-life plot for (a) life to 0.2% creep strain; (b) rupture life of TMW-4M3 alloy in comparison with reported U720Li[6], 718Plus[7] and ME3[8].

a temperature gain of about 76 °C can be expected from TMW-4M3-2 alloy by using of Larson-Miller parameter approach commonly employed for disk alloys (Figure 5a). Meanwhile, for the same 0.2% creep strain life (Figure 5a), the loading stress of TMW-4M3 was nearly twice as much as that of Alloy U720Li. The Larson-Miller comparison of rupture life for TMW-4M3 alloys along with those of U720Li [7], 718 PLUS [8] and ME3 alloy [9] (also known as Rene 104, with grain size of about 30 μm) shows that TMW-4M3 can be comparable with ME3 alloy at higher stress level (Figure 5b).

Representative TEM micrographs of the tensile tested samples are shown in Figures 6. The significant observation here is that the nano-scale coherent twin boundaries (TBs) as a result of high

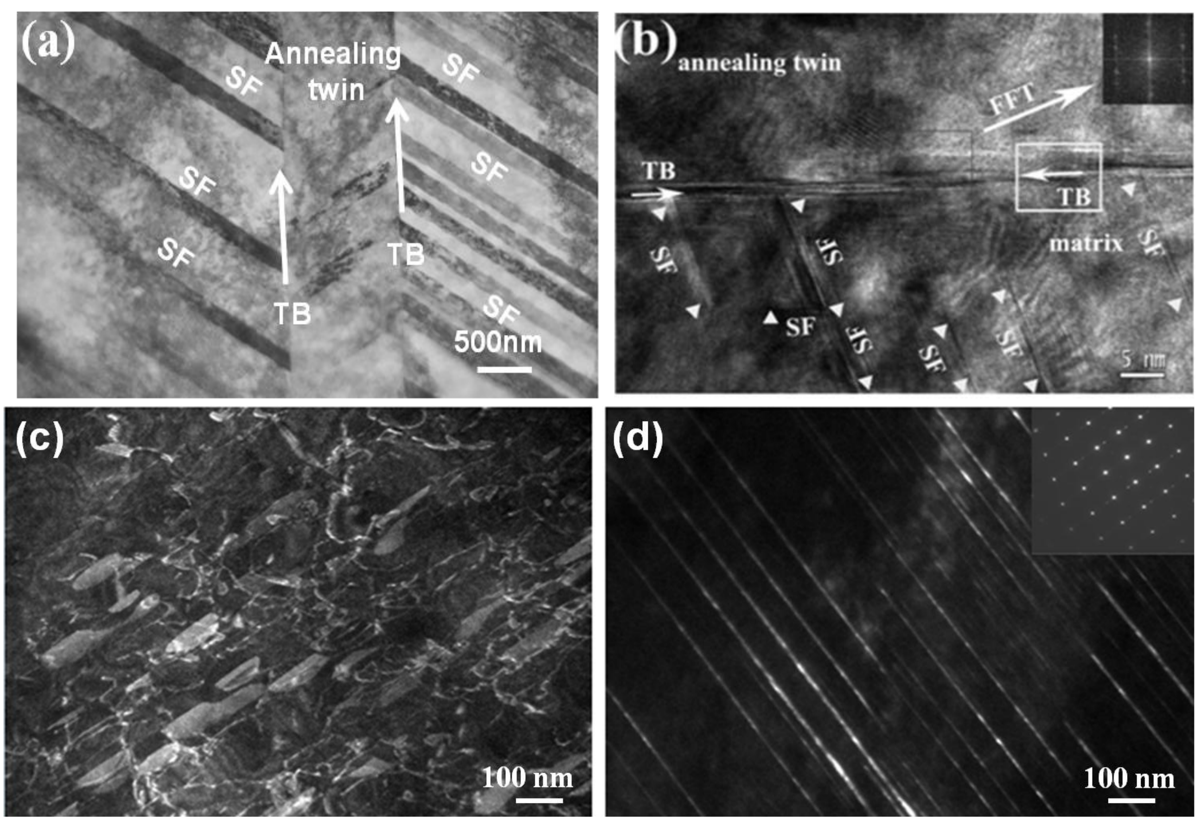

Figure 6. TEM micrographs showing the deformation substructures after tensile tested at 725 °C in
(a) TMW-4M3, (b) TMW-4M3, (c) Alloy 720Li, (d) TMW-4M3.

density annealing twins supply additional barriers to the movement of dislocation, and the dislocations could not penetrate directly through TBs during deformation (Figures 6a and 6b). In Alloy 720Li, shearing of γ' precipitates by super-dislocation pairs was the dominant deformation model up to 725°C (Figure 6C). In TMW-4M3 alloy, the deformation model was the same as that in Alloy 720Li at 25°C. However, at 725°C, γ' precipitates were mainly cut by stacking faults and deformation twins (Figure 6d).

Generally speaking, superalloys develop high temperature strength through solid solution strengthening, precipitate hardening and grain boundary strengthening. Compared with Alloy 720Li, TMW-4M3-2 alloy has similar grain size and lower contents of solid solution strengthening elements such as W and Mo. Therefore, the improvement in the strength of TMW-4M3 may mainly contribute from its higher γ' volume fraction and its large number of annealing twin boundaries (TBs). Because the distribution and the size of the tertiary γ′ precipitates in all tested alloys were not significantly affected by the heat treatment conditions (Table IV), the increase of the fractions of secondary γ′ precipitates and TBs was very likely responsible for the strength improvement at high temperatures, which implies a novel strategy for enhancing high-temperature strength in disk superalloys [10].

Low Cycle Fatigue (LCF) and Fatigue Crack Growth (FCG) Properties

LCF tests were conducted under strain control condition using a triangular waveform with a frequency of 0.5 Hz over a wide range of total strain amplitude of 0.8% to 1.2% and strain ratio $R_\varepsilon = \varepsilon_{min}/\varepsilon_{max} = 0$ on smooth cylindrical specimens at 650°C and 725°C. Normally, the peak stresses as a function of cumulative strain did not essentially change during cycling and the stress amplitude dropped rapidly at the end period of the test in TMW-4M3 alloy (Figure 7a), which indicates that most of the fatigue life was used to initiate crack.

It is obvious that the TMW-4M3 exhibits higher fatigue life at lower strain amplitudes at both 650°C and 725°C (Figures 7b and 7c). The benefit difference in fatigue life, however, narrows down at higher strain amplitudes and is comparable at 650°C and 725°C under $\triangle\varepsilon_t$=1.2%.

FCG tests were carried out in air at 650°C and 725°C for stress ratios of Rσ=0.05 and 0.5 ($R\sigma=\sigma_{min}/\sigma_{max}$) by using compact-tension specimens (CT) (12.7 mm in thickness, 61 mm in width). All specimens were pre-cracked at room temperature at a

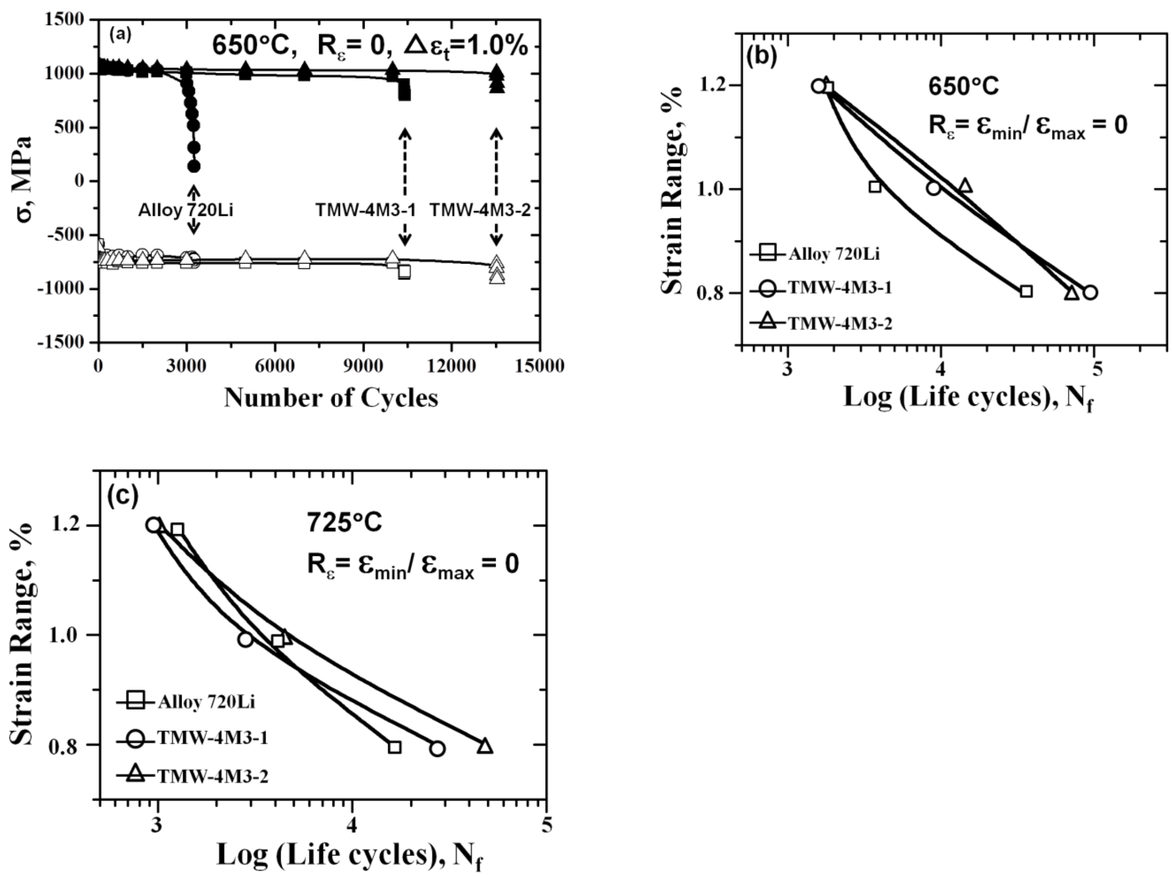

Figure 7. Dependence of fatigue life (N_f) on strain range ($\Delta\varepsilon_t$) of TMW-4M3 and Alloy 720Li

frequency of 20Hz. A closed-loop servo-hydraulic testing machine with specimens cycled under stress-intensity (*K*) control (a symmetric, triangular waveform with a frequency of 2Hz and various load ratios). During the tests, crack-length measurements were determined from the unloading elastic compliance measured by a capacitance gage mounted across the notch mouth. Stress intensities were determined from the linear-elastic solutions for the CT geometry given in ASTM Standard E-399.

Figure 8 shows schematically the crack growth rate *da/dN* as a function of the stress intensity factor range ΔK at 650°C and 725 °C for R=0.05 and 0.5 in a log-log scale. Assuming the Paris law

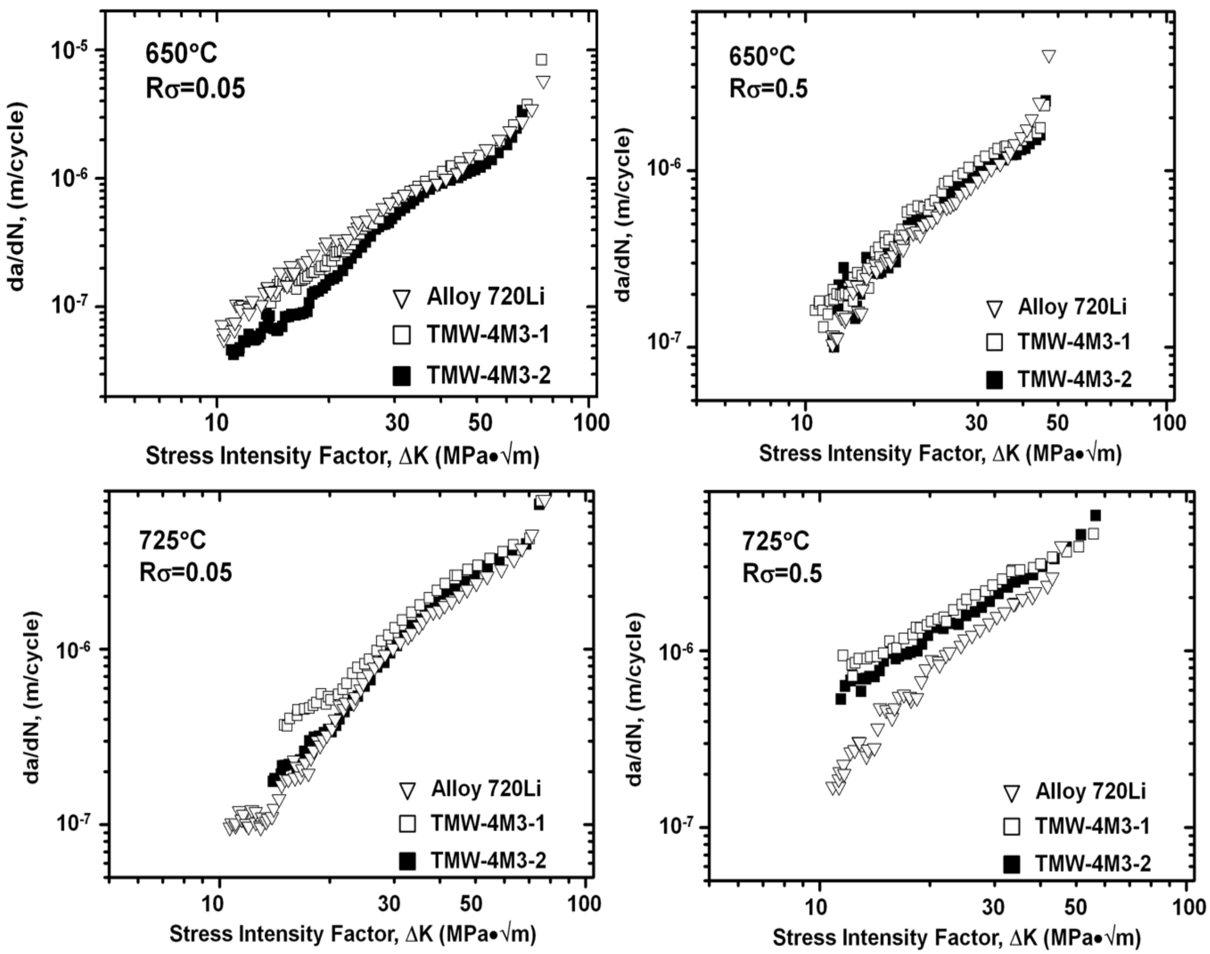

Figure 8. Cyclic fatigue crack growth rates tested at 650°C and 725°C for a stress ratios Rσ=0.05 and 0.5.

Table VII. *C* and *m* Values Determined from *da*/*dN* versus *ΔK* Plots for the Tested Alloys.

Para. / Alloy	650 °C				725 °C			
	R=0.05		R=0.5		R=0.05		R=0.5	
	C	m	C	m	C	m	C	m
Alloy 720Li	7.90×10^{-10}	1.96	9.78×10^{-10}	2.02	4.10×10^{-10}	2.24	2.07×10^{-9}	1.94
TMW-4M3-1	4.97×10^{-10}	2.06	1.96×10^{-9}	1.84	2.89×10^{-9}	1.77	4.31×10^{-8}	1.17
TMW-4M3-2	1.62×10^{-10}	2.31	2.00×10^{-9}	1.79	6.18×10^{-10}	2.14	2.34×10^{-8}	1.31

is applicable to the tested alloys, the slope (m value) and constant C values for Paris regime, where FCGR behavior is represented by $da/dN = C(\triangle K)^m$, were compared for Alloy 720Li and TMW-4M3 at various testing conditions in Table VII. At a given test condition, the m and C values for Alloy 720Li and TMW-4M3 alloy were comparable. The FCGRs of both Alloy 720Li and TMW-4M3 alloys were similar except the result at 725 °C for R= 0.5, where Alloy U720Li had lower FCGR when ΔK was below about 50 MPa√m (Figure 8d). This may be caused by the lower Cr content of TMW-4M3, which may decrease its oxidation resistance at high temperatures and long exposure time during tested at high R value.

Summary & Conclusions

The paper evaluates the thermal phase stability and mechanical properties of two C&W disk superalloys, TMW-4M3 and Alloy U720Li. It is shown that TMW-4M3 alloy has about 100MPa higher yield strength compared with Alloy U720Li at 750°C and can provide at least 40°C temperature advantage in creep-rupture performance over Alloy U720Li loaded under 630MPa. The resistances to LCF and FCGR are better at 650°C for TMW-4M3 and are comparable at 725°C. Meanwhile, a higher solution temperature over Alloy 720Li is beneficial for TMW-4M3 alloy to get superior mechanical properties, which implies that further enhancement of properties in this alloy is possible. These results indicate that TMW-4M3 is a promising C&W disk material for turbine applications beyond 700°C.

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