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LOW-CYCLE FATIGUE BEHAVIOR OF HAYNES® 282® ALLOY AND OTHER WROUGHT GAMMA-PRIME STRENGTHENED ALLOYS

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ABSTRACT

Key properties for wrought gamma-prime strengthened alloys used in aero and land-based gas turbine engines include fabricability, creep strength, and resistance to thermal fatigue. Since a definitive test method for measuring thermal fatigue resistance has not yet been accepted in the industry, isothermal low cycle fatigue (LCF) data are often used as a substitute. In this study, the LCF behavior of several gamma-prime strengthened sheet alloys was investigated. The test program emphasized the LCF behavior of HAYNES® 282® alloy, a material designed for excellent creep strength and fabricability (especially weldability). Data was also taken on other gamma-prime strengthened alloys including 263 alloy, R-41 alloy, and Waspaloy alloy for which little to no data existed in literature for sheet material. Fully reversed, strain-controlled LCF testing was performed at temperatures ranging from 1200 to 1600°F (649 to 871°C) on 0.125” (3.2 mm) thick sheet. The results of the testing are presented along with some microstructural characterization.

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INTRODUCTION

Gamma-prime strengthened alloys represent a significant portion of the material selected for use in the high-temperature regions of modern gas turbine engines. These alloys can be loosely grouped according their level of gamma-prime volume fraction: 1) high gamma-prime volume fraction alloys such as those used in compressor and turbine blades and vanes, 2) intermediate volume fraction alloys such as those used in rotating disks, and 3) lower volume fraction alloys used in a wide variety of structural components and which will be the focus of this article. The advantage of alloys with lower gamma-prime volume fraction is fabricability. These alloys, which include Waspaloy alloy, R-41 alloy, and 263 alloy, can be fabricated using processing routes including forging, hot and cold rolling, drawing, etc. to produce sheet, plate, wire, bar and billet forms. This allows for production of both small and large components at a cost significantly below that of investment cast or isothermally forged products. Furthermore, these alloys generally can be welded to allow for even greater flexibility in component design. Typical components include rings, seals, transitions, combustors, nozzles, cases, and many others.

A new weldable wrought gamma-prime strengthened superalloy, HAYNES 282 alloy, has recently been introduced [1]. This alloy was developed to address two key difficulties with the previously existing alloys in its family. In short, alloys with greater strength, such as the R-41 and Waspaloy alloys, are well known to have fabricability problems, especially with regard to welding. Conversely, alloys with better fabricability, such as the 263 alloy, have much lower creep strength and are limited in terms of their temperature capability. The 282 alloy was developed to possess both excellent fabricability and good high-temperature strength. Specifically, the 282 alloy was designed to have creep strength surpassing that of Waspaloy alloy and approaching that of R-41 alloy at temperatures up to around 1600°F (871°C), while having significantly better resistance to post weld strain-age cracking. A paper introducing the 282 alloy and detailing some of the key properties (tensile, creep, oxidation, fabricability, etc.) was presented at the ASME TurboExpo 2006 [1].

In service, gas turbine engine components normally are subjected to cycling which can result in high stresses arising from thermal expansion effects. This can lead to failure through a mechanism known as thermal fatigue. In practice, low cycle fatigue (LCF) resistance is a commonly used approximation of thermal fatigue resistance. In the present study, the LCF properties of 282 alloy have been investigated over a temperature range of 1200 to 1600°F (649 to 871°C). Additionally, comparative data have been generated on Waspaloy alloy, R-41 alloy, and 263 alloy.

MATERIAL AND EXPERIMENTAL PROCEDURE

The LCF test results presented in this paper are from commercially produced sheet material, with a nominal thickness of 0.125" (3.2 mm). The alloys considered were 282 alloy, R-41 alloy, Waspaloy alloy, and 263 alloy, the compositions of which are shown in Table 1. The as-received material was in the mill-annealed condition. For the 282 and 263 alloys, the mill annealing is conducted in a continuous hydrogen furnace ("bright annealing") at temperatures of 2100°F (1149°C). After passing through the furnace, the sheet is gas cooled. The mill annealing for the R-41 and Waspaloy alloys consists of annealing at 1975°F (1079°C) in air ("oxidize annealing") and water quenching. The latter of these annealing processes is less desirable since it oxidizes the surface of the sheet, cannot be done on a continuous coil, and can result in warping of the sheet, requiring an additional straightening operation. However, because of the tendency of the gamma-prime phase to quickly precipitate in R-41 and Waspaloy alloys, a water quench is necessary to maintain fabricability in the annealed condition.

Prior to machining, the annealed samples were subjected to age-hardening heat treatments appropriate for each alloy. These heat treatments are listed in Table 2 along with the grain size of each alloy in the as-heat treated condition. It can be seen that the grain sizes of the four alloys are fairly similar, a fact which allows for a more direct comparison of LCF properties between the alloys. Table 3 presents tensile and creep-rupture data for the alloys in this study in the temperature range of interest. The tensile data were obtained from the same material used in the LCF study, while the creep-rupture data were collected from previous internal studies at Haynes International. The tensile yield strength of 282 alloy is greater than that of 263 alloy at all temperatures, but less than that of R-41 and Waspaloy alloys at temperatures up to 1400°F (760°C). At temperatures of 1500°F (816°C) and above, 282 alloy has superior tensile yield strength to Waspaloy, but still less than that of R-41 alloy. More important than tensile strength in this temperature range is the creep strength. From Table 3, it can be seen that the 1% creep strength of 282 alloy is better than that of Waspaloy and 263 alloys at all temperatures, and is equivalent to or better than that of R-41 alloy at temperatures of 1400°F (760°C) and above. This is remarkable due to the lower gamma-prime content of 282 alloy relative the Waspaloy and R-41 alloys and is a testament to the excellent stability of the 282 alloy microstructure. Table 4 presents controlled heating rate tensile (CHRT) test data [1] for the alloys in this study. In this test, an annealed sample is heated to the test temperature at a rate appropriate to simulate that of a post-weld solution annealing treatment. For gamma-prime forming alloys, a minimum in the tensile ductility is normally observed at a temperature around 1500°F (816°C) [2-3]. A low value for the minimum ductility is indicative that an alloy will be susceptible to strain-age cracking - a problem which occurs in some gamma-prime strengthened alloys during post-weld heat treatment. It can be seen from the table that 282 alloy has superior resistance to strain-age cracking compared to Waspaloy and R-41 alloys, and is second only to the low-strength 263 alloy.

Fully reversed (R = -1.0) axial low cycle fatigue testing was carried out at 1200, 1400, 1500, and 1600°F (649, 760, 816, and 871°C) on 282 alloy, and at 1500°F (816°C) for the Waspaloy, R-41, and 263 alloys. The tests were conducted using a triangular wave form at 0.33Hz, under strain-controlled mode. The total strain range varied from 0.3 to 1.0%. The samples were dog bone shaped and were produced using low stress grinding and final polishing. The orientation of the samples was transverse to the rolling direction. In some tests, hysteresis loops were periodically plotted until the onset of crack initiation, while in other tests every loop was recorded electronically. The number of cycles to crack initiation was calculated at the point of transition of stable load response to load decay. The tests were continued to failure, which was defined as either complete fracture of the specimen, or as the point at which the maximum stress had dropped to 75% of its stabilized value. Selected specimens were chosen for metallographic analysis to determine the nature of secondary cracking.

RESULTS AND DISCUSSION

Fatigue Life

The results of the low cycle fatigue tests on 282 alloy are shown in Fig. 1. The data are presented in terms of total strain range ($\Delta\varepsilon_t$) versus the number of cycles to failure (N_f). The results are also tabulated in Table 5. The fatigue life was found to increase with decreasing temperature and strain range. The decrease in fatigue life with increasing temperature was gradual in the temperature range of 1200 to 1500°F (649 to 816°C), but dropped more strongly between 1500 and 1600°F (816 and 871°C). The stress amplitude as a function of the number of cycles is plotted in Fig. 2. The stress amplitude generally increased with increasing total strain. For tests where the total strain range was 0.5% or less, the stress amplitude was found to remain essentially constant over the length of the test. These were tests where the total strain range was mostly composed of elastic strain. At higher strain ranges (where the total strain range included a significant plastic component), the stress amplitude was found to decrease continually with increasing number of cycles. This cyclic softening was found to be more pronounced with increasing total strain range.

The results of the low cycle fatigue tests at 1500°F (816°C) on Waspaloy, R-41, and 263 alloys are shown in Fig. 3 along with 282 alloy for comparison. The data are presented in terms of total strain range versus the number of cycles to failure. The results are also tabulated in Table 6. The 263 alloy was found to have the poorest LCF resistance of the alloys, having a lower number of cycles to failure across the entire total strain range. The 282, Waspaloy, and R-41 alloys were found to have similar LCF resistance at the upper end of the total strain range. At lower total strain ranges, a greater distinction was observed between these alloys. R-41 alloy was found to have the best LCF resistance in this region, being significantly better than Waspaloy, which in turn was somewhat better than 282 alloy. The stress amplitude as a function of the number of cycles is plotted in Fig. 4. As with 282 alloy, the stress amplitude for these alloys was not observed to change significantly at total strain ranges of 0.5% or less. For 263 alloy, higher total strain ranges resulted in cyclic softening. For R-41 and Waspaloy alloys, the cyclic softening was very gradual at total strain ranges of 0.6 and 0.7%. Pronounced cyclic softening was not observed in these two alloys until a total strain range of 1.0% was reached.

Secondary Cracking

Broken LCF specimens were examined metallographically for signs of secondary cracking. Micrographs of specimens of all four alloys in this study are shown in Fig. 5. All of these specimens were tested at a temperature of 1500°F (816°C) and a high total strain range of 1.0%. In all four alloys, numerous secondary cracks were observed with the cracks being lengthy and transgranular in nature and perpendicular to the axial direction. Specimens tested with a low total strain range were also examined. In these specimens, long transgranular secondary cracks were rare, but many short intergranular cracks were observed in the specimens. It is believed that these cracks initiate along areas of intergranular oxidation. Typical cracks of this type are shown in Fig. 6. The grain boundary on the far left has been oxidized, but has not yet been cracked open. However, cracks can be observed along grain boundaries further to the right. This type of crack was observed in all four alloys at the lowest strain range where the number of cycles was greater, and thus the time for oxidation to occur was also greater. A similar mechanism for LCF crack initiation has been observed in 617 alloy [4].

Thermal Fatigue

As mentioned previously, low cycle fatigue data is often used to infer an alloy's resistance to thermal fatigue. A second property of interest when estimating thermal fatigue resistance is the coefficient of thermal expansion (CTE). A lower CTE will lead to a lower imposed strain in a thermally cycled component, thereby lowering the driving force for fatigue. The CTE of 282 alloy along with other gamma-prime forming alloys is shown in Fig. 7. The 282 alloy and R-41 alloy have the lowest CTE of these alloys (due, in part, to high Mo content), suggesting a benefit in thermal fatigue resistance.

Future Testing

It is useful to mention a couple of limitations of the current test program in predicting the response of these alloys to thermal fatigue conditions such as they will experience in service. This test program did not include an examination of hold-time effects where the cycle is modified such that the interaction of creep and fatigue can be determined. Moreover, due to the short duration of the tests (most tests lasted less than 100 hours) the negative effect that thermal exposure can have on the microstructure of the alloys was less of a factor in the results as might be expected in service. Since the 282 alloy has excellent creep strength and thermal stability relative to the other alloys [1], additional testing is planned to explore both hold-time and thermal exposure effects.

SUMMARY

The LCF behavior of a new gamma-prime strengthened superalloy, HAYNES 282 alloy, has been investigated. The testing was conducted using fully-reversed strain-control over a temperature range of 1200 to 1600°F (649 to 871°C). The LCF resistance was found to gradually increase with temperature up to 1500°C (816°C). Above this temperature, the LCF resistance decreased more rapidly. The stress amplitude was virtually constant in the elastic regime, while cyclic softening was observed in tests at a higher total strain range.

The 1500°F (816°C) LCF behavior of three other wrought superalloys was also investigated: Waspaloy alloy, R-41 alloy, and 263 alloy. It was found that 263 alloy had the lowest LCF resistance at all strain ranges of the four alloys in the study. The 282 alloy, Waspaloy alloy, and R-41 alloy were found to have very similar LCF resistance for higher total strain range conditions. At lower total strain ranges, the R-41 alloy had the best LCF resistance followed by Waspaloy and 282 alloy, in that order. As observed for 282 alloy, the stress amplitude during tests of the other three alloys was virtually constant in the elastic regime, while cyclic softening was observed in tests at a higher total strain range.

Extensive transgranular cracking was present in specimens of all four alloys tested at the highest total strain range of 1.0%. The cracks were perpendicular to the axial direction. At lower strain ranges, fewer of these long transgranular cracks were observed, but extensive short intergranular cracks were present which had apparently initiated along oxidized grain boundaries.

ACKNOWLEDGEMENTS

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Table 1 Nominal Composition of Alloys

Alloy	Ni	Cr	Co	Mo	Ti	Al	Fe	Mn	Si	C	B	Other
282	57[a]	20	10	8.5	2.1	1.5	1.5*	0.3*	0.15*	0.06	0.005	--
Waspaloy	58[a]	19	13.5	4.3	3	1.5	2*	0.1*	0.15*	0.08	0.006	Zr-0.05
R-41	52[a]	19	11	10	3.1	1.5	5*	0.1*	0.5*	0.09	0.006	--
263	52[a]	20	20	6	2.4*	0.6*	0.7*	0.4	0.2	0.06	0.005	Al+Ti-2.6

[a]As Balance *Maximum

Table 2 Annealing and Age-Hardening Heat Treatments and Grain Size of Material Used in This Study

Alloy	282 Alloy	Waspaloy alloy	R-41 alloy	263 alloy
Annealing Temperature	2100°F (1149°C)[b]	1975°F (1079°C)[o]	1975°F (1079°C)[o]	2100°F (1149°C)[b]
Age-Hardening Heat Treatment	1850°F (1010°C)/2h/AC + 1450°F (788°C)/8h/AC	1825°F (996°C)/2h/AC + 1550°F (843°C)/4h/AC + 1400°F (760°C)/16h/AC	2050°F (1121°C)/0.5h/RAC + 1650°F (899°C)/4h/AC	1472°C (800°C)/8h/AC
ASTM Grain Size	4½	5	5	4

[o]Oxidize anneal [b]Bright anneal AC = Air cool RAC = Rapid air cool (fan cool)

Table 3 Mechanical Properties of Alloys at Selected Temperatures

1200°F (649°C)		282 Alloy	Waspaloy alloy	R-41 alloy	263 alloy
Tensile	0.2% Offset Yield Strength, ksi (MPa)	92.1 (635)	113.8 (785)	106.9 (737)	78.4 (540)
	Ultimate Tensile Strength, ksi (MPa)	151.1 (1042)	165.4 (1140)	171.6 (1183)	130.0 (897)
	% Elongation	30.8	32.1	17.5	36.2
Creep	1000-Hour 1% Creep Strength, ksi (MPa)	80 (552)	67 (462)	84 (579)	58 (400)
	1000-Hour Rupture Strength, ksi (MPa)	81 (558)	80 (552)	90 (621)	64 (441)

1400°F (760°C)		282 Alloy	Waspaloy alloy	R-41 alloy	263 alloy
Tensile	0.2% Offset Yield Strength, ksi (MPa)	89.0 (614)	100.3 (692)	114.8 (792)	80.7 (556)
	Ultimate Tensile Strength, ksi (MPa)	121.0 (834)	119.1 (821)	140.8 (971)	101.1 (697)
	% Elongation	24.8	34.9	26.9	26.4
Creep	1000-Hour 1% Creep Strength, ksi (MPa)	35 (241)	28 (193)	34 (234)	25 (172)
	1000-Hour Rupture Strength, ksi (MPa)	38 (262)	36 (248)	43 (296)	28 (193)

1500°F (816°C)		282 Alloy	Waspaloy alloy	R-41 alloy	263 alloy
Tensile	0.2% Offset Yield Strength, ksi (MPa)	82.7 (570)	74.3 (512)	105.9 (730)	68.8 (501)
	Ultimate Tensile Strength, ksi (MPa)	99.8 (688)	92.2 (636)	116.7 (805)	78.3 (540)
	% Elongation	24.9	39.3	27.9	33.1
Creep	1000-Hour 1% Creep Strength, ksi (MPa)	21 (145)	16 (110)	18 (124)	12 (83)
	1000-Hour Rupture Strength, ksi (MPa)	23 (159)	20 (138)	24 (165)	15 (103)

1600°F (871°C)		282 Alloy	Waspaloy alloy	R-41 alloy	263 alloy
Tensile	0.2% Offset Yield Strength, ksi (MPa)	73.0 (504)	50.9 (351)	83.8 (578)	41.5 (286)
	Ultimate Tensile Strength, ksi (MPa)	80.3 (554)	66.1 (456)	91.2 (629)	50.4 (347)
	% Elongation	35.3	50.8	29.4	62.3
Creep	1000-Hour 1% Creep Strength, ksi (MPa)	10 (69)	7 (48)	9 (62)	6 (41)
	1000-Hour Rupture Strength, ksi (MPa)	13 (90)	10 (69)	13 (90)	7 (48)

Table 4 Controlled Heating Rate Tensile (CHRT) Test Data

Alloy	1500°F ductility (%)
263 alloy	26.0
282 alloy	14.2
Waspaloy alloy	4.1
R-41 alloy	3.1

Table 5 LCF Data for 282 Alloy

Total Strain Range, %	1200°F (649°C)		1400°F (760°C)		1500°F (816°C)		1600°F (871°C)	
	N_i	N_f	N_i	N_f	N_i	N_f	N_i	N_f
1.0	1,853	1,990	1,238	1,523	908	1,123	--	--
0.9	--	--	1,576	1,857	--	--	--	--
0.7	4,840	5,714	3,337	3,979	1,639	2,444	869	930
0.6	10,713	11,807	9,535	10,281	5,570	6,446	1,345	1,744
0.5	91,800	92,306	37,877	39,484	12,346	13,130	3,274	3,857
0.45	--	--	76,027	77,179	--	--	--	--
0.42	--	--	214,727	216,151	--	--	--	--
0.4	--	--	--	--	116,379	118,360	14,959	15,795
0.3	--	--	--	--	--	--	131,019	132,491

Table 6 LCF Data for Alloys at 1500°F (816°C)

Total Strain Range, %	Waspaloy alloy		R-41 alloy		263 alloy	
	N_i	N_f	N_i	N_f	N_i	N_f
1.0	840	1,049	924	1,100	608	684
0.7	3,567	4,064	5,319	6,035	1,253	1,430
0.6	5,882**	6,344**	6,603**	7,312**	2,361	2,870
0.5	30,476	31,520	>134,634*		6,152	7,527
0.4	> 200,309*		--	--	68,278	70,106

*sample discontinued prior to crack initiation **logarithmic average of duplicate tests

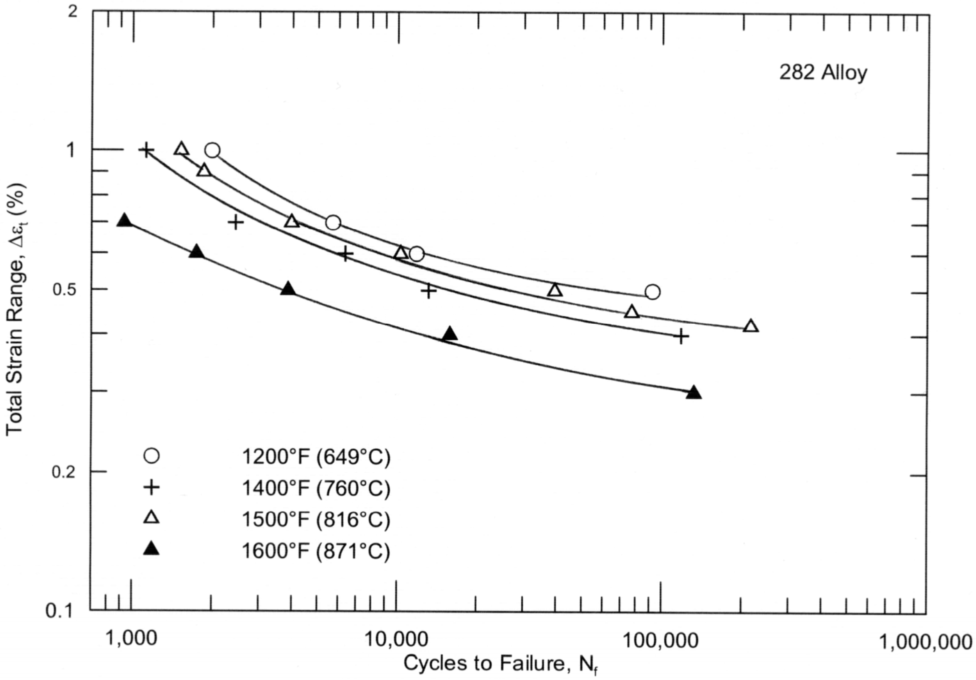

Figure 1 Strain-controlled LCF behavior of 282 alloy at selected temperatures.

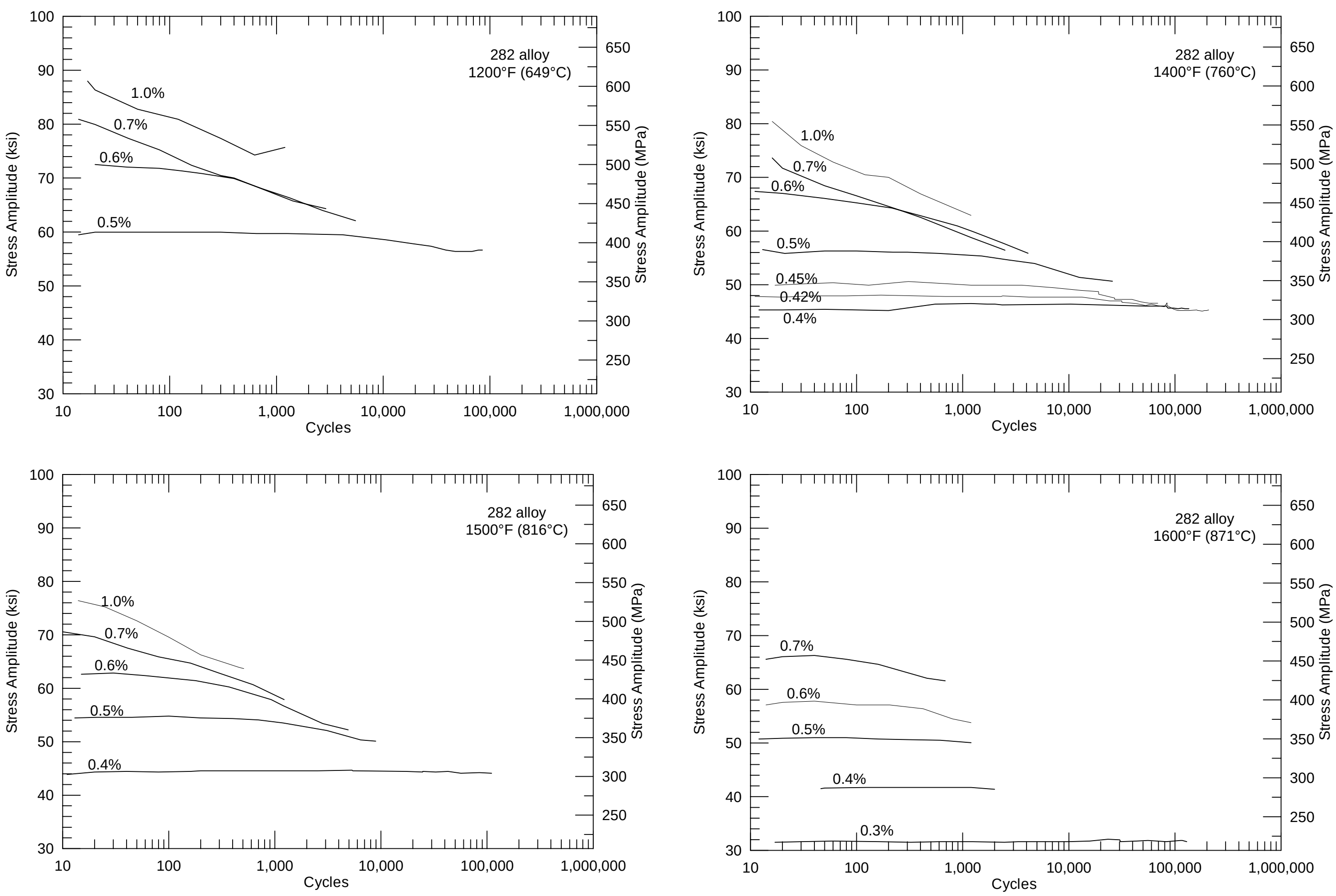

Figure 2 Stress amplitude response of 282 alloy during strain controlled LCF testing at selected temperatures. Each curve represents a different total strain range (shown).

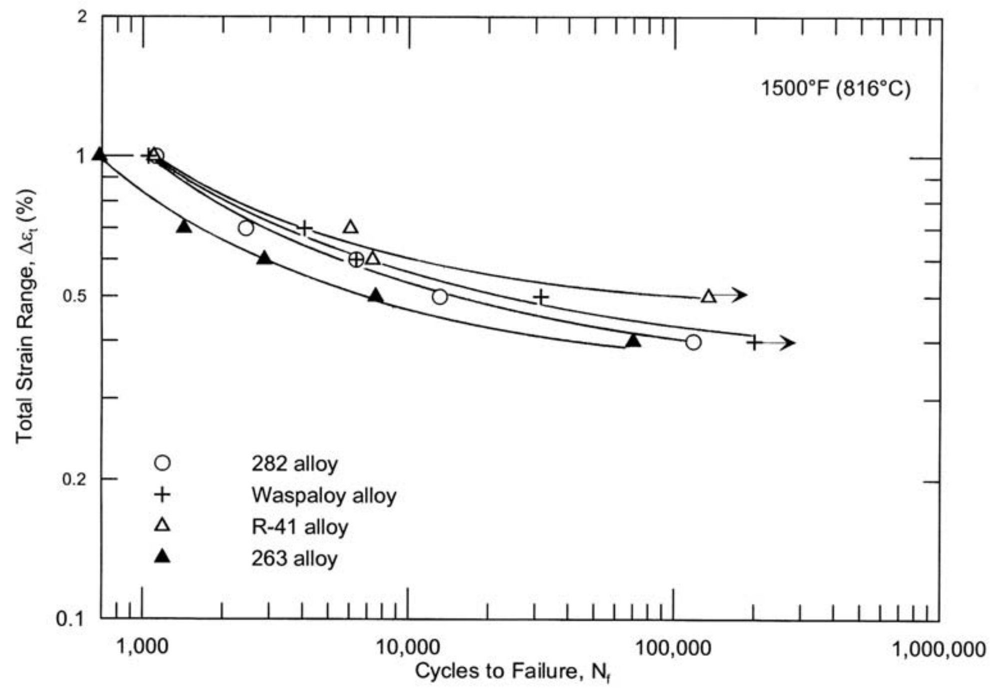

Figure 3 Strain-controlled LCF behavior of alloys at 1500°F (816°C).

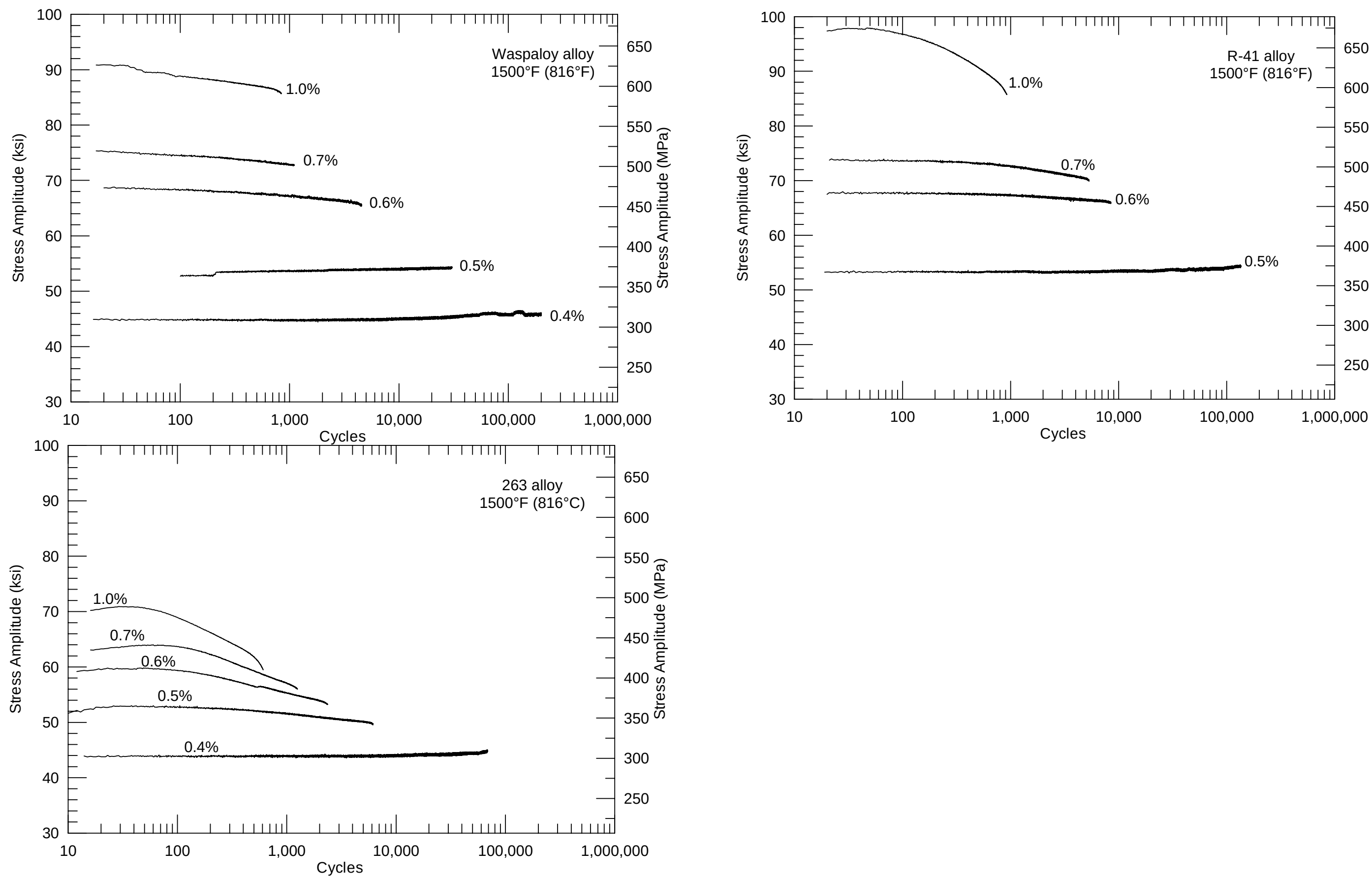

Figure 4 Stress amplitude response of alloys during strain controlled LCF testing at 1500°F (816°C). Each curve represents a different total strain range (shown). A comparable plot for 282 alloy can be found in Fig. 2.

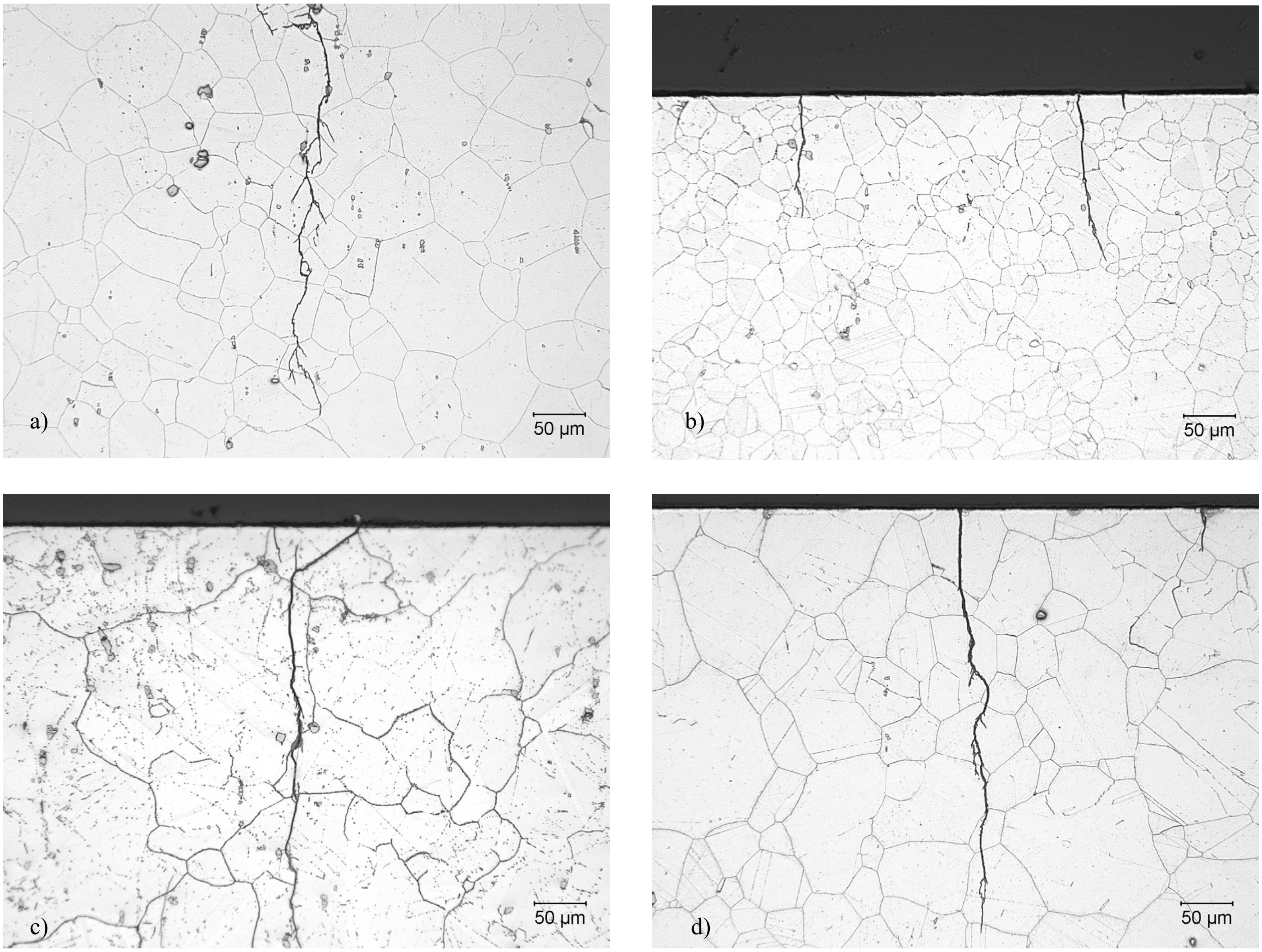

Fig. 5 Secondary cracking in LCF specimens under a total strain range of 1.0% at 1500°F (816°C). a) 282 alloy, b) Waspaloy alloy, c) R-41 alloy, d) 263 alloy.

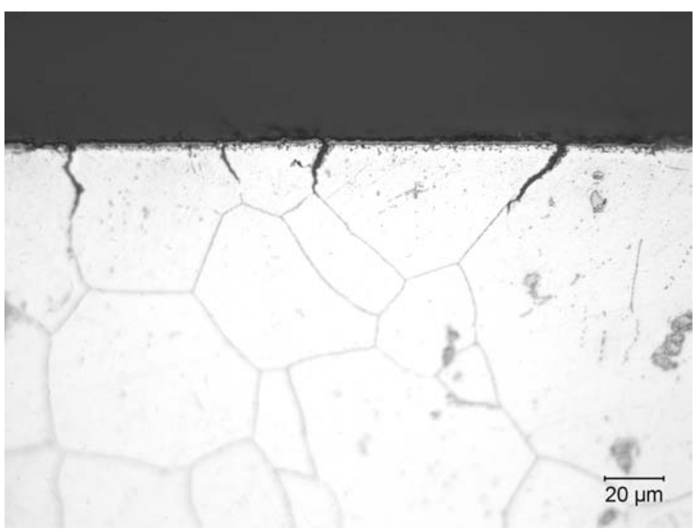

Fig. 6 A typical example of grain boundary oxidation leading to crack initiation.

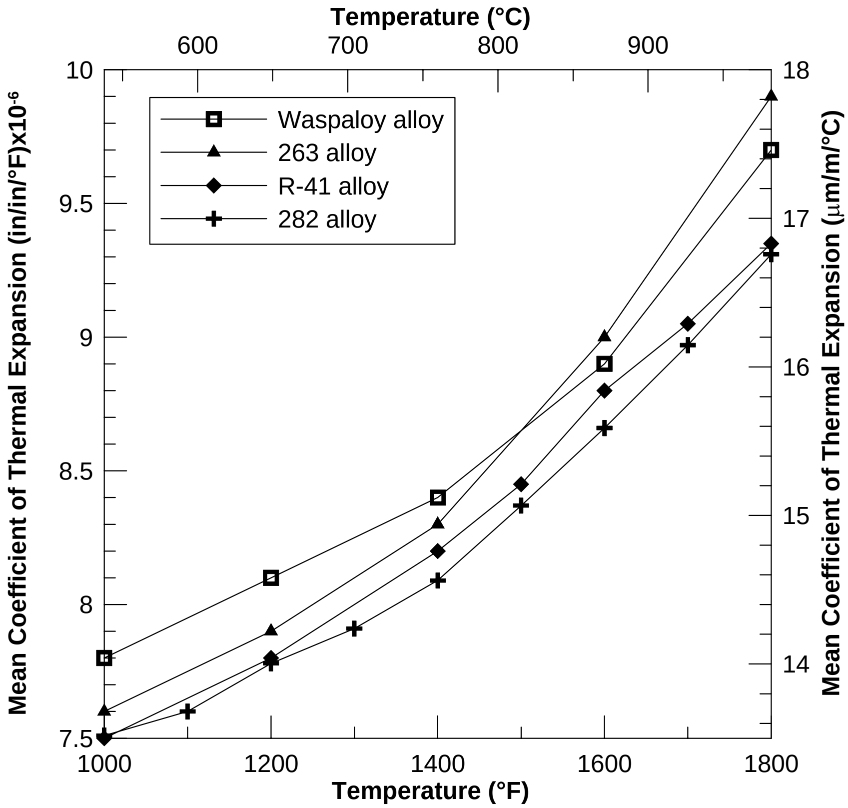

Fig. 7 Coefficient of thermal expansion of several wrought gamma-prime forming alloys.