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LONG TERM THERMAL EXPOSURE OF HAYNES 282 ALLOY

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Abstract

HAYNES® 282® alloy was recently introduced for applications in both aero and land-based gas turbine engines. While possessing excellent high temperature strength and LCF resistance, the alloy was designed to ensure adequate fabricability. The new alloy is readily hot and cold worked and has superior weldability relative to other alloys in its class. A key attribute of 282 alloy is the excellent stability of its microstructure upon long term thermal exposure. As a result, the alloy is not prone to severe embrittlement as are certain other alloys in its class. The stability of the alloy is also believed to contribute to the high temperature strength of the alloy over long exposure periods. In this paper, the thermal stability of 282 alloy will be investigated in two parts. The first being a comparative study of moderately long (1,000 hour) exposures between 282 alloy and other alloys in its class. The second part will investigate the effect of much longer thermal exposures of up to 16,000 hours on the tensile properties of 282 alloy.

Introduction

Thermal stability is a key feature of alloys intended for long-term service at elevated temperatures. For gamma-prime strengthened alloys in particular, there are two main issues which can arise due to microstructural instability: loss of ductility and loss of strength. Both issues can be problematic for components constructed from materials of poor thermal stability. A loss of ductility is often associated with the formation of secondary phases. If these secondary phases are deleterious in nature, such the TCP-type sigma, Laves, or mu phases, significant embrittlement can occur. This embrittlement is more often seen at room temperature (RT) than at elevated temperatures (ET). Loss of strength can arise in these types of alloys due to a number of reasons, including gamma-prime coarsening and/or dissolution as well as formation of TCP-type phases which can deprive the matrix of critical elements such as Mo.

Little data has been published to date on the thermal stability of HAYNES 282 alloy [1,2]. The present study will provide more insight on this topic in two main parts. The first will focus on moderately long (1,000 hour) thermal exposures of 282 alloy in comparison to other alloys in its class: R-41 (René 41) alloy, Waspaloy alloy, and 263 alloy. The effects of thermal exposure on both tensile properties and microstructural features will be presented. The second part of the study will focus on longer term exposures of up to 16,000 hours on the tensile properties of 282 alloy.

Experimental

For the first part of the study, samples of 282 alloy, R-41 alloy, Waspaloy alloy, and 263 alloy were taken from 0.063″ (1.6 mm) thick production sheet material in the mill annealed condition. The nominal compositions of these alloys are given in Table I. The samples were age-hardened according to typical heat treatment specifications for the particular alloy: 282 alloy, 1850°F (1010°C)/2h/AC + 1450°F (788°C)/8h/AC; R-41 alloy, 2050°F (1121°C)/0.5h/RAC + 1650°F (899°C)/4h/AC; Waspaloy alloy, 1825°F (996°C)/2h/AC + 1550°F (843°C)/4h/AC + 1400°F (760°C)/16h/AC; 263 alloy, 1472°C (800°C)/8h/AC. Samples were subjected to 1000-hour thermal exposures at 1200°F (649°C), 1400°F (760°C), 1500°F (816°C), and 1600°F (871°C). The exposures were conducted in a still air environment. Tensile tests were conducted on the thermally exposed material at room temperature as well as at the exposure temperature (all tensile testing in this study was performed on duplicate samples). For baseline reference, tensile testing was also performed on material in the as-heat treated (as-HT) condition. All tensile samples were oriented in the direction transverse to the rolling direction of the sheet. Flat tensile samples were machined from the sheet material with the sample surface remaining in the as-oxidized condition. The tensile properties of thermally exposed 282 alloy, R-41 alloy, Waspaloy alloy, and 263 alloy are given in Table 1 along with the tensile properties in the original as-heat treated condition. These results will be discussed in more detail in the next section of this manuscript. Optical microscopy was performed on as-exposed material using an electrolytic oxalic/hydrochloric acid etch. Additionally, thermally exposed samples were examined using a SEM/EDS system. Samples were given an electrolytic etch (15g CrO_3, 150mL H_3PO_4, 10mL H_2SO_4) to reveal the gamma-prime structure.

For the second part of the study, samples of 282 alloy were taken from ½″ (12.7 mm) thick production plate material obtained in the mill annealed condition. The samples were heat treated in the same manner as the first part of this study. Samples were then subjected to 100, 1000, 4000, 8000, and 16000 hour exposures at 1200°F (649°C), 1400°F (760°C), and 1600°F (871°C). Round tensile samples (transverse to the rolling direction) were machined from the plate material such that the oxidized surfaces had been completely machined away. Duplicate tensile tests were conducted on the as-heat treated and the thermally exposed samples.

Results and Discussion

Part One: Comparative Thermal Stability Study

A comparative study of moderately long (1,000 hour) thermal exposures was conducted on 282 alloy along with other alloys in its class: R-41 alloy, Waspaloy alloy, and 263 alloy. The effects of thermal exposure on both tensile properties and microstructural features are discussed.

Room Temperature Tensile. The RT tensile elongation is shown in Fig. 1a as a function of exposure temperature. (Note that for this plot, and analogous plots in this manuscript, the properties for the "RT exposed" samples are simply taken as the properties in the as-HT condition.) For 282 alloy the RT tensile elongation was found to decrease only mildly after thermal exposure, starting out at 31% in the as-HT condition and dropping to a low of 21% after the 1000-hour exposure at 1500°F – the exposure temperature resulting in the greatest loss in ductility. In a similar fashion, both Waspaloy alloy and 263 alloy were found to retain very respectable RT elongation after the 1000-hour thermal exposures. For 263 alloy, the elongation started out at 33%, dropped to 21% for the 1200°F thermal exposure, and then increased with increasing exposure temperature to a high of 41% for the 1600°F exposure. In contrast, the RT elongation of Waspaloy started at 24% in the as-HT condition and remained fairly constant with exposure temperature, dropping only to 18% for the 1600°F exposure. The alloy showing the greatest effect of thermal exposure was R-41 alloy, where the RT elongation dropped sharply for all exposure temperatures. With an initial value at 19%, the elongation dropped to 8.9% for the 1200°F exposure and to levels around 2% for exposures between 1400 and 1600°F.

The RT yield strength of the 1000-hour thermally exposed samples is shown in Fig. 1b as a function of exposure temperature. The yield strength of 282 alloy in the as-HT condition was 100.5 ksi; it increased to 112.9 ksi after the 1200°F exposure; likewise, it was also greater than in the as-HT condition after the 1400°F exposure (104.1 ksi). On the other hand, the thermal exposure of 282 alloy at 1500°F led to a modest drop in yield strength (91.9 ksi). The thermal exposure at 1600°F led to a more significant drop in yield strength, resulting in a value of 72.9 ksi after the 1000-hour period. The RT yield strengths of Waspaloy and R-41 alloys were greater than 282 alloy in the as-HT condition due to higher gamma-prime content. This was also true for samples thermally exposed at 1200°F which resulted in slightly higher yield strengths for both alloys. For samples thermally exposed at 1400°F, the two alloys differed significantly. R-41 alloy was found to further strengthen at this temperature, while Waspaloy alloy suffered a drop in strength. In fact, of the four alloys in this study, only Waspaloy was found to lose RT strength after the 1000-hour exposure at 1400°F. The yield strength of R-41 alloy and Waspaloy alloy decreased with further increases in exposure temperature. The RT yield strength of 263 alloy was the lowest of the four alloys. After the 1200°F exposure, the yield strength increased slightly, while after the 1400°F exposure it was virtually unaffected. Thermal exposures of 1500 and 1600°F resulted in significant drops in yield strength for 263 alloy.

Elevated Temperature Tensile. Of more interest than the RT tensile properties in determining the *in-service* effects of thermal exposure are the elevated temperature tensile properties at the exposure temperature itself. The tensile elongation at the exposure temperature is shown in Fig. 2a. For 282 alloy, Waspaloy alloy, and 263 alloy, the ET elongations were all very high, being around 25% or higher for all exposure temperatures. In contrast, the R-41 alloy did exhibit a low elongation value as a result of thermal exposure, but only for the case of the 1200°F exposure. In this case, the 1200°F ductility was only 11% after the thermal exposure. For higher thermal exposures, the elongation of R-41 alloy was greater than 25%.

The yield strength at the exposure temperature is plotted in Fig. 2b as a function of the exposure temperature. After a 1200°F exposure, the 1200°F yield strength of the R-41 alloy and Waspaloy alloy was significantly higher than 282 alloy and 263 alloy. However, after a 1400°F exposure the situation was quite different. In this case , the 1400°F yield strength of Waspaloy significantly dropped, particularly in comparison to 282 alloy. After thermal exposure in the range of 1400 to 1600°F, 282 alloy was found to have a higher yield strength at the exposure temperature than Waspaloy, which in turn was stronger than 263 alloy. Only R-41 alloy had higher strength after thermal exposure in this range than 282 alloy.

Another way to consider the effects of thermal exposure on the yield strength is shown in Fig. 3 where the yield strength of the four alloys is shown before and after thermal exposure. For thermal exposures at 1200°F, the yield strength of all four alloys was found to increase as a result of the thermal exposure. However, thermal exposures of 1400°F resulted in a decrease in the yield strength for three of the alloys: R-41 alloy, Waspaloy alloy, and 263 alloy. Only 282 alloy was found to increase in strength after the 1400°F thermal exposure. The yield strength of all four alloys was found to decrease after thermal exposures at 1500 and 1600°F, with the decreases generally more severe in the latter case. Explanations for the observed effects of thermal exposure on the mechanical properties can be tied to changes in the microstructure as will be discussed later in this manuscript.

Microstructural Stability. Optical micrographs of thermally exposed 282 alloy, R-41 alloy, Waspaloy alloy, and 263 alloy are presented in Figs. 4-7. For each alloy, four micrographs are shown which correspond to 1000-hour exposures at 1200, 1400, 1500, and 1600°F. For 282 alloy little difference can be seen between the various exposure temperatures. No evidence of deleterious phases can be seen. In contrast, for R-41 alloy significant intragranular precipitation can be seen for thermal exposures between 1400 and 1600°F. Previous investigators have reported the presence of mu phase and sigma phase in thermally exposed R-41 alloy [3,4]. For 263 alloy there is no evidence of deleterious phase formation except after the 1600°F exposure. In this case, plate-like precipitates can be observed. These are likely the eta phase (Ni_3Ti) which has been reported in thermally exposed 263 alloy [5,6]. For Waspaloy alloy, the optical micrographs do not differ significantly between exposure temperatures and no evidence of deleterious phases was observed. (Note that the magnification of the optical micrographs is insufficient to resolve the gamma-prime phase.)

To resolve the effect of thermal exposure on the gamma-prime phase it is necessary to use an SEM. Such SEM images for the four alloys in this study are shown in Figs. 8, 9, 10, and 11 for 1000-hour thermal exposures of 1200, 1400, 1500, and 1600°F, respectively. For the 1200°F exposure, the gamma-prime precipitates did not increase much in size compared to the as-HT condition (not shown). The 282 and 263 alloys had smaller gamma-prime precipitates relative to R-41 and Waspaloy alloys, which is believed to be a result more of their original heat treatment conditions than the 1200°F thermal exposure itself. After the 1400°F exposure, the gamma-prime precipitates were observed to coarsen somewhat for all four alloys, and were homogeneously distributed (as they also had been in the as-HT and 1200°F exposed samples). For exposures at 1500°F, the gamma-prime precipitates coarsened more for all four alloys. The gamma-prime was again homogenously distributed, except for 263 alloy where the gamma-prime could be seen to be aligning along preferred directions. After the 1600°F exposure, considerable coarsening was seen in all four alloys. For 282 alloy, Waspaloy alloy, and 263 alloy the gamma-prime precipitates appeared to be adopting a somewhat cuboidal shape, while for R-41 alloy these remained spherical. In 263 alloy, the volume fraction of the gamma-prime phase was considerably lower after the 1600°F exposure than for the other exposure temperatures.

The phases depicted in Figs. 8-11 were mostly gamma-prime and secondary grain boundary carbides. Also seen in a few images (e.g. Fig. 8b) were large primary carbides. For 282 alloy and Waspaloy alloy, no additional phases were observed for any of the exposure temperatures. In R-41 alloy exposed at temperatures between 1400 and 1600°F, certain large intragranular phases (mu and possibly sigma) can be seen throughout the microstructure, consistent with the optical micrographs in Fig. 5. Finally, in thermally exposed 263 alloy, a small amount of a eta phase was observed in the images, particularly for samples exposed at 1500°F.

A limited SEM/EDS analysis of precipitate phases was conducted on the four alloys in the as-HT condition as well as after the 1000-hour exposure at 1400°F. The results are given in Table 3 and backscatter images taken of the samples are shown in Fig. 12. The primary phases TiN and MC were found in all four alloys. In R-41 alloy, the M_6C phase was also identified as a primary precipitate. Secondary $M_{23}C_6$ carbides were found in all four alloys predominantly along grain boundaries. Additionally, secondary M_6C carbides were observed in 282 alloy and R-41 alloy. In addition to the gamma-prime phase observed in all samples, the eta and mu phases were observed in 263 alloy and R-41 alloy, respectively, after the 1000-hour exposure. No sigma phase was identified in the thermally exposed R-41 sample (as has been found previously [4]), but an exhaustive search for the sigma phase was not conducted in the present study.

Correlation of Microstructure/Tensile Properties. The residual tensile properties of the thermally exposed alloys can be correlated to certain microstructural features. For example, the high elongation of thermally exposed 282 alloy, Waspaloy alloy, and 263 alloy at both RT and the exposure temperature (Figs. 1a and 2a) can be attributed to the lack of significant formation of deleterious phases. In the case of 263 alloy, the fairly small amount of eta phase was apparently not enough to result in significant embrittlement. A future study would be to look at longer thermal exposures of 263 alloy to determine if further precipitation of the eta phase would lead to loss of ductility. For R-41 alloy, the drop in both RT and ET temperature ductility in samples thermally exposed at temperatures between 1400 and 1600°F can be attributed to the precipitation of mu phase (and possibly sigma phase).

The effect of microstructure on the yield strength of these thermally exposed alloys is somewhat complicated and can depend on gamma-prime size and volume fraction, the presence of deleterious phases, etc. Generally, the yield strength will decrease if the exposure temperature for a given alloy results in gamma-prime "overaging" and/or loss of phase fraction. An example is the case of 263 alloy exposed at 1600°F for 1,000 hours. The yield strength may also decrease as a result of deleterious phase formation. In R-41 alloy, mu-phase formation results in a loss of strength when tested at the exposure temperature, but this effect is apparently not seen when tested at RT (see Figs. 2a and 2b – 1400°F exposure).

Part Two: Long Term (16,000-hour) Thermal Exposures – 282 alloy

The present manuscript details the tensile properties of 282 alloy exposed for up to 16,000 hours. A thorough examination of the resulting microstructures will be presented elsewhere [7]. Please note that corresponding tests for R-41, Waspaloy, and 263 alloy were not part of the present study.

Room Temperature Tensile. The RT elongation of 282 alloy is shown in Fig. 13a as a function of exposure duration. In the as-HT condition the RT elongation was 30%. When exposed at 1200°F, the elongation dropped to 27% after 100 hours. Longer thermal exposures led to only very gradual further decreases in elongation, and after 16,000 hours the elongation was still 23%. The largest drops in RT elongation were observed in samples exposed at 1400°F. When exposed at this temperature, the elongation dropped with increasing exposure duration out to about 4,000 hours. At this point the elongation was 21%. The elongation was essentially constant with further thermal exposure at 1400°F, only dropping to 20% after the full 16,000 hour exposure. For 1600°F exposures the RT elongation was virtually independent of exposure duration, increasing only very slightly from 30% to 33% after 16,000 hours.

The RT yield strength is shown in Fig. 13b as a function of exposure duration. In the as-HT condition the yield strength was 102.3 ksi. Thermal exposure at 1200°F resulted in an increase in the yield strength. After 100 hours the yield strength was 115.8 ksi; it remained essentially constant after that, falling in the range of 118 to 120 ksi for exposures between 1,000 and 16,000 hours. For exposures at 1400°F, the yield strength initially increased as had been observed for the sheet material in Part One above. At longer exposure times the yield strength decreased gradually with increasing exposure, but retained a high level even after the full exposure duration. After 16,000 hours, the RT yield strength was still 95.5 ksi - a value 93% of the original strength. For the 1600°F exposure the yield strength dropped with increasing exposure duration out to 4,000 hours, reaching a level of 70.7 ksi. However, with continued thermal exposure the yield strength was fairly constant, dropping only to 65.5 ksi after the full 16,000 hours.

Elevated Temperature Tensile. As was done in Part One of this study, the elevated temperature tensile properties were characterized by testing at the exposure temperature. The ET elongation of thermally exposed 282 alloy is shown in Fig. 14a. For 1200°F exposures, the 1200°F elongation dropped from 32% to 26% after 100 hours, but only slightly after that, reaching 23% after 16,000 hours. For both 1400°F and 1600°F thermal exposures, the ET elongation increased with exposure duration. In both cases, the largest increase occurred within the first 1,000 hours of exposure, with only gradual increases with further thermal exposure.

The ET yield strength is shown in Fig. 14b. At 1200°F, the yield strength increased from 93.3 ksi to 103.1 ksi after 100 hours and increased only very slightly with continued exposure duration. After 16,000 hours a value of 107.2 ksi was reached. The 1400°F yield strength after exposure at 1400°F increased from 91.7 ksi to 98.5 ksi after 1,000 hours; continued exposure led to a modest drop in yield strength, eventually reaching a level of 79.2 ksi after 16,000 hours - a value 86% of the original strength. For 1600°F exposures the yield strength at the exposure temperature dropped from 74.5 ksi to 36.5 ksi after 4,000 hours; longer exposures did not result in further loss of strength.

Implications for Long Term Service of 282 Alloy. The results of the thermal stability study of 282 alloy are very encouraging for applications involving long term service at elevated temperatures up to 1600°F. The ductility of the alloy remains high, with RT and ET tensile elongations not falling below ~ 20% even after exposures of 16,000 hours. The strength of 282 alloy also holds up well after thermal exposure. At 1200°F, the RT and ET yield strengths increase with long term exposure. While the RT and ET yield strengths do eventually decrease somewhat after very long exposure times, they retain much of their original strength after the 16,000 hours (93% and 86% for the RT and ET yield strengths, respectively). Despite this decrease, the yield strength of thermally exposed 282 alloy is still far superior to solid-solution strengthened alloys such as HAYNES 230® alloy [8] as shown in Fig. 15. Even at 1600°F, where the yield strength of 282 alloy decreased the most, the retained RT and ET yield strengths are greater than those of 230 alloy. Furthermore, the yield strengths were found to have reached an essentially constant value between 4,000 and 16,000 hours at 1600°F, suggesting that further degradation beyond 16,000 hours would very likely be insignificant.

Summary and Conclusions

1. The effect of thermal exposures on the tensile properties and microstructure of 282 alloy, R-41 alloy, Waspaloy alloy, and 263 alloy in the range of 1200 to 1600°F was determined using 1,000 hour exposures. The behaviors of the four alloys were found to be quite different.

2. The retained yield strength of R-41 alloy was the highest of the four alloys for all exposure temperatures at both RT and ET, however, the alloy is subject to severe embrittlement when exposed at temperatures between 1400 and 1600°F due to the formation of deleterious phases.

3. The other three alloys did not suffer embrittlement and with the exception of 263 alloy (eta phase), did not form deleterious phases within the 1,000 exposures at any temperature.

4. The retained yield strength *at the exposure temperature* of thermally exposed 282 alloy was higher than those of both Waspaloy alloy and 263 alloy after exposures at 1400 to 1600°F.

5. Of the four alloys in the study, only 282 alloy was found to increase in strength after the 1,000 hour exposure at 1400°F.

6. The thermal stability of 282 alloy was investigated using RT and ET tensile tests of materials exposed for up to 16,000 hours at temperatures between 1200 and 1600°F. The results were very favorable for use in that temperature range in terms of both elongation and yield strength.

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Table I Nominal Composition of Several Wrought Gamma-Prime Alloys (wt.%)

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 II. Tensile properties* for the as-HT and thermally exposed (1000-hour) conditions

Alloy	Exposure Temp.		Test Temp.		0.2% YS		UTS		Elong.
	(°F)	(°C)	(°F)	(°C)	(ksi)	(MPa)	(ksi)	(MPa)	(%)
282 alloy	None (As-HT)		RT	RT	100.5	693	163.5	1128	31
			1200	649	88.2	608	143.7	991	27
			1400	760	86.7	598	119.4	823	22
			1500	816	79.9	551	98.2	677	19
			1600	871	71.7	494	80.0	552	23
	1200	649	RT	RT	112.9	778	172.8	1191	26
	1400	760			104.1	718	170.5	1176	23
	1500	816			91.9	634	159.8	1102	21
	1600	871			72.9	502	141.4	975	24
	1200	649	1200	649	98.6	680	150.4	1037	24
	1400	760	1400	760	92.6	639	118.7	818	27
	1500	816	1500	816	61.8	426	84.3	581	37
	1600	871	1600	871	37.8	260	58.7	405	44
R-41 alloy	None (As-HT)		RT	RT	113.8	785	179.2	1235	19
			1200	649	108.2	746	174.1	1201	19
			1400	760	112.7	777	139.6	962	27
			1500	816	102.1	704	114.6	790	27
			1600	871	78.5	541	89.1	614	23
	1200	649	RT	RT	141.9	979	189.4	1306	8.9
	1400	760			167.0	1151	197.2	1359	1.9
	1500	816			137.9	951	177.5	1224	1.8
	1600	871			103.8	715	148.0	1021	2.6
	1200	649	1200	649	126.4	871	183.8	1267	11
	1400	760	1400	760	104.1	718	137.5	948	26
	1500	816	1500	816	64.8	447	98.0	675	34
	1600	871	1600	871	42.0	290	69.2	477	37
Waspaloy alloy	None (As-HT)		RT	RT	127.9	882	188.8	1301	24
			1200	649	110.3	760	162.0	1117	34
			1400	760	98.9	682	117.8	812	34
			1500	816	73.8	509	91.0	628	38
			1600	871	50.3	347	65.3	450	48
	1200	649	RT	RT	136.5	941	196.2	1353	23
	1400	760			112.9	779	182.4	1258	24
	1500	816			103.5	714	170.1	1173	23
	1600	871			84.6	584	149.3	1030	18
	1200	649	1200	649	120.4	830	168.4	1161	26
	1400	760	1400	760	79.7	549	111.0	765	43
	1500	816	1500	816	57.3	395	85.4	589	45
	1600	871	1600	871	37.6	259	60.3	415	39
263 alloy	None (As-HT)		RT	RT	92.6	638	148.1	1021	33
			1200	649	77.1	531	126.5	872	31
			1400	760	78.5	541	100.5	693	27
			1500	816	67.6	466	76.2	525	37
			1600	871	41.1	283	49.0	338	50
	1200	649	RT	RT	113.6	783	166.6	1149	21
	1400	760			92.7	639	160.3	1105	32
	1500	816			71.4	493	144.0	993	35
	1600	871			55.0	379	125.2	863	41
	1200	649	1200	649	96.1	663	144.1	993	29
	1400	760	1400	760	73.3	505	95.0	655	34
	1500	816	1500	816	45.9	316	64.9	448	45
	1600	871	1600	871	27.2	187	42.7	295	54

*Values represent an average of duplicate samples

Table III. Phases Present in the as-HT and 1400°F (760°C)/1000-hour samples

	282 alloy	R-41 alloy	Waspaloy alloy	263 alloy
Primary precipitates	TiN MC	TiN MC M_6C	TiN MC	TiN MC
Secondary carbides	$M_{23}C_6$ M_6C	$M_{23}C_6$ M_6C	$M_{23}C_6$	$M_{23}C_6$
Other secondary phases	gamma-prime	gamma-prime *mu* *sigma**	gamma-prime	gamma-prime *eta*

*Collins [4] - not confirmed in present study

Note: phases listed in *italics* were present only after the 1400°F (760°C) exposure

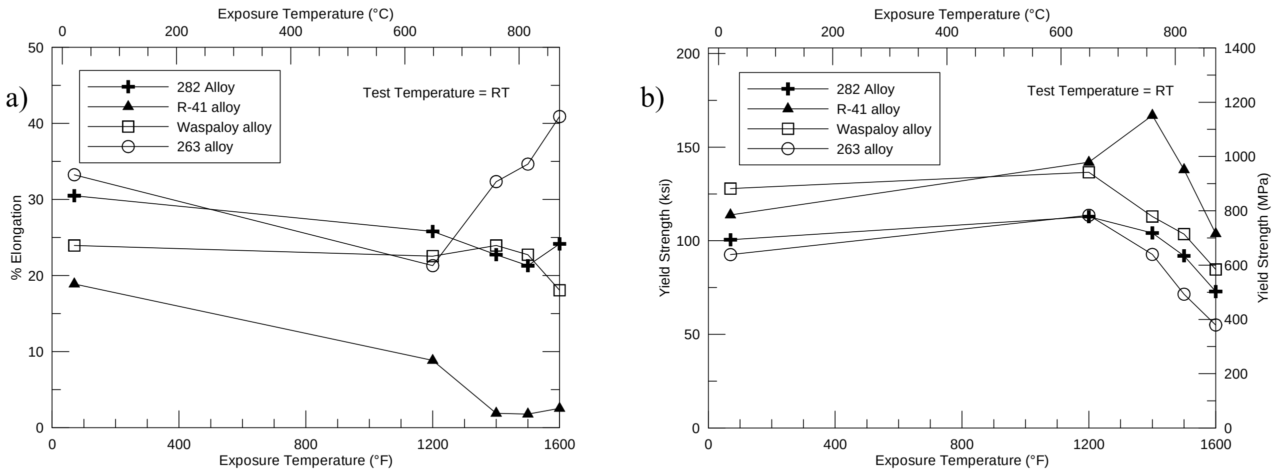

Fig. 1 Comparative RT tensile properties vs. thermal exposure temperature (1000-hour exposure). a) elongation, b) yield strength

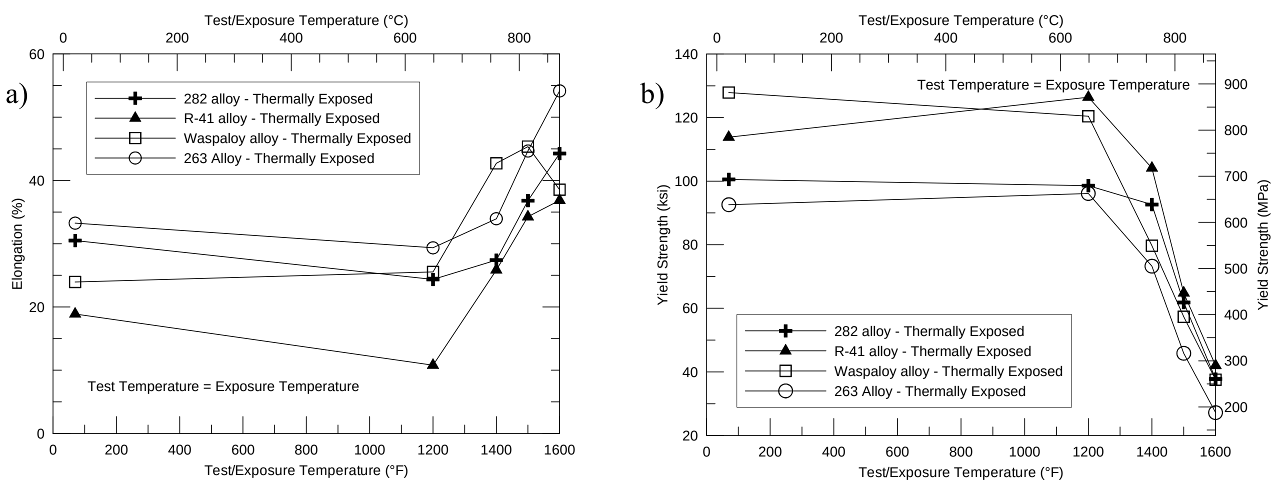

Fig. 2 Comparative ET tensile properties vs. thermal exposure temperature (1000-hour exposure). Tensile tests performed at the thermal exposure temperature. a) elongation, b) yield strength

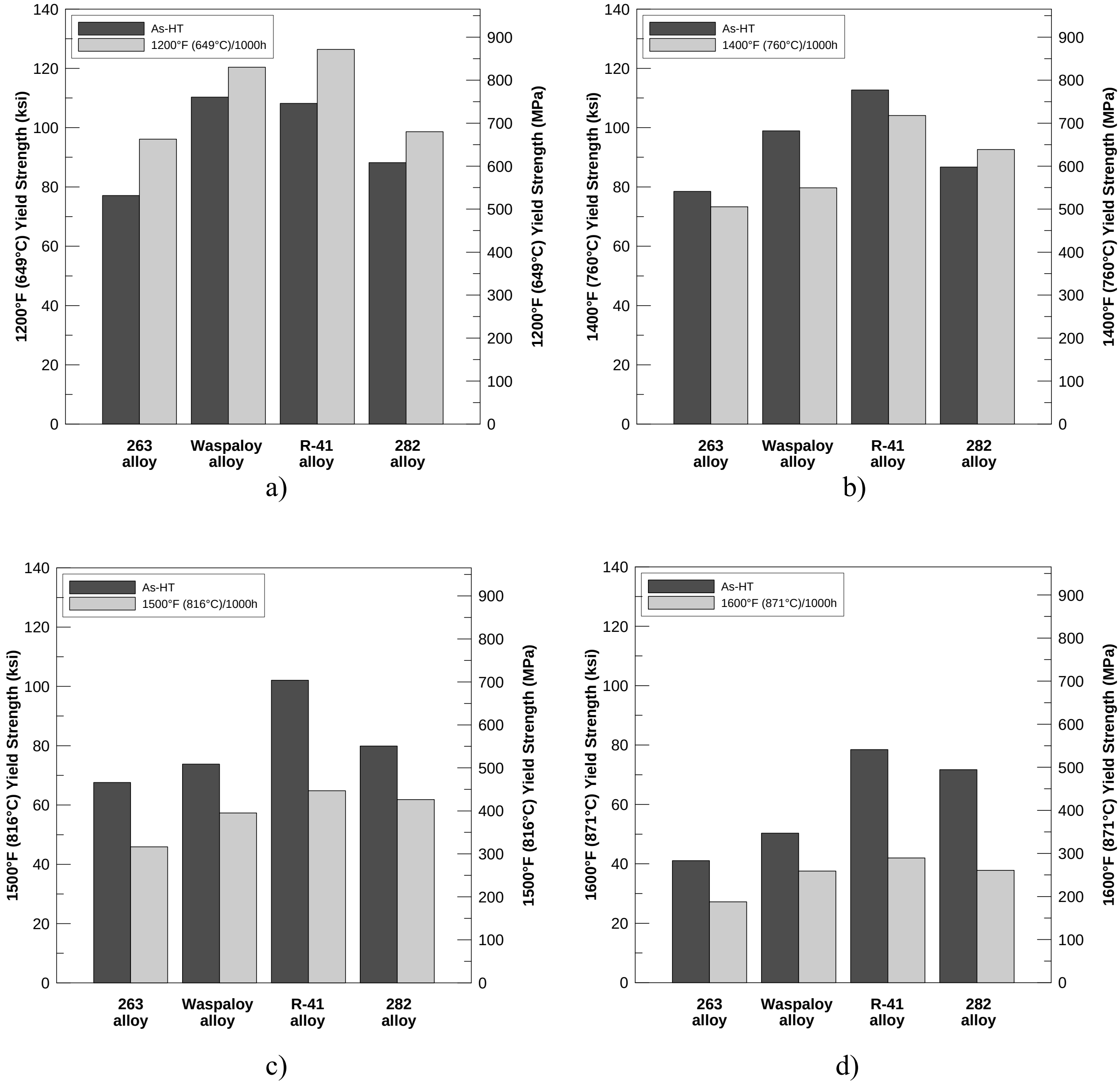

Fig. 3 Comparative ET yield strength of the four alloys before and after 1000-hour thermal exposure. Tensile tests performed at the thermal exposure temperature. a) 1200°F (649°C), b) 1400°F (760°C), c) 1500°F (816°C), d) 1600°F (871°C).

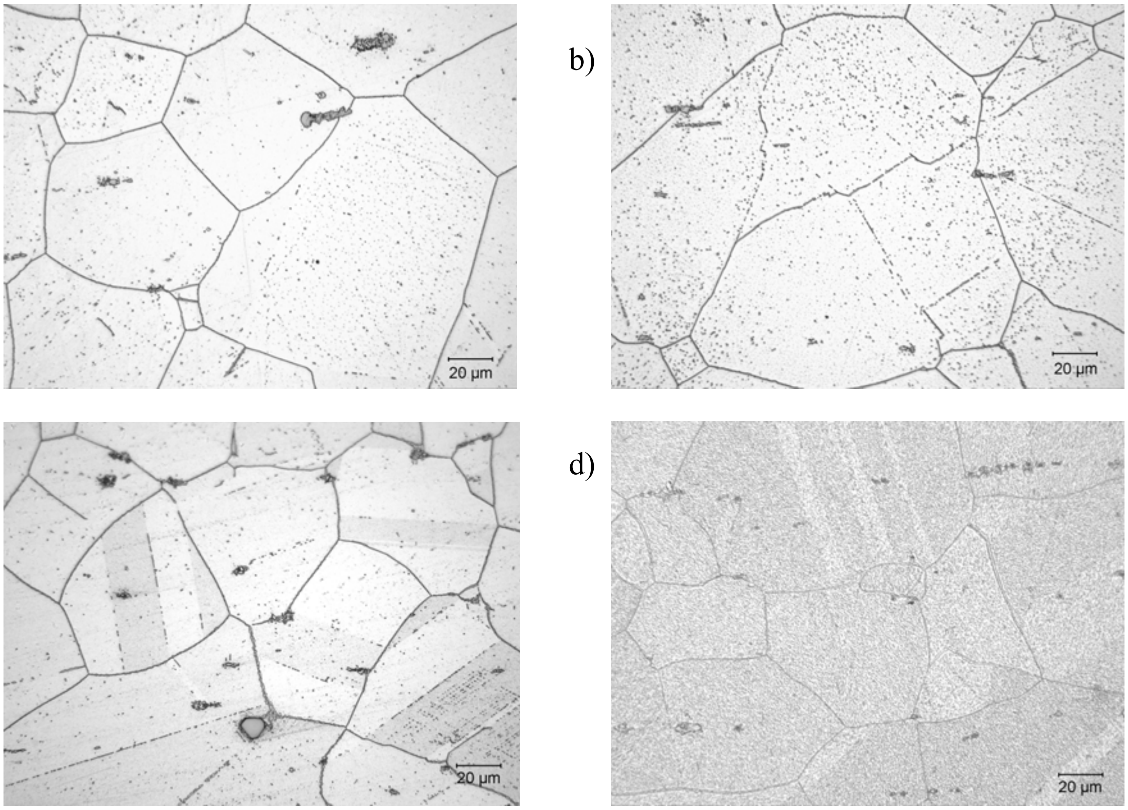

Fig. 4 Optical micrographs of thermally exposed 282 alloy (1000-hour exposure). a) 1200°F (649°C), b) 1400°F (760°C), c) 1500°F (816°C), d) 1600°F (871°C).

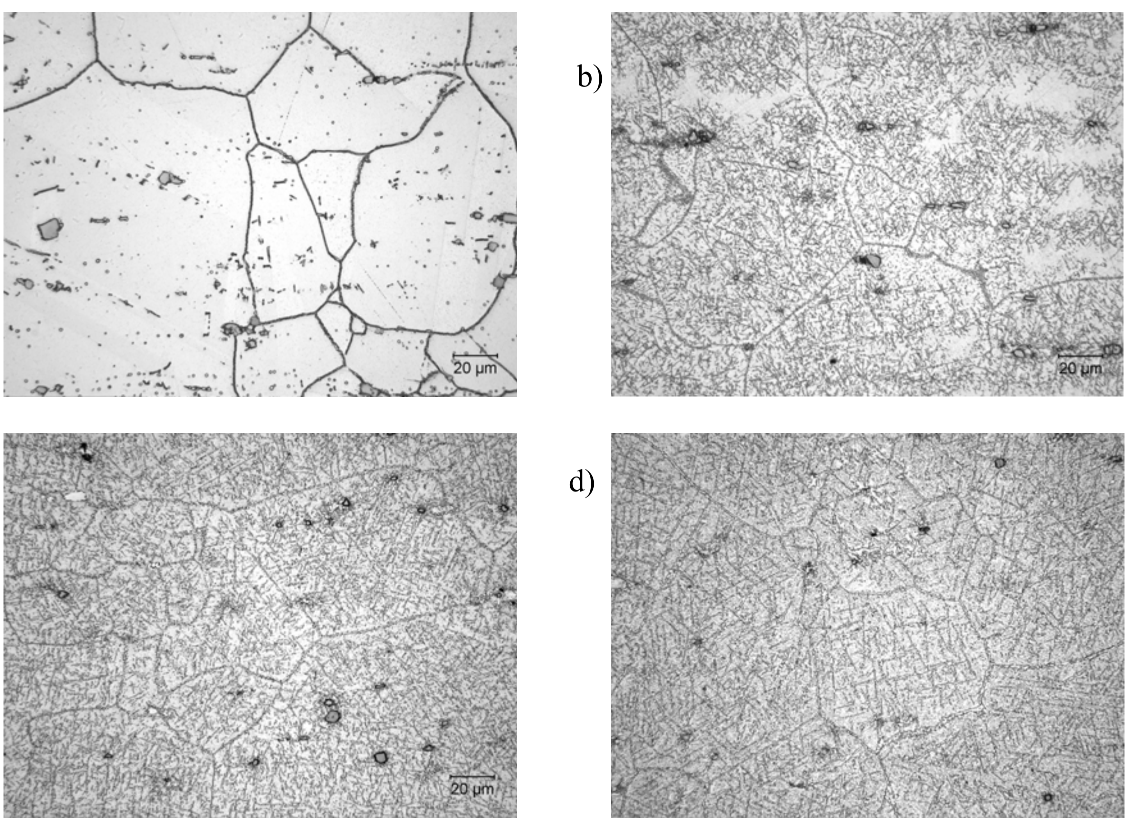

Fig. 5 Optical micrographs of thermally exposed R-41 alloy (1000-hour exposure). a) 1200°F (649°C), b) 1400°F (760°C), c) 1500°F (816°C), d) 1600°F (871°C).

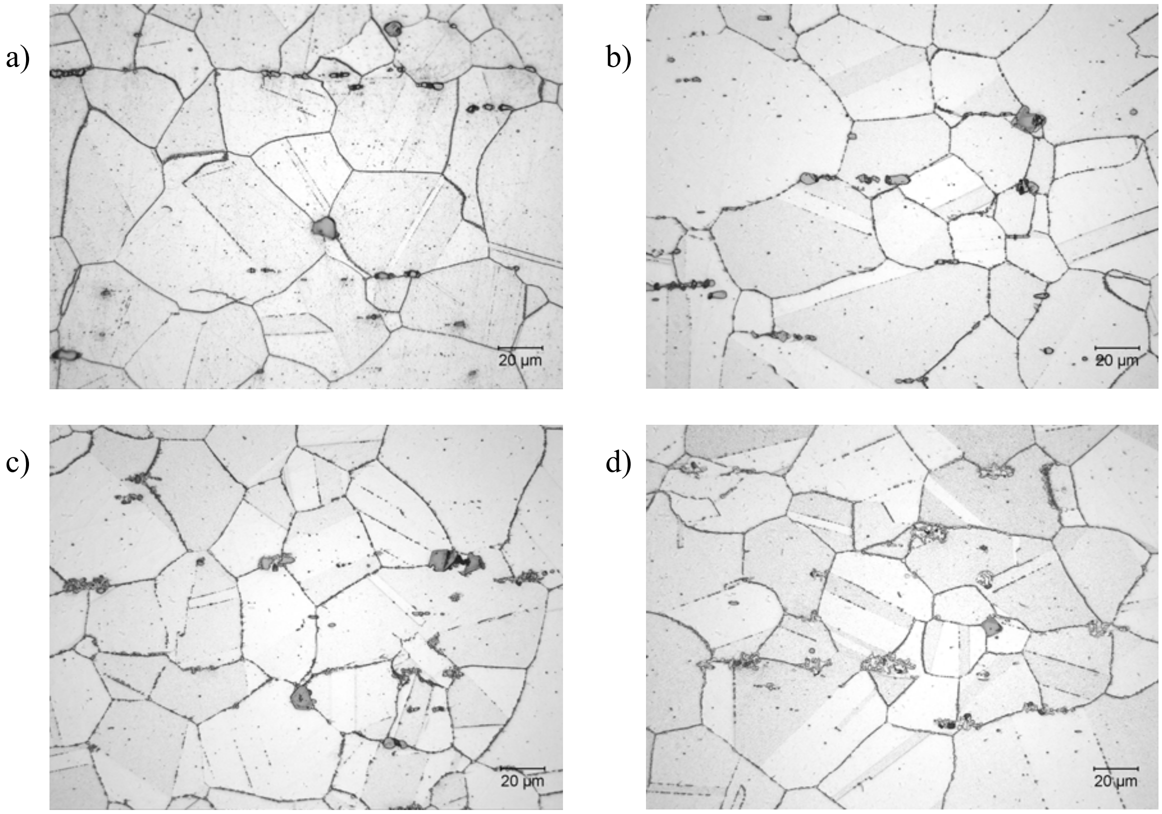

Fig. 6 Optical micrographs of thermally exposed Waspaloy alloy (1000-hour exposure). a) 1200°F (649°C), b) 1400°F (760°C), c) 1500°F (816°C), d) 1600°F (871°C).

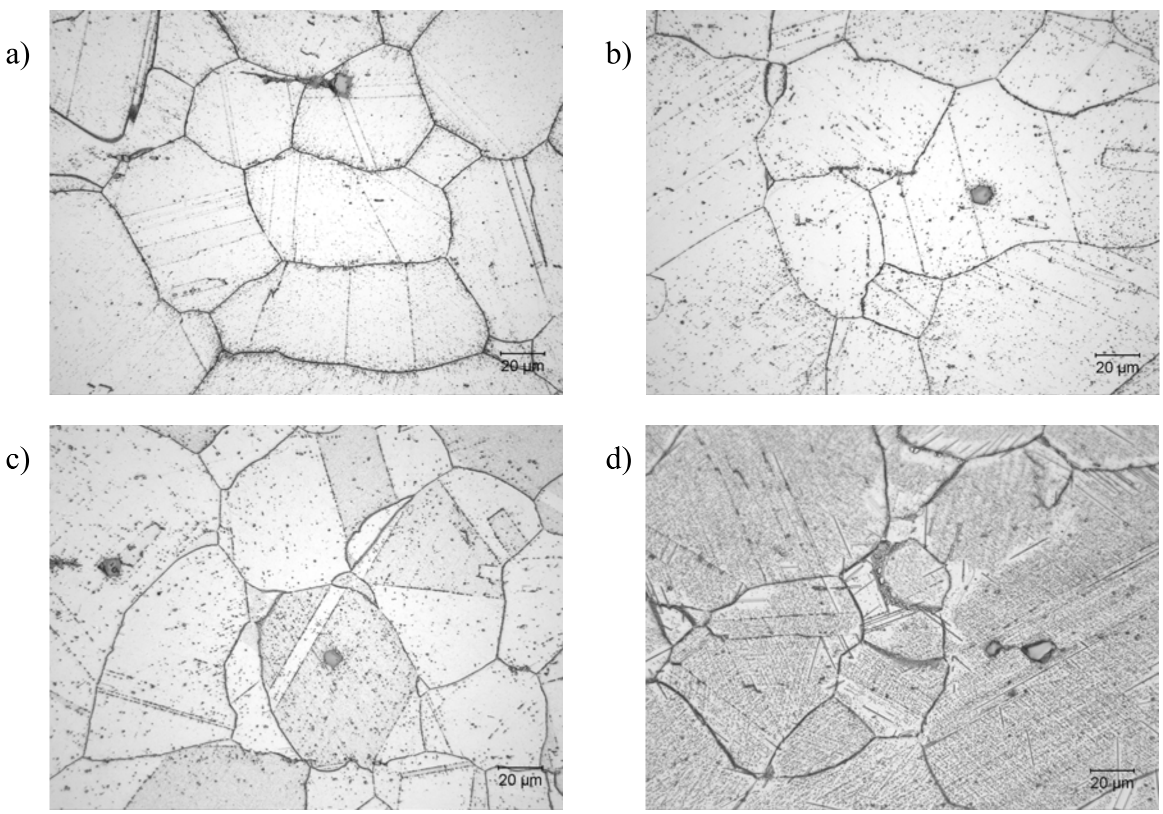

Fig. 7 Optical micrographs of thermally exposed 263 alloy (1000-hour exposure). a) 1200°F (649°C), b) 1400°F (760°C), c) 1500°F (816°C), d) 1600°F (871°C).

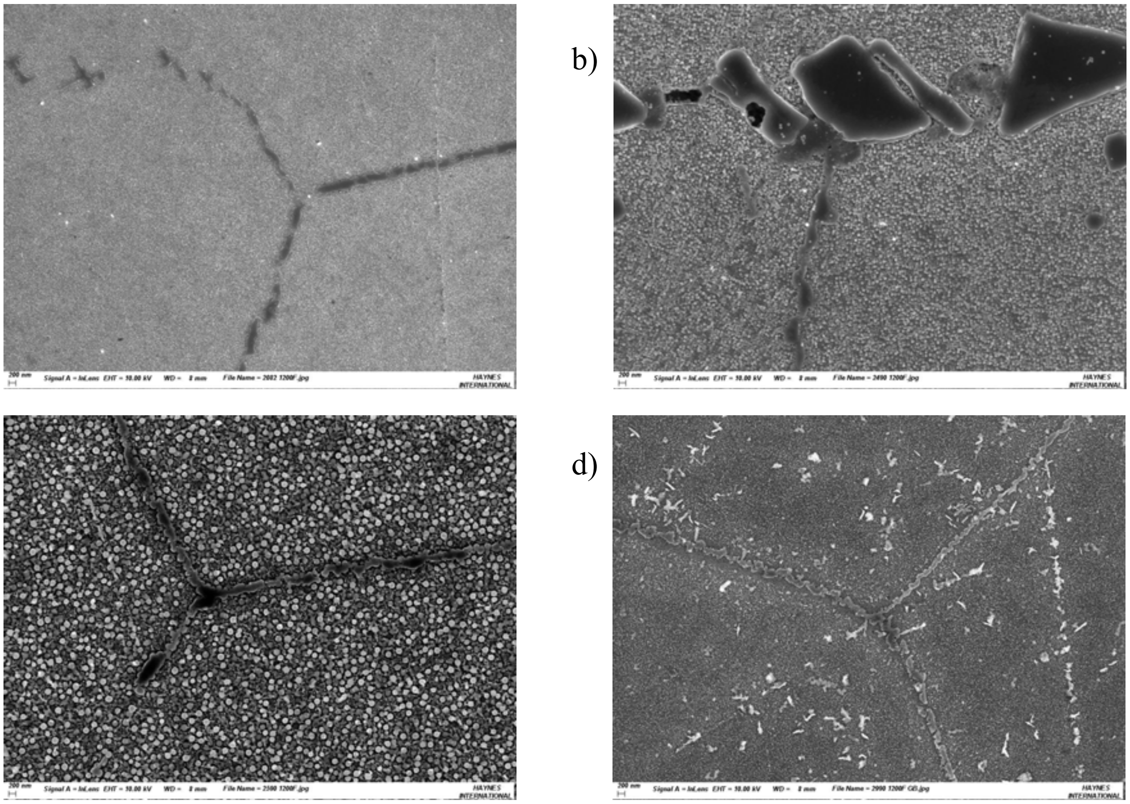

Fig. 8 SEM images (SE) of samples exposed at 1200°F (649°C)/1000-hour. a) 282 alloy, b) R-41 alloy, c) Waspaloy alloy, d) 263 alloy.

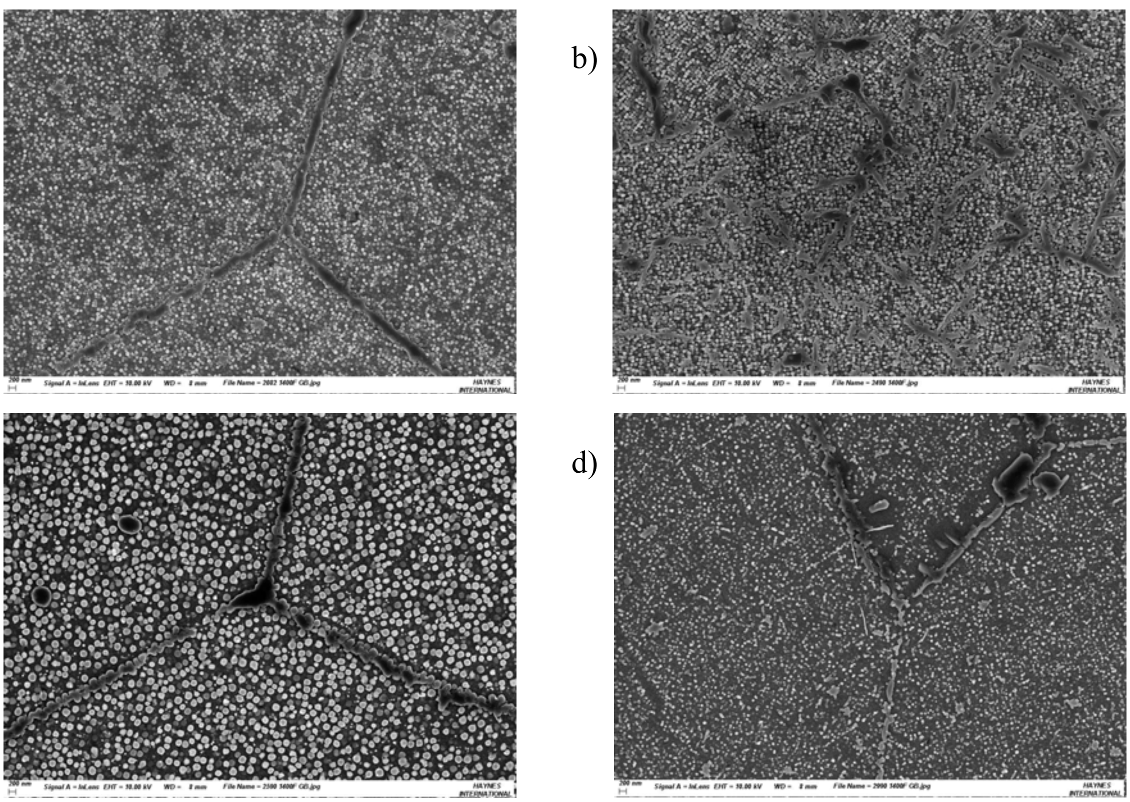

Fig. 9 SEM images (SE) of samples exposed at 1400°F (760°C)/1000-hour. a) 282 alloy, b) R-41 alloy, c) Waspaloy alloy, d) 263 alloy.

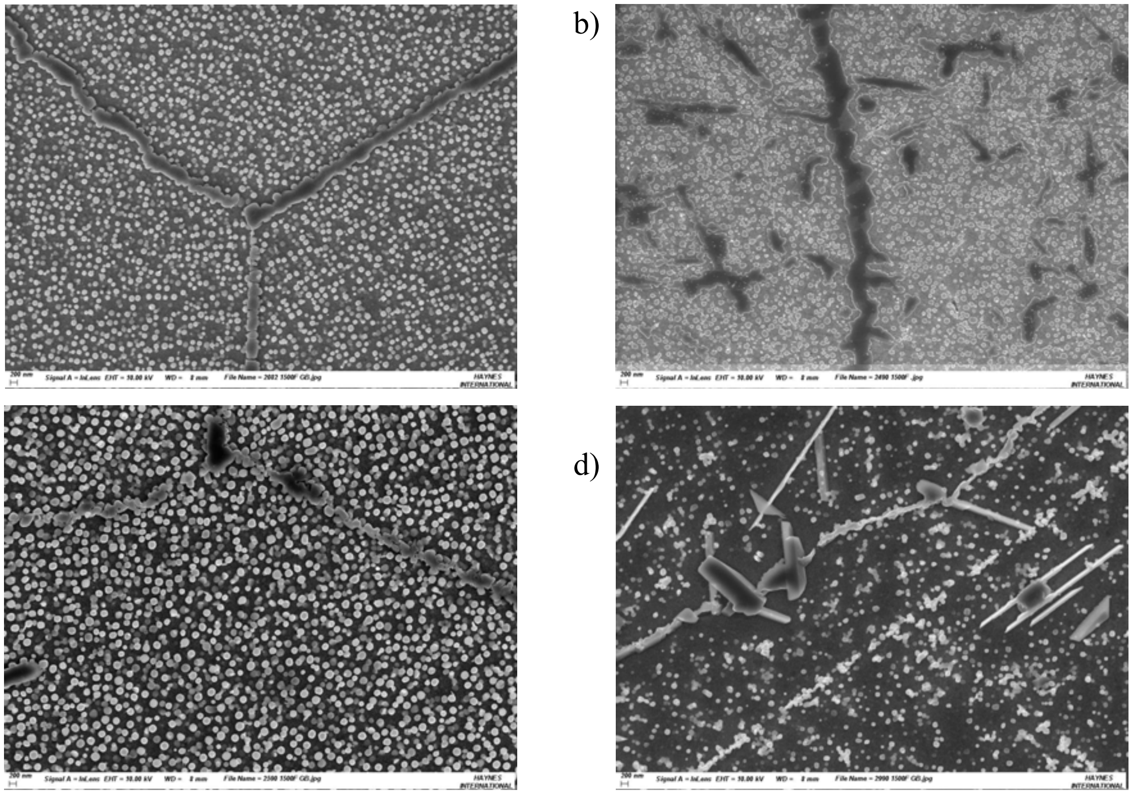

Fig. 10 SEM images (SE) of samples exposed at 1500°F (816°C)/1000-hour. a) 282 alloy, b) R-41 alloy, c) Waspaloy alloy, d) 263 alloy.

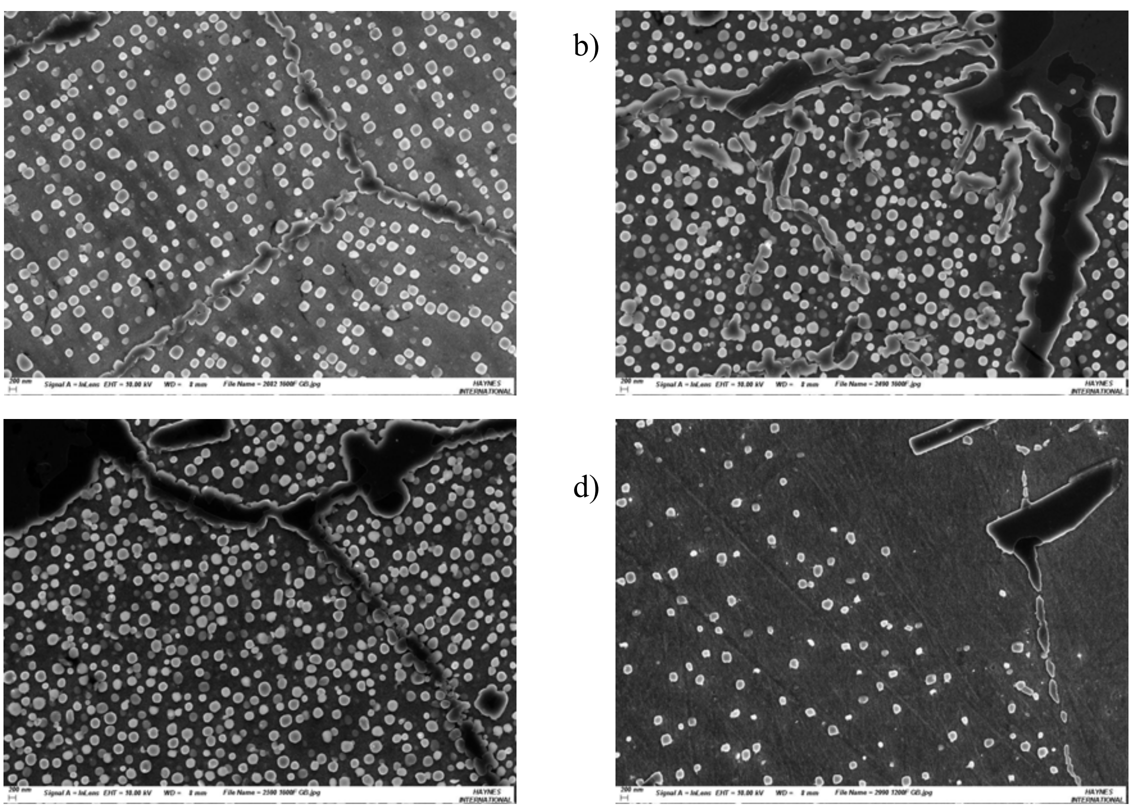

Fig. 11 SEM images (SE) of samples exposed at 1600°F (871°C)/1000-hour. a) 282 alloy, b) R-41 alloy, c) Waspaloy alloy, d) 263 alloy.

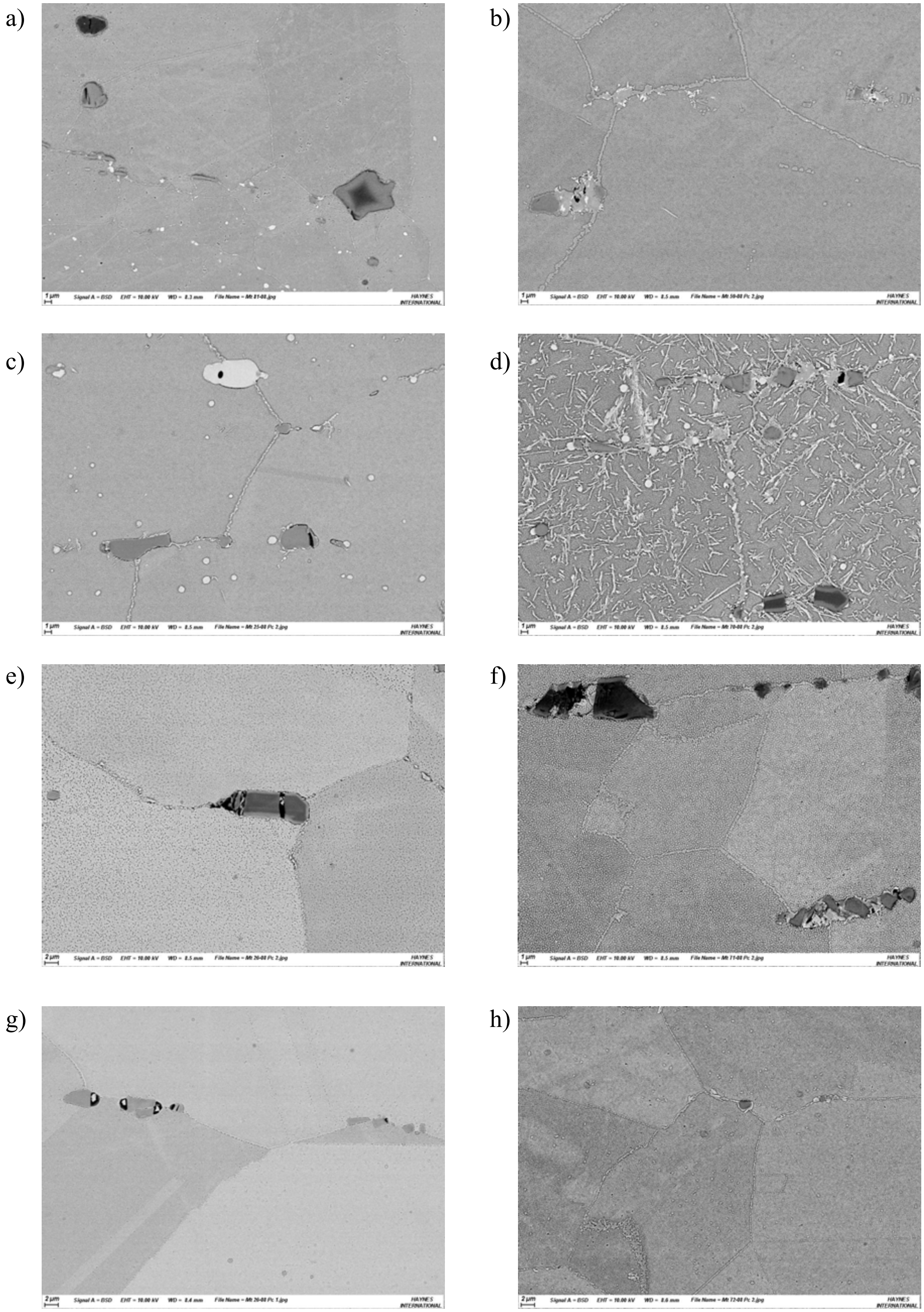

Fig. 12 SEM images (BSE). The images on the left are the as-HT condition and on the right are after the 1400°F (760°C)/1000-hour exposure. a) and b) 282 alloy, c) and d) R-41 alloy, e) and f) Waspaloy alloy, g) and h) 263 alloy.

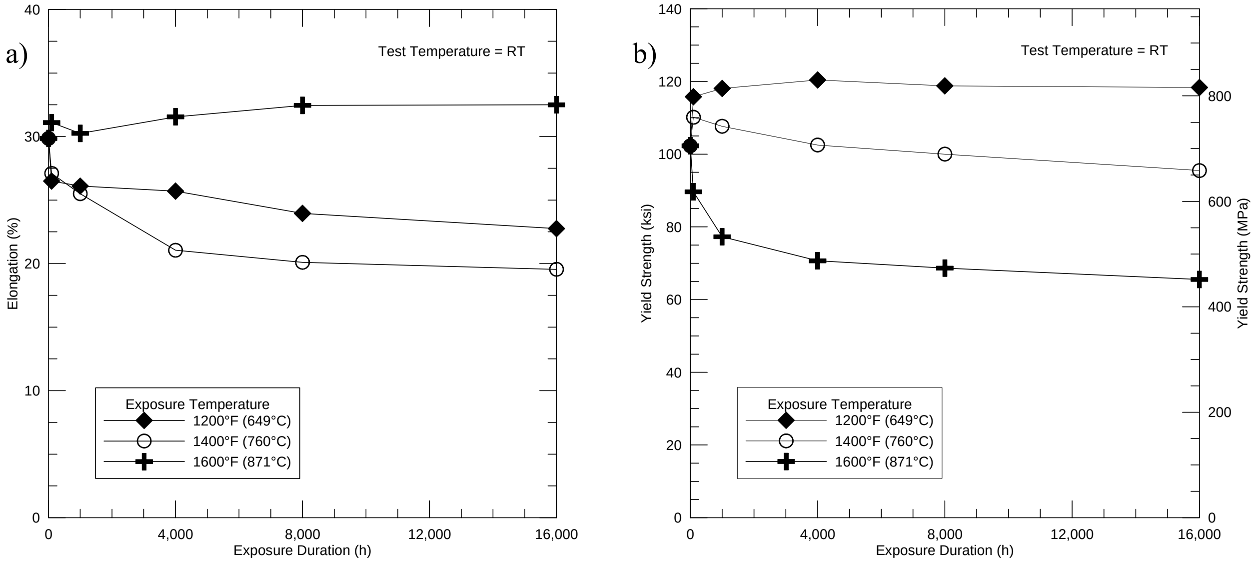

Fig. 13 RT tensile properties of 282 alloy vs. thermal exposure duration. a) elongation, b) yield strength

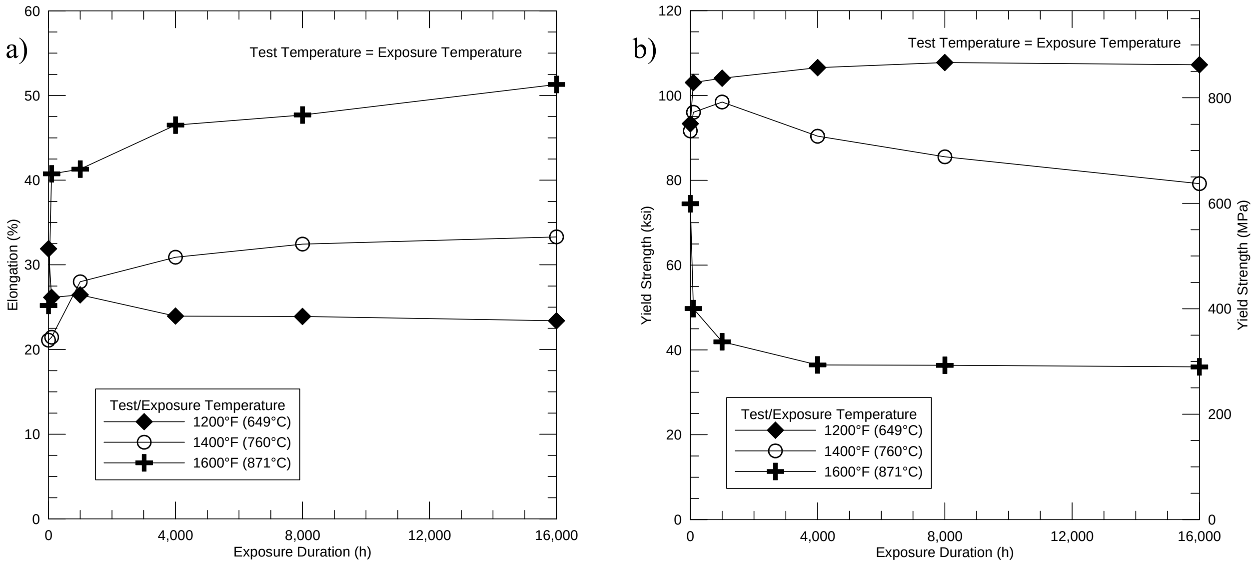

Fig. 14 ET tensile properties of 282 alloy vs. thermal exposure duration. Tensile tests performed at the thermal exposure temperature. a) elongation, b) yield strength

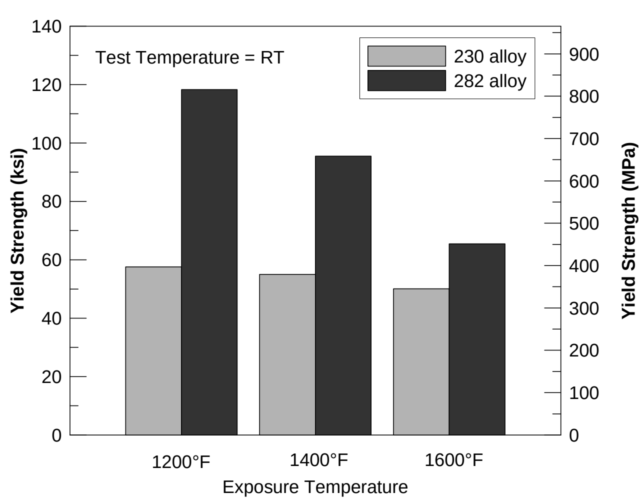

Fig. 15 RT yield strength after long term exposure: 230 alloy (20,000 hours), 282 alloy (16,000 hours).