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HAYNES® 282™ ALLOY - A NEW WROUGHT SUPERALLOY DESIGNED FOR IMPROVED CREEP STRENGTH AND FABRICABILITY

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ABSTRACT

A new wrought, gamma-prime strengthened superalloy, HAYNES 282 alloy, has been developed for high temperature structural applications, especially those in aero and land-based gas turbine engines. The new alloy possesses a unique combination of creep strength, thermal stability, and fabricability not found in currently available commercial alloys. The new alloy has excellent creep strength in the temperature range of 1200 to 1650°F (650 to 900°C), surpassing that of Waspaloy alloy and approaching that of R-41 alloy. This level of creep strength is realized despite the alloy having a significantly lower volume fraction of the strengthening gamma-prime phase. The lower gamma-prime content of the new alloy provides a considerable improvement in terms of fabricability and resistance to strain-age cracking, a problem often associated with this class of alloys. In this paper, the major characteristics and attributes of the new alloy including mechanical properties, oxidation resistance, thermal stability, and weldability are presented.

HAYNES and 282 are a registered trademark and a trademark of Haynes International, respectively.

INTRODUCTION

A number of wrought gamma-prime strengthened alloys are available commercially as flat products, typically in the form of cold rolled sheet and/or hot rolled plate. Most of these alloys, which include R-41, Waspaloy, 263, and X-750 alloys, have been around for a long time, dating back to between the 1930's and 1960's. Despite their age, the alloys are still produced in considerable volume. However, there are serious limitations which restrict their use in terms of both temperature capability and component fabricability. 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 and X-750 alloys, have much lower temperature capability due to a loss of strength. In the past, designers have worked around these limitations by restricting either the use temperature or the size/geometry of their components. However, the need for an alloy which would combine high temperature strength with excellent fabricability has long been recognized. To meet this need, an alloy development program was initiated at Haynes International. The objective of the program was to develop an alloy which would have creep strength approaching that of Waspaloy and R-41 alloys at temperatures around 1600°F (871°C), while having improved fabricability. Specifically, the alloy was to have significantly better resistance to post weld strain-age cracking. The end result of this alloy development program was HAYNES 282 alloy. The composition of 282 alloy is shown in Table 1 along with those of several other gamma-prime strengthened alloys.

PROCESSING

Several production scale heats of 282 alloy have been successfully processed. The 20,000 lb (9080 kg) heats were primary melted using vacuum induction melting (VIM) and secondary melted using electroslag remelting (ESR). The resulting ingots have been processed using several methods including hot forging and rolling as well as cold rolling and drawing. Product forms have included hot rolled plate and bar, cold rolled sheet, reforge billet, and wire. Several gauges of cold rolled sheet ranging in thickness from 0.023 to 0.125" (0.6 to 3.2 mm) from two separate production scale heats were used to generate the data for this paper.

METALLURGY AND HEAT TREATMENT

HAYNES 282 alloy is provided in the solution annealed condition. The typical solution annealing temperature of 282 alloy is in the range of 2025 to 2100°F (1107 to 1149°C). Sheet, such as that used in this study, would typically be "bright" annealed at 2100ºF (1149ºC) in a hydrogen furnace and gas cooled, resulting in an ASTM grain size of 4 to 4½. After solution annealing, the alloy is in a soft condition which is readily formable. The annealed microstructure includes scattered primary MC carbides and carbonitrides and has grain boundaries which are essentially free of precipitates.

After solution annealing, a two step age hardening treatment is required to put the alloy into the high strength condition. This two step treatment is: 1850°F (1010°C)/2 hours/AC (air cool) + 1450°F (788°C)/8 hours/AC. The first step of the heat treatment, which is above the gamma-prime solvus temperature of 1827ºF (997ºC), results in the formation of secondary $M_{23}C_6$ carbides, predominantly at the grain boundaries. The second step of the treatment results in the precipitation of gamma-prime and significant strengthening of the alloy. A micrograph of 282 alloy sheet in the age hardened condition is shown in Figure 1.

MECHANICAL PROPERTIES

The mechanical properties, including creep-rupture, tensile, and thermal stability, of HAYNES 282 alloy sheet are described in the following sections. For comparative purposes, corresponding data for R-41, Waspaloy, and 263 alloy sheet are included. With the exception of the thermal stability testing, the data for the latter three alloys were taken from Haynes internal reports. All of the material used in the testing of the comparison alloys was originally mill annealed sheet given the appropriate annealing temperature: R-41 alloy, 2050°F (1121°C); Waspaloy alloy, 1975°F (1079°C); 263 alloy, 2100°F (1149°C). Typical ASTM grain size ranges for these three alloys after the above annealing treatments are 6-7, 5-6, and 4-5 for the R-41, Waspaloy, and 263 alloys, respectively. The following age-hardening heat treatments were applied to the three alloys after solution annealing: R-41 alloy, 1650ºF (900ºC)/4h/AC; Waspaloy, 1825ºF (996ºC)/2h/AC + 1550ºF (843ºC)/2h/AC + 1400ºF (760ºC)/16h/AC, 263 alloy, 1472ºF (800ºC)/8h/AC.

Creep-Rupture

Creep-rupture testing was performed on 282 alloy in the age-hardened condition at temperatures ranging from 1200 to 1700ºF (650 to 927ºC). The majority of the testing was on 0.063” (1.6 mm) sheet, but a few tests were performed on other gauges. From the data, the stress values required to produce 1% creep and rupture in 100 and 1000 hours were determined and are given in Table 2 along with such values for age-hardened R-41, Waspaloy, and 263 alloys. Of the four alloys, 263 alloy had the lowest creep and rupture strength across the entire temperature range. The rupture strengths of 282 and Waspaloy alloys are about the same at 1200 to 1300ºF (650 to 704ºC), but at higher temperatures 282 alloy has a distinct advantage. In terms of 1% creep, the 282 alloy was found to be significantly stronger than Waspaloy over the entire temperature range of 1200 to 1700ºF (650 to 927ºC). When compared to R-41 alloy, the 282 alloy had a lower rupture strength in the temperature range of 1200 to 1400ºF (650 to 760ºC), but the two alloys had essentially the same rupture strengths at temperatures of 1500ºF (816ºC) or greater. Similarly, the R-41 alloy had slightly higher 1% creep strength at 1200 to 1400ºF (650 to 760ºC). Again, however, the distinction between 282 alloy and R-41 alloy disappeared at higher temperatures, with the 1% creep strength of the two alloys being virtually the same at temperatures of 1500ºF (816ºC) or greater. This can be seen clearly in Figure 2, in which the 1% creep lives of 282, R-41, Waspaloy, and 263 alloys are shown in a Larson-Miller plot. The plot shows experimental data points for samples tested between 1500 and 1700ºF (816 and 927ºC). In this plot it is clear that 282 and R-41 alloys have virtually the same creep strength, while both alloys are clearly stronger than Waspaloy and 263 alloys.

Tensile

Tensile testing was performed on several gauges of 282 alloy sheet from two different production scale heats. The results are given in Table 3. The yield strength of 282 alloy as a function of temperature is shown in Figure 3. The yield strength decreased only gradually from room temperature up to around 1400°F (760ºC). At temperatures between 1400 and 1600°F (760 and 871ºC) , the decline in the yield strength with temperature was more rapid, but still relatively gradual. However, at temperatures greater than 1600°F (871ºC) the yield strength dropped rapidly with increasing temperature.

Also shown in Figure 3 is the yield strength of sheet products of R-41, Waspaloy, and 263 alloys. At room temperature, the yield strength of 282 alloy was lower than that of R-41 and Waspaloy alloys, but greater than that of 263 alloy. As with 282 alloy, the yield strengths of R-41, Waspaloy, and 263 alloys decreased only slightly with temperature up to 1400ºF (760ºC). However, at temperatures greater than 1400ºF (760ºC) the yield strength of both Waspaloy and 263 alloys dropped off sharply with increasing temperature. Only R-41 alloy exhibited a more gradual decrease in the 1400 to 1600ºF (760 to 871ºC) range similar to that seen for 282 alloy. With the sharp drop in yield strength of Waspaloy above 1400ºF (760ºC), the relative strength of the alloys changed with 282 alloy having greater strength than Waspaloy alloy at 1600ºF (871ºC).

The tensile elongation of 282 alloy is shown in Figure 4 as a function of temperature. The elongation is seen to slightly increase with temperature up to around 1000ºF (538ºC). An intermediate temperature ductility minimum can be observed between 1000 and 1700ºF (538 and 927ºC), with a minimum of 19% at 1400 to 1500ºF (760 to 816ºC). At greater temperatures the elongation increases rapidly. The elongations of R-41, Waspaloy, and 263 alloys are also plotted in Figure 4. The elongation of 263 alloy was quite high, being greater than 30% for all temperatures. In contrast, the elongations of R-41 and Waspaloy dropped to as low as around 11% in the intermediate temperature range.

Thermal Stability

The thermal stability of 282 alloy was investigated using thermal exposures of 1000 hours at temperatures of 1200, 1400, and 1600ºF (650, 760, and 871ºC). The thermal exposures were applied to material initially in the age-hardened condition. After the thermal exposure, samples were given a room temperature tensile test to determine their retained ductility. The results are given in Table 4. The retained ductility for 282 alloy was found to be greater than 22% for all three exposure temperatures, suggesting that it has excellent thermal stability at least out to 1000 hours. For comparison, thermal stability testing was conducted on sheet material of R-41, Waspaloy, and 263 alloys. A thermal exposure of 1000 hours at 1600ºF (871ºC) was given to all three alloys subsequent to the appropriate age-hardening treatment for each alloy. The results are also given in Table 4. A dramatic loss of retained ductility was observed for R-41 alloy, which had a room temperature elongation of only 2.6%. This embrittlement resulted from the formation of the brittle sigma and mu phases, which have been reported by other investigators to be present in thermally exposed R-41 alloy [1-3]. The retained ductility of Waspaloy alloy dropped to 12.8% after the thermal exposure, despite the fact that brittle phases have not been found in thermally exposed samples [2-3]. In contrast, the retained ductility of 263 alloy was quite high, being greater than 40% after the thermal exposure. This 1000 hour thermal stability data is considered preliminary, and thermal exposures of up to 16,000 hours are currently underway.

FABRICABILITY

Resistance to Strain-Age Cracking

HAYNES 282 alloy was designed to have excellent resistance to strain-age cracking compared to other high-strength gamma-prime alloys. Strain-age cracking typically occurs during heat up in the first post-weld heat treatment (usually a solution anneal) of a welded component. The cracking has been associated with residual stresses in the material which are created by shrinkage due the solidification of the weld metal and to the formation of gamma-prime during the post-weld heat treatment. The use of many tests developed to determine the susceptibility of alloys to strain-age cracking is hindered by difficulties such as high cost, lack of reproducibility, and lack of ease. One test which can be performed without these difficulties is the controlled heating rate tensile (CHRT) test developed at Rocketdyne in the late 1960's [4]. The CHRT test was found to successfully identify individual heats of R-41 alloy which had greater susceptibility to strain age cracking as determined using the more difficult and costly circular patch test. More recently, a study of several gamma-prime strengthened sheet alloys was conducted by M.D. Rowe at Haynes International [5]. In the CHRT test, the sample is heated to the test temperature at a rate chosen to simulate the heat up during the first heat treatment after welding. The sample is originally in the solution annealed condition (little to no gamma-prime present) so that gamma-prime precipitates continuously during the test. A range of test temperatures are chosen (typically between 1400 and 1600ºF (760 to 871ºC)) and the strain-age cracking resistance of a given alloy is taken to be related to the minimum elongation observed in that temperature range. A great advantage of the CHRT test over other test methods for evaluating susceptibility of alloys to strain-age cracking is that it has a quantitative result (minimum elongation) which can be used to compare alloys, rather than a less useful pass/fail result.

Controlled heating rate tensile tests were performed on two different production scale heats of 282 alloy sheet. For consistency with the study of Rowe [5] all testing was done on 0.063" (1.6 mm) sheet. The sample surface was lightly ground to remove any oxide formed during the age-hardening heat treatment. The results are shown in Figure 5, where each data point represents an average of duplicate tests on each of the two heats. Also shown in Figure 5 are the data from the Rowe study for R-41, Waspaloy, and 263 alloys. In the plot, it is evident that the R-41 and Waspaloy alloys (both of which are well known to be susceptible to strain-age cracking) have minimum elongations less than 5%. In contrast, 282 alloy has a minimum elongation of around 14%, which suggests the alloy is very resistant to strain-age cracking. The 263 alloy had the best performance of the four alloys in the CHRT test, as might be expected from its reputation as being readily weldable.

The susceptibility of alloys to strain-age cracking is strongly dependent on the amount of gamma-prime forming elements, such as Al and Ti [5]. This relationship was reflected in the CHRT data, with the more susceptible R-41 and Waspaloy alloys having higher levels of Al + Ti than does 282 alloy, which in turn has more than 263 alloy.

Formability

In the solution annealed condition, 282 alloy has excellent formability characteristics, particularly when compared to higher gamma-prime containing alloys such as R-41 and Waspaloy alloys. Typical room temperature yield strength values for solution annealed 282, R-41, Waspaloy, and 263 alloy mid-gauge sheet (0.060 to 0.125" (1.5 to 3.2 mm)) produced by Haynes International are given in Table 5. From this data, it is clear that both 282 and 263 alloys have a significantly lower yield strength in the solution annealed condition than the R-41 and Waspaloy alloys, indicating greater formability for the former two alloys. This suggests that in the solution annealed condition, little to no gamma-prime is present in the former two alloys relative to the latter two. This is a noteworthy result in light of the fact that both 282 and 263 alloys are cooled from the annealing temperature at a much slower rate (gas cool vs. water quench) than R-41 and Waspaloy alloys. The slower age-hardening kinetics of the 282 and 263 alloys can be attributed the lower content of gamma-prime forming elements (Al and Ti) relative to the R-41 and Waspaloy alloys. Also shown in Table 5 are the typical ultimate tensile strength and elongation of the alloys in the annealed condition. Again, the high elongation of 282 alloy as well as 263 alloy, indicates that these alloys have significantly better formability that the Waspaloy and R-41 alloys. Initial sheet cold forming trials with 282 alloy have confirmed formability expectations based on the tensile data.

OXIDATION RESISTANCE

The oxidation resistance of 282 alloy was investigated with a static oxidation test at 1700ºF (927ºC). For comparative purposes, the test was also performed on R-41, Waspaloy, and 263 alloys. The testing was performed for 1008 hours in a flowing air environment. The samples were cycled to room temperature once a week (total of 6 cycles). Duplicate samples were included for each alloy, for a total of eight samples. After testing, the oxide was chemically descaled from the samples. The samples were weighed and the metal loss was calculated from the weight change. The descaled samples were mounted in metallographic mounts and examined to measure internal oxidation. The metal loss was calculated from the weight loss, and the average and maximum internal penetrations were determined as shown in Figure 6. The average and maximum metal affected values were calculated as the sum of the metal loss and the average and maximum internal penetrations, respectively. The results of the testing are given in Table 6.

The metal loss was very low and essentially the same for all four alloys in the test, ranging from 0.1 to 0.3 mils (3 to 8 μm). A somewhat more significant difference in the alloys was observed in the internal penetration measurements, with values of 1.6 to 1.8 mils (41 to 46 μm) recorded for the 282 and R-41 alloys, and values of 2.9 to 3.4 mils (74 to 86 μm) recorded for the 263 and Waspaloy alloys. Similar results were found for the maximum metal affected values. In summary, the static oxidation resistance of 282 alloy would appear to be similar to or slightly better than the other alloys in its family at this temperature. More extensive oxidation testing of the alloy, including dynamic oxidation testing, is currently in progress and will be reported later.

SUMMARY

A new gamma-prime strengthened superalloy, HAYNES 282 alloy, has been developed and recently introduced into the marketplace. This alloy was designed to have excellent creep resistance at temperatures around 1600ºF (871ºC), while also having superior thermal stability, and fabricability (particularly with regard to strain-age cracking). Several full scale heats of the new alloy have produced and evaluated. The new alloy was found to have creep strength which surpassed 263 and Waspaloy alloys at temperatures from 1200 to 1700ºF (650 to 927ºC), and was equivalent to R-41 alloy at temperatures from 1500 to 1700ºF (816 to 927ºC). The new alloy has excellent thermal stability, having a high retained ductility after 1000 hour exposures at 1200, 1400, and 1600ºF (650, 760, and 871ºC). This in contrast to R-41 alloy (and to a lesser extent Waspaloy alloy), which had a severe loss of ductility after the 1600ºF (871ºC) exposure. The fabricability of the alloy is very good, with room temperature tensile properties suggesting excellent cold formability, and with a very satisfactory performance in the CHRT test, a test designed to evaluate resistance to strain age cracking. The oxidation resistance of the new alloy at 1700ºF (927ºC) was found to be comparable to or better than other alloys in its family. The metallurgy, processing, heat treatment, and tensile properties of the new alloy were also presented.

ACKNOWLEDGEMENTS

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Table 1 Nominal Composition of Several Wrought Gamma-Prime 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 Stress to Produce 1% Creep and Rupture in 100 and 1000 Hours for Several Gamma-Prime Alloys - Sheet

Property	Test Temperature		263 Alloy	R-41 Alloy	Waspaloy Alloy	282 Alloy
	°F	°C				
Stress-to-Produce 1% Creep, in 100 h ksi (MPa)	1200	649	75 (517)	105 (724)	81 (558)	--
	1300	704	54 (372)	75 (517)	63 (434)	75 (517)
	1400	760	37 (255)	53 (365)	41 (283)	48 (331)
	1500	816	22 (152)	32 (221)	25 (172)	32 (221)
	1600	871	11 (76)	17 (117)	15 (103)	18 (124)
	1700	927	6 (41)	8 (55)	6 (41)	9 (62)
Stress-to-Produce 1% Creep, in 1000 h ksi (MPa)	1200	649	58 (400)	84 (579)	67 (462)	80 (552)
	1300	704	41 (283)	59 (407)	46 (317)	53 (365)
	1400	760	25 (172)	34 (234)	28 (193)	35 (241)
	1500	816	12 (83)	18 (124)	16 (110)	21 (145)
	1600	871	6 (41)	9 (62)	7 (48)	10 (69)
	1700	927	3 (21)	5 (34)	3 (21)	5 (34)
Stress-to-Produce Rupture, in 100 h ksi (MPa)	1200	649	77 (531)	110 (758)	92 (634)	--
	1300	704	60 (414)	85 (586)	75 (517)	--
	1400	760	42 (290)	63 (434)	53 (365)	56 (386)
	1500	816	25 (172)	39 (269)	32 (221)	37 (255)
	1600	871	14 (97)	23 (159)	19 (131)	22 (152)
	1700	927	7 (48)	13 (90)	10 (69)	12 (83)
Stress-to-Produce Rupture, in 1000 h ksi (MPa)	1200	649	64 (441)	90 (621)	80 (552)	80 (552)
	1300	704	45 (310)	68 (469)	58 (400)	57 (393)
	1400	760	28 (193)	43 (296)	36 (248)	38 (262)
	1500	816	15 (103)	24 (165)	20 (138)	23 (159)
	1600	871	7 (48)	13 (90)	7 (48)	13 (90)
	1700	927	4 (28)	7 (48)	3 (21)	7 (48)

Table 3 Tensile Properties of HAYNES 282 alloy - Sheet

Temperature		0.2% Yield Strength		Ultimate Tensile Strength		Elongation
°F	°C	ksi	MPa	ksi	MPa	%
RT	RT	100.0	690	163.8	1129	31
200	93	95.3	657	157.1	1083	31
400	204	91.0	627	154.3	1064	34
600	316	90.7	625	145.9	1006	36
800	427	90.7	625	141.0	972	37
1000	538	89.6	618	137.4	947	36
1200	649	89.2	615	143.2	988	26
1300	704	90.5	624	136.5	941	24
1400	760	86.8	598	119.1	821	19
1500	816	79.9	551	98.2	677	19
1600	871	70.6	487	79.3	547	27
1700	927	43.9	302	50.2	346	37
1800	982	18.2	125	24.1	166	58

Table 4 Room Temperature Tensile Ductility After Long Term Thermal Exposure

Alloy	% Elongation after 1200°F/1000 hours	% Elongation after 1400°F/1000 hours	% Elongation after 1600°F/1000 hours
263 alloy	--	--	40.9
282 alloy	25.8	22.8	22.9
Waspaloy alloy	--	--	12.8
R-41 alloy	--	--	2.6

Table 5 Average Room Temperature Data – Mill Annealed Sheet

Alloy	0.2% Yield Strength		Ultimate Tensile Strength		Elongation
	ksi	MPa	ksi	MPa	%
282 alloy	58	402	121	835	56
263 alloy	48	327	116	798	58
Waspaloy alloy	71	490	135	930	46
R-41 alloy	86	592	152	1047	39

Table 6 Static Oxidation Test at 1700ºF (927ºC)/ 1008 hours

Alloy	Metal Loss mils (µm)	Avg. Internal Penetration mils (µm)	Max. Internal Penetration mils (µm)	Avg. Metal Affected mils (µm)	Max. Metal Affected mils (µm)
282 Alloy	0.1 (3)	1.0 (25)	1.8 (46)	1.1 (28)	1.9 (49)
R-41 Alloy	0.2 (5)	1.3 (33)	1.6 (41)	1.5 (38)	1.8 (46)
Waspaloy alloy	0.3 (8)	3.1 (79)	3.4 (86)	3.4 (86)	3.7 (94)
263 Alloy	0.2 (5)	0.6 (15)	2.9 (74)	0.8 (20)	3.1 (79)

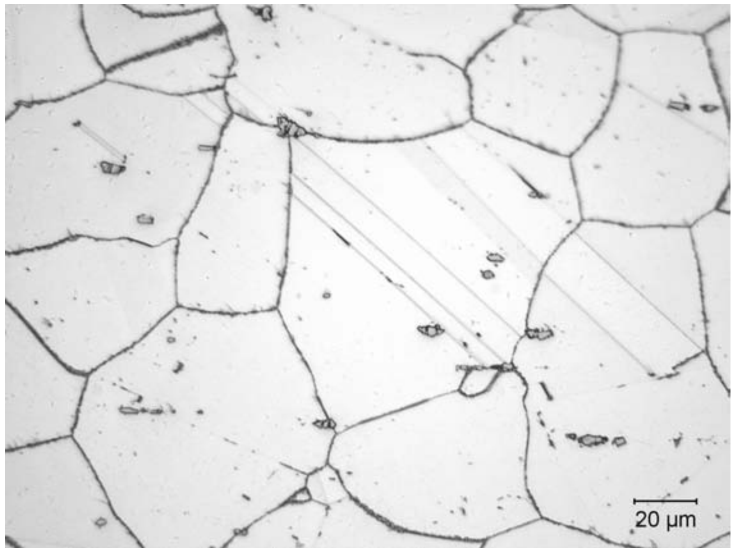


Figure 1. Typical microstructure of age-hardened HAYNES 282 alloy sheet

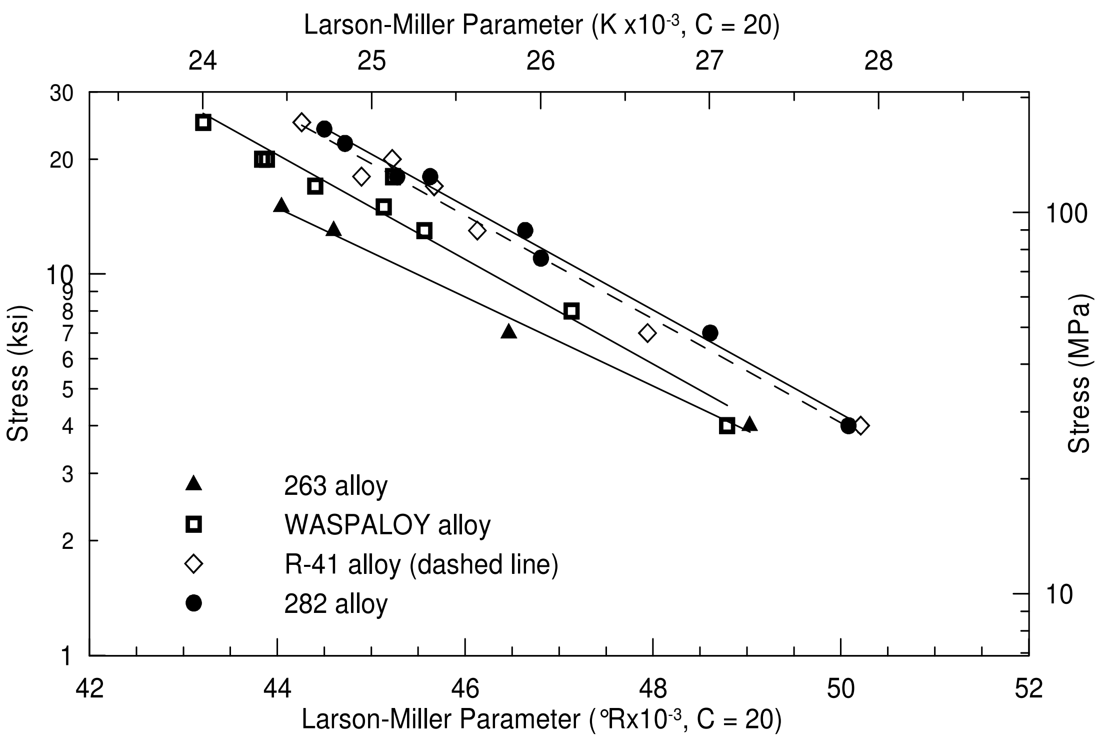


Figure 2. Comparative 1% Creep Data at 1500 to 1700ºF (816 to 927ºC) – Age Hardened Sheet

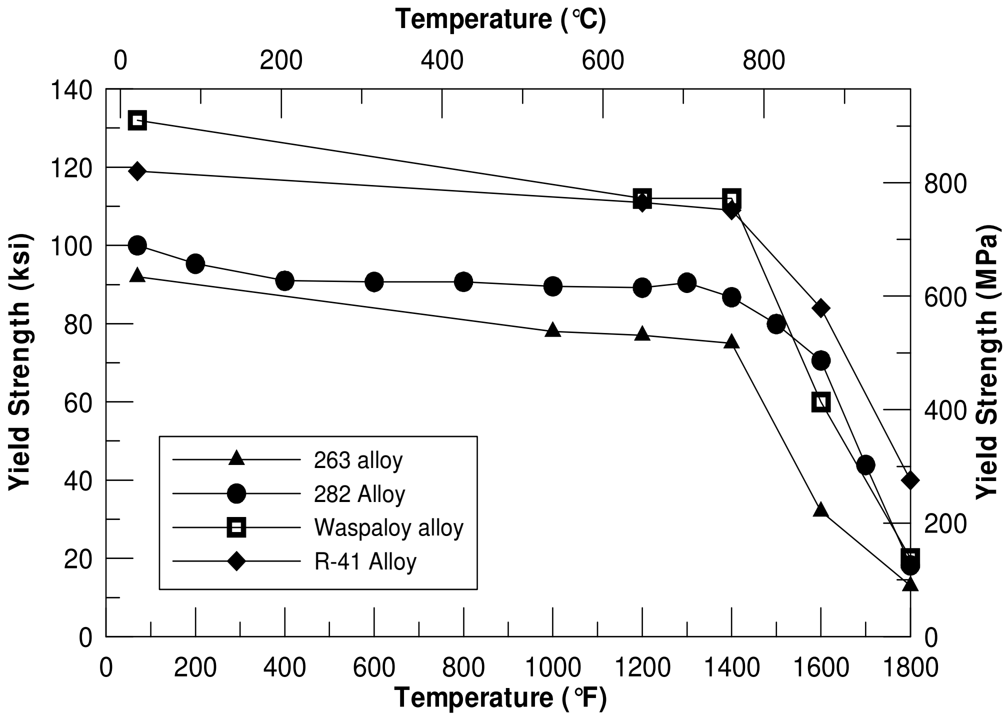


Figure 3. Comparative Yield Strength – Age Hardened Sheet

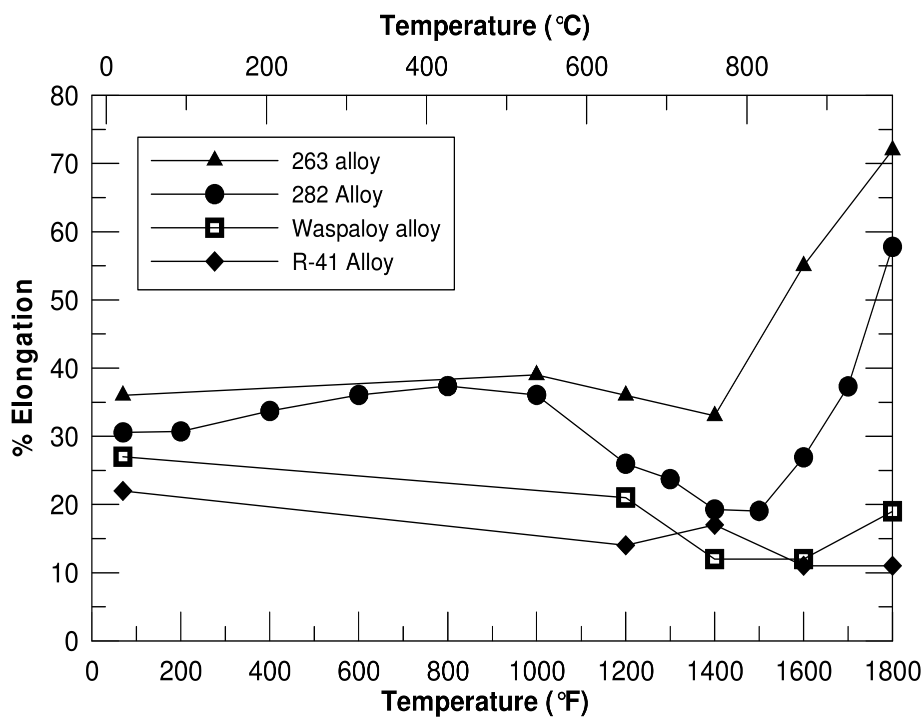


Figure 4. Comparative Tensile Elongation – Age Hardened Sheet

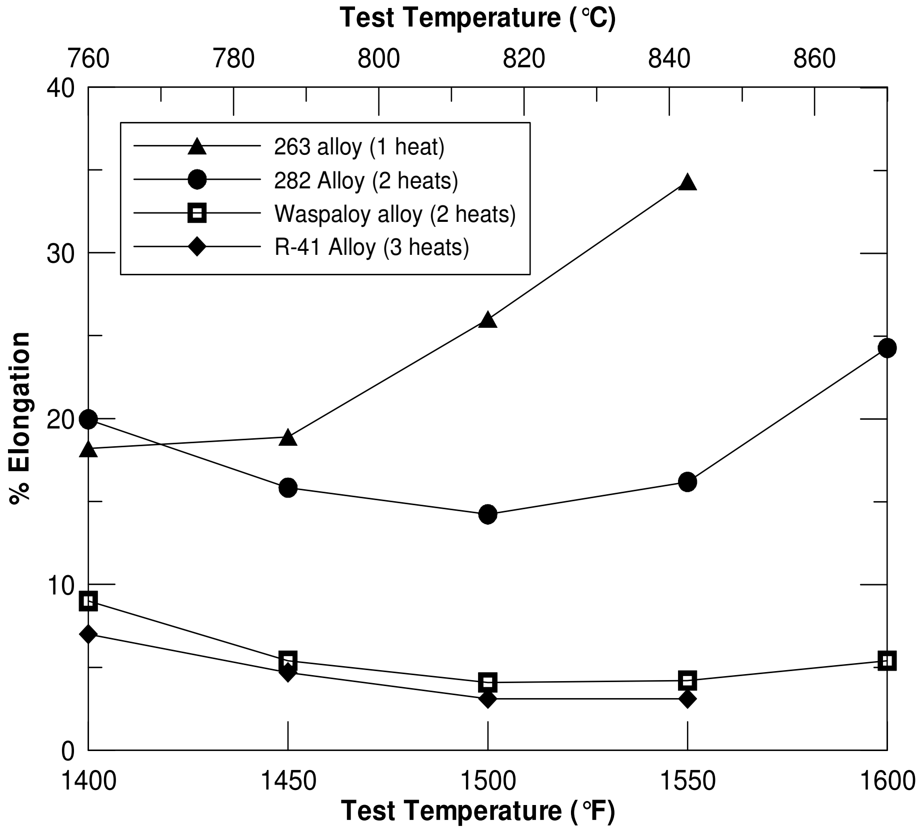
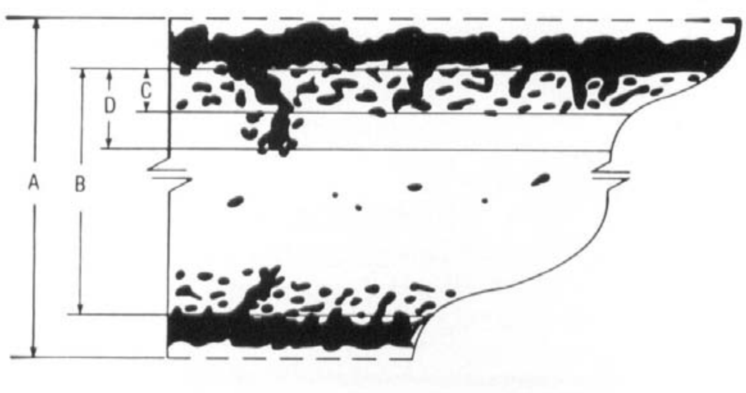


Figure 5. Comparative CHRT Test Results - Sheet



Metal Loss = (A-B)/2
Avg. Internal Penetration = C
Max. Internal Penetration = D
Avg. Metal Affected = Metal Loss + Avg. Internal Penetration
Max. Metal Affected = Metal Loss + Max. Internal Penetration

Fig 6 Schematic diagram illustrating the metallographic measurements of oxidation attack.