INDUSTRIAL HEATING

Heat & Corrosion Resistant Materials

Selecting an Appropriate Heat-Resistant Alloy

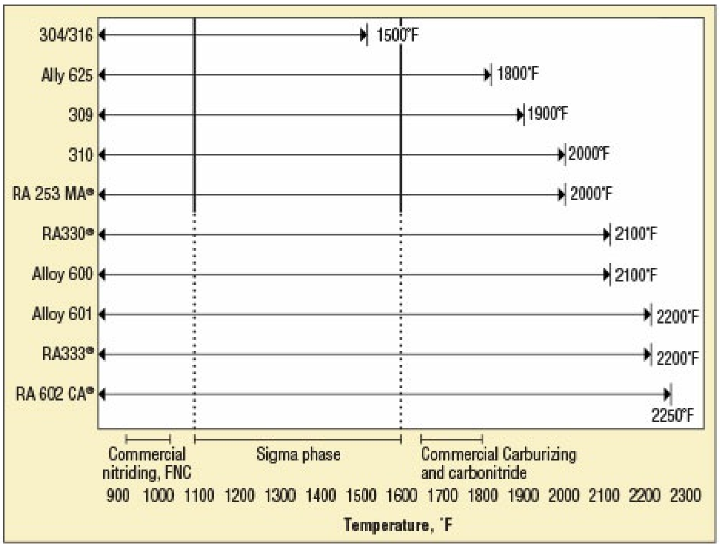


Fig. 1. Oxidation limits of some heat-resistant alloys. Note that for alloy 600, different sources limit this alloy to 2000Â°F.

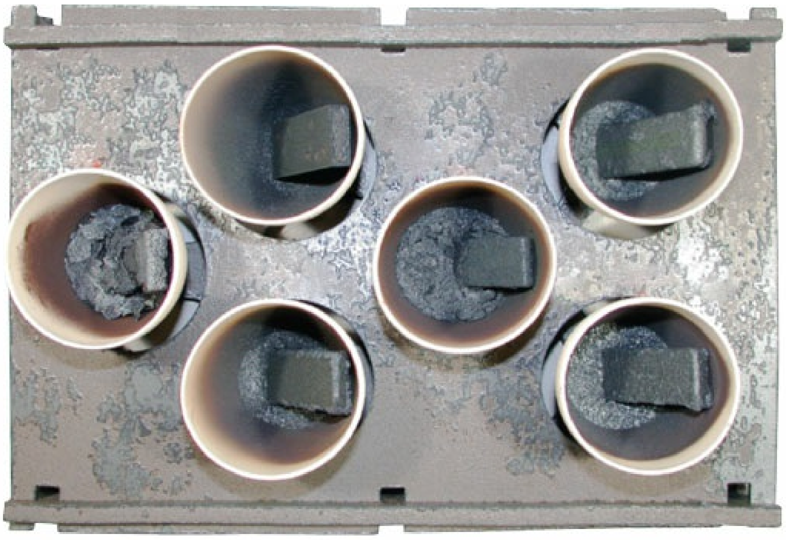


Fig. 2. Oxidation testing fixture, 2,880 hours at 2200Â°F.

Fig. 3. Photograph illustrating creep. The least creep is observed in alloy RA253MA and worst in 321.

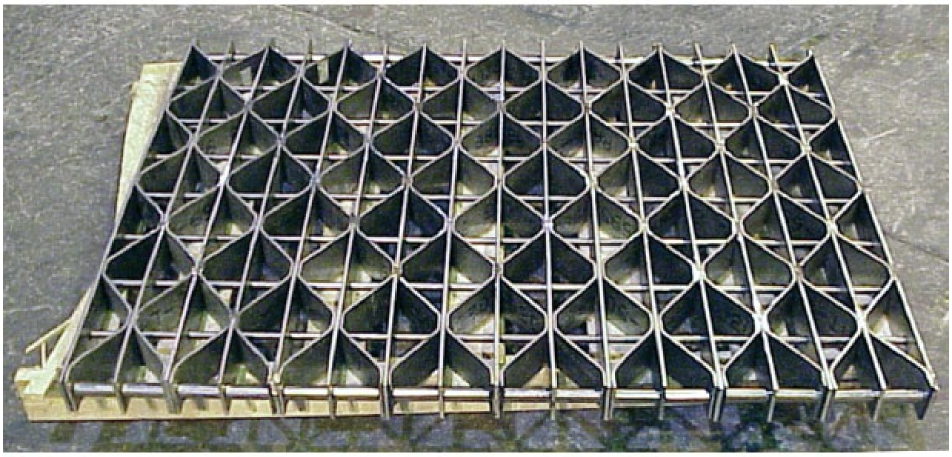


Fig. 4. Serpentine grid. Note that the only welds are between the nut and the threaded rods holding the entire assembly together and allowing freedom of movement during expansion and contraction.

Fig. 5. (left) 0.5-inch (12.7-mm) diameter, RA330 basket top frame. (right) 0.625-inch (15.9-mm) diameter, RA330 from same heat treaat basket

Table 1. Charpy properties response to temperature exposure and test temperatures

Test Temp (°F)	Condition	304 ft-lb	321 ft-lb	347 ft-lb	316 ft-lb	310 ft-lb	800 ft-lb
68	Unexposed	100	100	100		100	100
	18 mo @ 1200°F	100	100	50	65	25	50
	36 mo @ 1200°F	50	75	35	40	10	55
68	18 mo @ 1350°F	85	100	90	70	10	60
	36 mo @ 1350°F	75	95	45	30	5	30
68	4 mo @ 1500°F			65		20	
	6 mo @ 1500°F	100	100		65		100
	18 mo @ 1500°F	70	100		35		
	30 mo @ 1500°F		100				
	34 mo @ 1500°F				25		
	36 mo @ 1500°F						
1200	Unexposed	100	100	100	100	100	100
	18 mo @ 1200°F	100	100	85	100	85	75
	36 mo @ 1200°F	100	100	85	100	65	80
1350	Unexposed		100	100	100		
	18 mo @ 1350°F	100	100	100	95	35	85
	36 mo @ 1350°F	100	100	100	85	40	70
1500	Unexposed	100	100	100	100	100	100
	4 mo @ 1500°F			100		30	
	6 mo @ 1500°F	100	100		100		100
	12 mo @ 1500°F	100	100		100		
	18 mo @ 1500°F	100	100		100		
	30 mo @ 1500°F		100				
	34 mo @ 1500°F				40		

Table 2. Reduction in toughness in 10,000-hour exposure to various temperatures

Condition	RA253MA ft-lb	310S ft-lb
Annealed	85	159
10,000 hrs @ 1292 °F	3.7	3
10,000 hrs @ 1472 °F	3	3
10,000 hrs @ 1652 °F	30	18

Table 3. RA330 toughness retention after 1,000 hours		
Test Temp °F	Condition	Impact Toughness ft-lb
75	As Received	240
75	1,000 hr @1400°F	96
1400	As Received	167
1400	1,000 hr @1400°F	130

Table 4. Room-temperature toughness on metal exposed to 1600˚F			
Exposure	309	310	RA253MA
Hours	ft-lb	ft-lb	ft-lb
500	73	8.8	17.9
1200	58.4	8.5	15.1

Appendix A. High temperature properties

Average 10,000 Hour Rupture Strength, psi Temperature °F

ALLOY	900	1000	1100	1200	1300	1400	1500	1600	1700	1800	1900	2000	2100	2200
COR-TEN® B	22,000	12,500	--	2,000 +	--	–	--	--	--	–	--	--	--	–
RA446	--	–	3,500	2,700	--	1,100	--	450	--	230	--	--	--	–
304L	--	25,000	15,600	9,700	6,000	3,700	2,300	1,400	--	–	--	--	--	–
304, 304H	--	36,000	22,200	13,800	8,500	5,300	3,250	--	--	–	--	--	--	–
316L	--	39,000	23,500	14,200	8,500	5,100	3,050	--	--	–	--	--	--	–
321	--	–	23,500	12,900	7,200	4,000	2,280	--	--	–	--	--	--	–
321H	–	–	24,800	15,200	9,200	5,600	3,400	--	--	–	--	--	--	–
347,347H	–	48,000	27,500	15,600	9,000	5,100	2,900	--	--	–	--	--	--	–
RA 253 MA®	--	–	22,000	14,000	8,500	5,200	3,750	2,500	1,650	1,150	860	680	--	–
RA309	--	–	--	17,000	8,000	4,800	2,700	1,600	1,000	560	--	--	--	–
RA 602 CATM	--	–	--	31,200	--	11,300	--	3200	2180	1490	990	670	440	–
RA310	--	–	--	14,400	7,400	4,500	2,800	1,500	940	660	--	--	--	–
RA330®	--	29,000	17,000	11,000	7,200	4,300	2,700	1,700	1,050	630	400	(280)	--	–
RA800AT	--	–	--	17,500	11,000	7,300	5,200	3,500	1,900	1,200	--	--	--	–
RA 353 MA®	--	–	19,300	12,200	7,800	5,400	3,600	2,600	1,860	1,300	930	680	(450)	(320)
RA333®	--	–	25,000	16,500	12,000	9,200	5,700	3,100	1,800	1,050	630	360	--	140
RA625	--	–	--	42,500	22,500	12,000	--	--	--	–	--	--	--	–
RA601	--	42,000	29,000	21,000	10,000	6,200	4,000	2,600	--	1,200	--	(620)	(480)	–
RA718	--	128,000	98,000	70,000	--	–	--	--	--	–	--	--	--	–

* COR-TEN® B is a Registered Trademark of US Steel Corporation + One Heat Tested () Extrapolated

Average Stress, psi, for 0.00001% Per Hour Minimum Creep Rate, Extrapolated (1% in 100,000 hr M.C.R.)											
	Temperature, °F										
Alloy	1000	1100	1200	1300	1400	1500	1600	1700	1800	1900*	2000*
COR-TEN® B	8,200	--	1,000+	--	--	--	--	--	--	--	--
RA446	4,500	2,000	900	330	120	--	--	--	--	--	--
304L	7,800	5,100	3,250	2,100	1,340	880	--	--	--	--	--
304, 304H	17,900	11,100	7,200	4,500	2,900	1,800	--	--	--	--	--
316L	22,500	12,000	6,400	3,500	1,850	1,000	--	--	--	--	--
321	--	9,200	3,900	1,700	740	320	--	--	--	--	--
321H	--	12,400	7,000	4,000	2,250	1,280	--	--	--	--	--
347, 347H	30,500	16,200	8,700	4,700	2,500	1,300	--	--	--	--	--
RA 253 MA®	--	12,000	8,200	5,700	3,800	2,250	1,750	1,150	550	(320)	(150)
RA309	--	--	--	--	--	--	--	--	--	--	--
	--	--	--	--	--	--	--	--	--	--	--
RA310	--	--	--	--	--	--	--	--	--	--	--
RA330®	14,500	7,400	5,800	3,900	2,600	1,900	1,500	520	290	--	--
RA 353 MA®	--	--	--	--	3,200	2,100	1,450	930	520	--	--
RA333®	--	--	6,800	5,400	4,600	2,900	1,900	1,100	560	--	--
RA625	--	--	--	--	--	--	--	--	--	--	--
RA601	--	--	1,400	5,200	2,900	1,900	1,400	--	480	--	(300)

* NOTE: In our opinion it is not good engineering practice to extrapolate data to 100,000 hours at temperatures above 1800°F. These data are for general interest only. +One heat tested. Minimum Creep Rate is a different measure of creep than is Total Creep, and the numbers do not compare.

Average Stress, psi, for 0.0001% Per Hour Minimum Creep Rate												
Alloy	Temperature °F											
	900	1000	1100	1200	1300	1400	1500	1600	1700	1800	1900	2000
COR-TEN® B	20,800	11,100	--	1,700 +	--	--	--	--	--	--	--	--
RA446	16,000	6,000	3,000	1,500	680	260	130	--	--	--	--	--
304L	--	--	7,700	4,950	3,200	2,050	1,300	--	--	--	--	--
304, 304H	--	25,500	16,500	10,800	7,000	4,600	2,950	--	--	--	--	--
316L	--	23,500	14,000	8,300	4,900	2,900	1,750	--	--	--	--	--
321	--	--	20,000	8,800	3,850	1,700	750	--	--	--	--	--
321H	--	--	20,300	12,000	7,100	4,200	2,500	--	--	--	--	--
347, 347H	--	53,000	27,500	14,800	7,800	4,100	2,150	--	--	--	--	--
RA 253 MA®	--	--	18,000	11,600	7,700	5,000	3,350	2,300	1,500	890	490	(250)
RA309	--	--	--	16,000	8,800	3,400	2,400	1,400	600	220	--	--
	--	--	--	--	--	--	--	--	--	--	--	--
RA310	--	--	--	14,900	5,900	3,300	2,100	1,100	570	280	--	--
RA330®	--	21,000	10,500	7,600	5,300	3,600	2,700	2,100	1,000	500	--	--
RA800AT	--	--	--	17,000	9,100	6,000	--	3,600	1,500	1,050	--	--
RA 353 MA®												
RA333®	--	--	22,000	9,800	7,700	6,400	4,200	2,700	1,650	880	--	--
RA601	--	41,000	27,000	18,000	7,200	4,100	2,700	2,000	--	760	--	430
RA718	--	--	100,000	74,000	43,000+	--	--	--	--	--	--	--

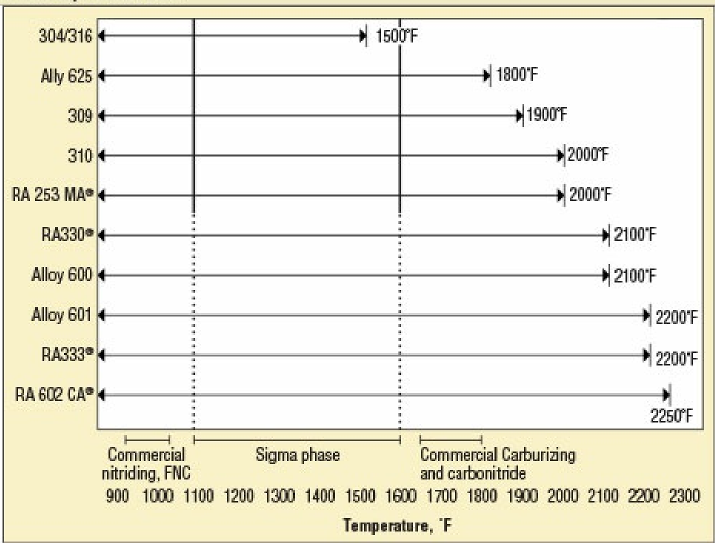
Average Stress, psi, for 1% Total Creep in 10,000 Hr										
	Temperature °F									
ALLOY	1100	1200	1300	1400	1500	1600	1700	1800	1900	2000
RA 253 MA®	18,000	10,000	6,400	4,200	2,700	1,700	1,000	450	250	(180)
RA85H®	--	8,500	5,600	3,800	2,500	1,700	1,100	750	500	--
RA330®	--	6,600	--	3,800	--	1,800	--	220	--	--
RA 353 MA®	13,300	8,000	4,800	3,000	1940	1360	990	710	540	410
RA 602 CATM	--	26,800	--	9400	--	2380	1520	960	590	330
RA333®	19,500	--	--	5,300	--	2,450	--	770	--	--

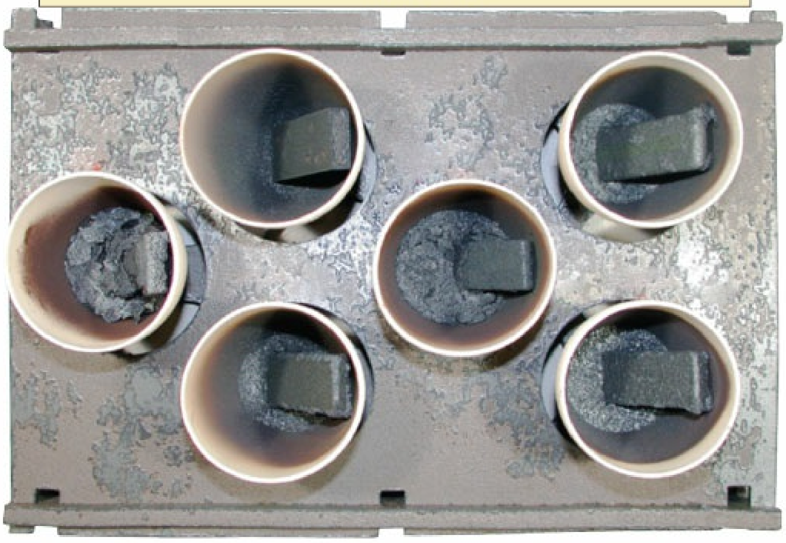
( ) Extrapolated. 1% total creep includes the primary stage creep when the specimen is first loaded, as well as secondary stage creep. Minimum creep rate data is based entirely on second stage creep

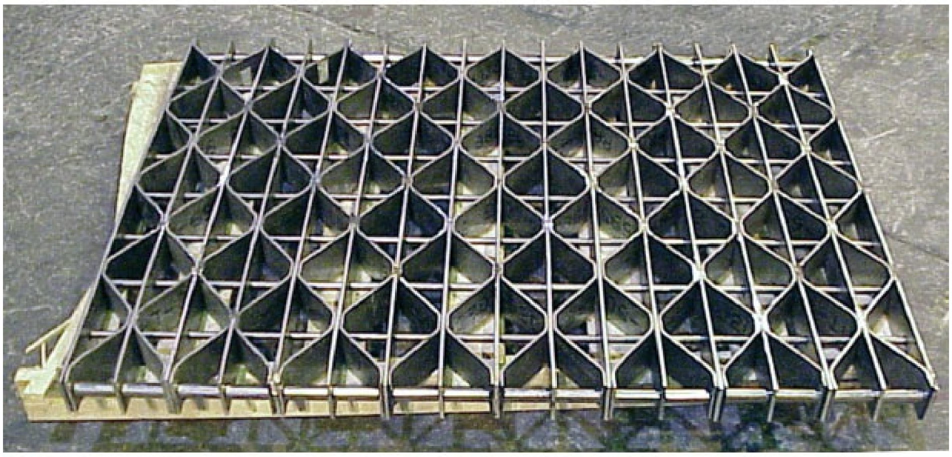
Average Extrapolated 100,000 Hour Rupture Strength, psi

	Temperature °F											
ALLOY	1000	1100	1200	1300	1400	1500	1600	1700	1800	1900	2000*	2100*
COR-TEN B®	8,000	–	1,000+	--	--	--	–	–	--	--	–	–
RA446	–	2,300	1,800	--	740	--	270	–	(140)	--	–	–
304L	19,500	11,600	6,900	4,100	2,400	1,450	–	–	--	--	–	–
304, 304H	25,800	15,800	9,800	6,000	3,700	2,300	–	–	--	--	–	–
316L	34,500	18,500	10,100	5,500	3,000	1,600	–	–	--	--	–	–
321	–	16,500	8,700	4,600	2,450	1,270	–	–	--	--	–	–
321H	29,000	17,400	10,300	6,100	3,600	2,100	–	–	--	--	–	–
347, 347H	37,500	20,800	11,500	6,400	3,550	1,950	–	–	--	--	–	–
RA 253 MA®	–	15,000	8,700	4,600	2,900	2,100	1,450	970	700	(540)	(440)	–
RA309	–	–	--	--	--	--	–	–	--	--	–	–
RA 602 CATM	–	–	20,300	--	5800	--	1750	1100	740	485	(310)	(200)
RA310	–	–	--	--	--	--	–	–	--	--	–	–
RA330®	20,000	12,000	7,800	4,800	2,700	1,650	1,000	580	330	--	–	–
RA800AT	–	–	13,000	8,000	5,300	3,700	2,500	1,200	800	--	–	–
RA 353 MA®	–	12,300	7,700	5,100	3,400	2,300	1,640	1,130	780	(550)	(400)	–
RA333®	–	–	11,500	8,400	6,500	3,700	1,900	1,050	580	(330)	(170)	–
RA625	–	–	--	--	--	--	–	–	--	--	–	–
RA601	–	–	1,500	6,800	4,000	--	–	–	700	--	(380)	(300)

* NOTE: In our opinion it is not good engineering practice to extrapolate data to 100,000 hours at temperatures above 1800°F. These data are for general interest only. + One heat tested.







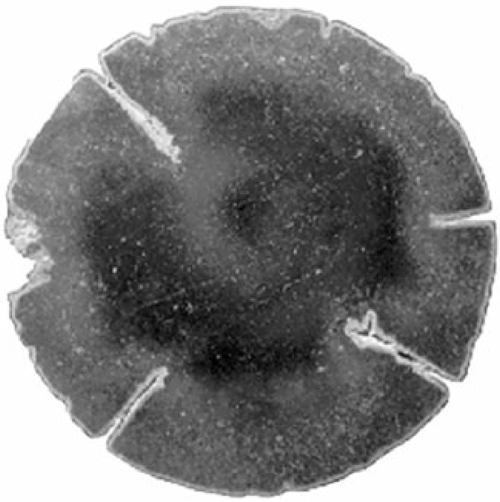


Table 1. Charpy properties response to temperature exposure and test temperatures

Test Temp (°F)	Condition	304 ft-lb	321 ft-lb	347 ft-lb	316 ft-lb	310 ft-lb	800 ft-lb
68	Unexposed	100	100	100		100	100
	18 mo @ 1200°F	100	100	50	65	25	50
	36 mo @ 1200°F	50	75	35	40	10	55
68	18 mo @ 1350°F	85	100	90	70	10	60
	36 mo @ 1350°F	75	95	45	30	5	30
68	4 mo @ 1500°F			65		20	
	6 mo @ 1500°F	100	100		65		100
	18 mo @ 1500°F	70	100		35		
	30 mo @ 1500°F		100				
	34 mo @ 1500°F				25		
	36 mo @ 1500°F						
1200	Unexposed	100	100	100	100	100	100
	18 mo @ 1200°F	100	100	85	100	85	75
	36 mo @ 1200°F	100	100	85	100	65	80
1350	Unexposed		100	100	100		
	18 mo @ 1350°F	100	100	100	95	35	85
	36 mo @ 1350°F	100	100	100	85	40	70
1500	Unexposed	100	100	100	100	100	100
	4 mo @ 1500°F			100		30	
	6 mo @ 1500°F	100	100		100		100
	12 mo @ 1500°F	100	100		100		
	18 mo @ 1500°F	100	100		100		
	30 mo @ 1500°F		100				
	34 mo @ 1500°F				40		

Table 2. Reduction in toughness in 10,000-hour exposure to various temperatures

Condition	RA253MA ft-lb	310S ft-lb
Annealed	85	159
10,000 hrs @ 1292 °F	3.7	3
10,000 hrs @ 1472 °F	3	3
10,000 hrs @ 1652 °F	30	18

Table 3. RA330 toughness retention after 1,000 hours

Test Temp °F	Condition	Impact Toughness ft-lb
75	As Received	240
75	1,000 hr @1400°F	96
1400	As Received	167
1400	1,000 hr @1400°F	130

Table 4. Room-temperature toughness on metal exposed to 1600˚F

Exposure	309	310	RA253MA
Hours	ft-lb	ft-lb	ft-lb
500	73	8.8	17.9
1200	58.4	8.5	15.1

Appendix A. High temperature properties

Average 10,000 Hour Rupture Strength, psi Temperature °F

ALLOY	900	1000	1100	1200	1300	1400	1500	1600	1700	1800	1900	2000	2100	2200
COR-TEN® B	22,000	12,500	--	2,000 +	--	–	--	--	--	–	--	--	--	–
RA446	--	–	3,500	2,700	--	1,100	--	450	--	230	--	--	--	–
304L	--	25,000	15,600	9,700	6,000	3,700	2,300	1,400	--	–	--	--	--	–
304, 304H	--	36,000	22,200	13,800	8,500	5,300	3,250	--	--	–	--	--	--	–
316L	--	39,000	23,500	14,200	8,500	5,100	3,050	--	--	–	--	--	--	–
321	--	–	23,500	12,900	7,200	4,000	2,280	--	--	–	--	--	--	–
321H	–	–	24,800	15,200	9,200	5,600	3,400	--	--	–	--	--	--	–
347,347H	–	48,000	27,500	15,600	9,000	5,100	2,900	--	--	–	--	--	--	–
RA 253 MA®	--	–	22,000	14,000	8,500	5,200	3,750	2,500	1,650	1,150	860	680	--	–
RA309	--	–	--	17,000	8,000	4,800	2,700	1,600	1,000	560	--	--	--	–
RA 602 CATM	--	–	--	31,200	--	11,300	--	3200	2180	1490	990	670	440	–
RA310	--	–	--	14,400	7,400	4,500	2,800	1,500	940	660	--	--	--	–
RA330®	--	29,000	17,000	11,000	7,200	4,300	2,700	1,700	1,050	630	400	(280)	--	–
RA800AT	--	–	--	17,500	11,000	7,300	5,200	3,500	1,900	1,200	--	--	--	–
RA 353 MA®	--	–	19,300	12,200	7,800	5,400	3,600	2,600	1,860	1,300	930	680	(450)	(320)
RA333®	--	–	25,000	16,500	12,000	9,200	5,700	3,100	1,800	1,050	630	360	--	140
RA625	--	–	--	42,500	22,500	12,000	--	--	--	–	--	--	--	–
RA601	--	42,000	29,000	21,000	10,000	6,200	4,000	2,600	--	1,200	--	(620)	(480)	–
RA718	--	128,000	98,000	70,000	--	–	--	--	--	–	--	--	--	–

* COR-TEN® B is a Registered Trademark of US Steel Corporation + One Heat Tested () Extrapolated

Average Stress, psi, for 0.00001% Per Hour Minimum Creep Rate, Extrapolated (1% in 100,000 hr M.C.R.)											
	Temperature, °F										
Alloy	1000	1100	1200	1300	1400	1500	1600	1700	1800	1900*	2000*
COR-TEN® B	8,200	--	1,000+	--	--	--	--	–	--	–	--
RA446	4,500	2,000	900	330	120	--	--	–	--	–	--
304L	7,800	5,100	3,250	2,100	1,340	880	--	–	--	–	--
304, 304H	17,900	11,100	7,200	4,500	2,900	1,800	--	–	--	–	--
316L	22,500	12,000	6,400	3,500	1,850	1,000	--	–	--	–	--
321	--	9,200	3,900	1,700	740	320	--	–	--	–	--
321H	--	12,400	7,000	4,000	2,250	1,280	--	–	--	–	--
347, 347H	30,500	16,200	8,700	4,700	2,500	1,300	--	–	--	–	--
RA 253 MA®	--	12,000	8,200	5,700	3,800	2,250	1,750	1,150	550	(320)	(150)
RA309	--	--	--	--	--	--	--	–	--	–	--
	--	--	--	--	--	--	--	–	--	–	--
RA310	--	--	--	--	--	--	--	–	--	–	--
RA330®	14,500	7,400	5,800	3,900	2,600	1,900	1,500	520	290	–	--
RA 353 MA®	--	--	--	--	3,200	2,100	1,450	930	520	–	--
RA333®	--	--	6,800	5,400	4,600	2,900	1,900	1,100	560	–	--
RA625	--	--	--	--	--	--	--	–	--	–	--
RA601	--	--	1,400	5,200	2,900	1,900	1,400	–	480	–	(300)

* NOTE: In our opinion it is not good engineering practice to extrapolate data to 100,000 hours at temperatures above 1800°F. These data are for general interest only. +One heat tested. Minimum Creep Rate is a different measure of creep than is Total Creep, and the numbers do not compare.

Average Stress, psi, for 0.0001% Per Hour Minimum Creep Rate												
Alloy	Temperature °F											
	900	1000	1100	1200	1300	1400	1500	1600	1700	1800	1900	2000
COR-TEN® B	20,800	11,100	--	1,700 +	--	--	--	--	--	--	--	--
RA446	16,000	6,000	3,000	1,500	680	260	130	--	--	--	--	--
304L	--	--	7,700	4,950	3,200	2,050	1,300	--	--	--	--	--
304, 304H	--	25,500	16,500	10,800	7,000	4,600	2,950	--	--	--	--	--
316L	--	23,500	14,000	8,300	4,900	2,900	1,750	--	--	--	--	--
321	--	--	20,000	8,800	3,850	1,700	750	--	--	--	--	--
321H	--	--	20,300	12,000	7,100	4,200	2,500	--	--	--	--	--
347, 347H	--	53,000	27,500	14,800	7,800	4,100	2,150	--	--	--	--	--
RA 253 MA®	--	--	18,000	11,600	7,700	5,000	3,350	2,300	1,500	890	490	(250)
RA309	--	--	--	16,000	8,800	3,400	2,400	1,400	600	220	--	--
	--	--	--	--	--	--	--	--	--	--	--	--
RA310	--	--	--	14,900	5,900	3,300	2,100	1,100	570	280	--	--
RA330®	--	21,000	10,500	7,600	5,300	3,600	2,700	2,100	1,000	500	--	--
RA800AT	--	--	--	17,000	9,100	6,000	--	3,600	1,500	1,050	--	--
RA 353 MA®												
RA333®	--	--	22,000	9,800	7,700	6,400	4,200	2,700	1,650	880	--	--
RA601	--	41,000	27,000	18,000	7,200	4,100	2,700	2,000	--	760	--	430
RA718	--	--	100,000	74,000	43,000+	--	--	--	--	--	--	--

Average Stress, psi, for 1% Total Creep in 10,000 Hr										
	Temperature °F									
ALLOY	1100	1200	1300	1400	1500	1600	1700	1800	1900	2000
RA 253 MA®	18,000	10,000	6,400	4,200	2,700	1,700	1,000	450	250	(180)
RA85H®	--	8,500	5,600	3,800	2,500	1,700	1,100	750	500	--
RA330®	--	6,600	--	3,800	--	1,800	--	220	--	--
RA 353 MA®	13,300	8,000	4,800	3,000	1940	1360	990	710	540	410
RA 602 CATM	--	26,800	--	9400	--	2380	1520	960	590	330
RA333®	19,500	--	--	5,300	--	2,450	--	770	--	--

( ) Extrapolated. 1% total creep includes the primary stage creep when the specimen is first loaded, as well as secondary stage creep. Minimum creep rate data is based entirely on second stage creep

Average Extrapolated 100,000 Hour Rupture Strength, psi

	Temperature °F											
ALLOY	1000	1100	1200	1300	1400	1500	1600	1700	1800	1900	2000*	2100*
COR-TEN B*	8,000	–	1,000+	--	--	--	–	–	--	--	–	–
RA446	–	2,300	1,800	--	740	--	270	–	(140)	--	–	–
304L	19,500	11,600	6,900	4,100	2,400	1,450	–	–	--	--	–	–
304, 304H	25,800	15,800	9,800	6,000	3,700	2,300	–	–	--	--	–	–
316L	34,500	18,500	10,100	5,500	3,000	1,600	–	–	--	--	–	–
321	–	16,500	8,700	4,600	2,450	1,270	–	–	--	--	–	–
321H	29,000	17,400	10,300	6,100	3,600	2,100	–	–	--	--	–	–
347, 347H	37,500	20,800	11,500	6,400	3,550	1,950	–	–	--	--	–	–
RA 253 MA*	–	15,000	8,700	4,600	2,900	2,100	1,450	970	700	(540)	(440)	–
RA309	–	–	--	--	--	--	–	–	--	--	–	–
RA 602 CATM	–	–	20,300	--	5800	--	1750	1100	740	485	(310)	(200)
RA310	–	–	--	--	--	--	–	–	--	--	–	–
RA330*	20,000	12,000	7,800	4,800	2,700	1,650	1,000	580	330	--	–	–
RA800AT	–	–	13,000	8,000	5,300	3,700	2,500	1,200	800	--	–	–
RA 353 MA*	–	12,300	7,700	5,100	3,400	2,300	1,640	1,130	780	(550)	(400)	–
RA333*	–	–	11,500	8,400	6,500	3,700	1,900	1,050	580	(330)	(170)	–
RA625	–	–	--	--	--	--	–	–	--	--	–	–
RA601	–	–	1,500	6,800	4,000	--	–	–	700	--	(380)	(300)

* NOTE: In our opinion it is not good engineering practice to extrapolate data to 100,000 hours at temperatures above 1800°F. These data are for general interest only. + One heat tested.

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Marc Glasser

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The first factor in choosing a heat-resistant alloy for a particular application is its temperature limit. In order to obtain the desired service life, however, there are many additional factors that must be taken into account in order to succeed in your application. Failure to consider these factors can result in premature failures and, in some instances, lead to serious safety risks for your employees.

This article will introduce the reader to a broader understanding of many of the factors to consider when selecting an alloy of construction for a heat-resistant application.

Oxidation

The first and foremost variable to consider is the oxidation limit of a particular alloy. A continuous layer of chromium oxide on the surface of austenitic alloys is responsible for promoting oxidation resistance. Silicon and aluminum, at high enough levels in an alloy, will allow the formation of subscales of silica or alumina, which will further enhance oxidation resistance. Finally, the addition of rare-earth and other heavy metals will add another level of oxidation resistance by adding an oxide that will bond to the other oxides to create a tighter, thinner, more adherent oxide that is harder to break. A thinner oxide scale is less prone to crack and spall than a thicker oxide.[1]

The surface oxide of any oxidation-resistant alloy is responsible for its oxidation resistance, but it is also subjected to conditions that can eventually destroy the oxide. Thermal cycling can pop the oxide layer off of the base over time. The scale can break down locally by formation of warts or nodules.[1] When the scale breaks off in a spot, it may either regenerate or be the initiation sight for more serious scale breakdown.

Laboratory testing is done to define oxidation limits and compare alloys to competitive material. Such testing can be done at any temperature up to and including 2250°F (1232°C). The measurement of choice is weight gain due to oxide (and nitride) formation. Samples are heated in porcelain crucibles in order to contain spalled oxide. The samples are removed weekly. After employing procedures to ensure that no spalled oxide is lost, they are cooled, weighed and then reintroduced into the furnace until the samples are at temperature for 3,000 hours. Weight gain is reported in mg/cm^2.

Such testing is useful as a guide, but it does not adequately simulate all conditions that all alloy may see in actual production use, including more frequent thermal cycling, creep, stagnant atmospheres, differences in oxidizing atmospheres (e.g., moisture content) and real time. Alloys of construction may be used for years instead of months, and extrapolations may or may not be accurate.

Despite all these limitations, the oxidation testing is useful for comparisons. In these laboratory tests, results with losses under 20 mg/cm^2 suggest that an alloy, in plate form, should not lose structural integrity based on oxidation losses. Given all these considerations, Figure 1 shows the oxidation limits of Rolled Alloys' corrosion-resistant-alloy portfolio. Figure 2 is an illustration of an actual experiment showing easily observable differences in the oxidation resistance of several alloys.

Exposure to Other Atmospheres

In the heat-treating world, materials of construction can be exposed to other atmospheres, including carburizing, nitriding (and combinations of these two), vacuum, hydrogen, inert gas and more. In vacuum, and to a large extent inert-gas atmosphere, oxidation resistance is less important because the purpose of these atmospheres is to create an oxygen-free atmosphere. It should also be understood that products of combustion contain both carbon and nitrogen at high temperatures, which can lead to nitriding and carburizing. In commercial heat treating, carburizing and carbonitriding are generally performed in the temperature range of 1600-1750°F (871-954°C), while nitriding and ferritic nitrocarburizing are generally performed at 985-1050°F (530-565°C).

Carburizing, nitriding and combinations of the two processes embrittle heat-resistant alloys. Therefore, the materials can no longer be straightened or welded at some point in time. Embrittlement is imparted from both surface chemistry changes from the atmosphere that diffuses into the base metal with prolonged exposure and, if the temperature is high enough, grain growth. Resistance to carburization (or nitriding) is dependent on nickel content, scale integrity and grain size. Nickel lowers the solubility of carbon in the alloy so that it simply will not diffuse into the metal.[1,2,3]

In heat-resistant alloys, combinations of chromia, silica and alumina are found on the surface and are also a layer of defense against carburization. Even though an atmosphere is reducing to iron, it can still be oxidizing to chromium, silicon or aluminum. This can be determined from an Ellingham diagram. Suffice it to say that the tendency of a scale to be oxidizing or reducing is thermodynamically complex but can be estimated through careful analysis of Ellingham diagrams.[4]

RA330® is very commonly used for fixturing in these environments and will typically last a year. RA333®, 600, 601 and RA 602 CA® are more carburization-resistant but at increasing costs. Alloy 800HT, despite having a similar chemistry to RA330 with less Si and an addition of aluminum, exhibits decreased carburization resistance in large part because of large grain size and less silica.

As a result of complex atmospheres, carburization testing is more difficult and must be tailored to the particular environment that an actual furnace will exhibit. This includes carbon potential, temperature and oxygen content of the atmosphere. This last parameter cannot be stressed enough because the formation of a comparable protective scale is critical to getting a valid comparison.[1]

Vacuum carburization presents a unique problem. At the oxygen partial pressures involved in this process, silica and chromia scales are not thermodynamically stable. Therefore, they are not present. Carburization resistance comes largely from alumina, requiring a minimum of 2.5% or a combination of aluminum and silicon of at least 3%. A current practice is to run carburization testing of new alloys for comparison in an actual carburization furnace – with samples welded or otherwise attached to fixturing – in order to get apples-to-apples comparisons.

There is one final form of carburization to consider, and that is the phenomenon of carbon dusting. This most typically occurs at lower temperatures of 800-1200°F (427-650°C). This happens when a component is introduced through a furnace through an insulated wall. The metal in the insulation is at a much lower temperature, and the metal away from the wall is at furnace temperature. A dramatic thermal gradient exists in the zone close to the wall. The metal appears to be worm-eaten on the surface.[1] RA333 has been the heat-treating industry's alloy of choice for decades to resist carbon dusting. One capital-equipment manufacturer has shown that both RA 602 CA and 625 are acceptable alternatives to RA333 for metal-dusting applications.

Creep and Rupture Strength

Tensile strength can no longer be used as a design parameter above 1000°F (538°C). Instead, two very important factors in deciding on a heat-resistant alloy are the ability of the alloy to resist sagging and breakage with an applied load at temperature. These two parameters are known as high temperature creep and rupture resistance, respectively. Simply stated, creep is the phenomenon of metal stretching from its own weight or from an applied load at an elevated temperature.

A simple visual created to help understand creep phenomenon is shown in Figure 3, where perfect concentric round samples are welded to a fixture, placed in a furnace for a period of time and then air cooled. Some samples have severely sagged, while others have barely deformed at all. Those that have not deformed have better creep resistance. Creep rate is expressed in % per hour and increases with increasing temperature.

During creep testing, there are three stages of creep: the initial stage; the secondary stage, where there is a constant slope that is the lowest sloped region of the curve; and the final stage. The U.S. measures the minimum creep rate, which is the constant rate exhibited in the secondary stage of creep. Europe uses total creep, or the stress required at a particular temperature for the specimen to stretch for a total of 1%. The minimum creep rate and total creep rate are not interchangeable.

Rupture strength is reported as both a stress and the number of hours required to break a specimen at a specific amount of time. Creep strength is the more critical measurement. The reason is that while many similar alloys have comparable rupture strengths, they may not have similar creep strengths. In this case, one alloy with much higher creep strength will retain shape for years, while others will sag so much that the furnace is rendered useless.

Finally, like many variables, both creep and rupture strength are not exact parameters. There will be variation from test to test of the same alloy. Furthermore, furnace and part design criteria must contain a safety factor since failure can have safety consequences. So, design criteria are much lower than the actual creep and rupture strengths. One governing body, ASME, uses the lower of 67% of the extrapolated 100,000-hour rupture stress or 100% of the extrapolated 1% in 100,000-hour minimum creep rate.[5]

Some creep and rupture properties of select common wrought alloys are given in Appendix A (online only).

It has been shown that coarse-grain materials exhibit higher creep and rupture strength than fine-grain materials. However, the trade-off is that coarse-grain materials lose thermal-fatigue resistance as they gain creep and rupture strength.

Finally, oxidation has an apparent strengthening effect on some alloys over 1800°F (982°C). When thin specimens were used for the creep and rupture testing, RA333, which is known to have better creep and rupture resistance than RA330, actually exhibited lower creep strength.[1] Visual examination showed a good degree of oxidation on the RA330 and none on the RA333. Using a thicker sample minimized the effect of oxidation and gave more predictable results.

In summary, proper design must take into account the creep and rupture strength at a specific maximum temperature with an acceptable safety factor. This will allow for a material that will not deform or break during a reasonable life cycle at temperature.

Embrittlement

High-chromium, low-nickel materials (stainless steels) change from ductile to brittle after anywhere from a few hundred to several thousand hours of service in the 1100-1600°F (593-871°C) range. This is due to the precipitation of a hard, brittle intermetallic phase known as sigma phase. While sigma phase may not be harmful when the material is at temperature, it can completely embrittle the alloy at room temperature.

Furthermore, weld repair at room temperature can end up propagating cracks, leading to a catastrophic failure. This can cause a real safety hazard should a repair of a large, heavy component be attempted. In such a situation, the material has the potential to shatter like a piece of glass, and that can harm an employee in the vicinity. Ferrite-stabilizing elements (Cr, Mo, Si) promote sigma-phase formation, while austenite-stabilizing elements (Ni-N-C) retard formation.[2] In RA330, no appreciable amount of sigma phase is observed. This suggests that sigma-phase embrittlement can be completely suppressed in stainless steels with high enough Ni levels, as well as all nickel-based alloys.[1,2]

Sigma-phase formation has a kinetic component, which is governed by a C curve. Chemistry also has an effect on sigma-phase formation. As a general rule, all elements that stabilize ferrite promote sigma-phase formation, especially Si and Mo as well as V, W, Ti and Cb. Elements that stabilize austenite retard sigma-phase formation. Coarse grain size retards sigma-phase formation, while prior cold work promotes it.[6]

An ASME study on superheater materials[7] shows that the kinetics of sigma-phase formation varies by alloy. Regardless of alloy, time to precipitate is long. Finally, the kinetics follow a C curve: There is a temperature in the middle of the precipitation range where precipitation occurs in the shortest time.

The C curves vary from alloy to alloy. Results are shown in Table 1. An internal study by Rolled Alloys[8] shows the loss in toughness after 10,000 hours of exposure to various temperatures (Table 2). Another study[9] shows how RA330 retains toughness after 1,000-hour exposure to 1400°F (760°C), and results are shown in Table 3. Finally, a Rolled Alloys' study[8] suggests that 309 may retain impact strength more than either 310S or RA 253 MA at 1600°F (871°C). This is shown in Table 4. Unfortunately, these studies cannot be extrapolated to other temperatures.

Thermal Cycling/Expansion

Thermal fatigue as it relates to heat-resistant alloys is cracking that occurs after repeated heating and cooling (quenching) of an alloy. Heat-resistant alloys have high coefficients of thermal expansion and low thermal conductivity. Simply stated, the metal surface heats and cools before the center does. During heating, the surface is expanding quicker than the center, which places strain on the center. Then during quenching, the surface is contracting faster than the center, placing more strain on the surface.[1]

The best example of this phenomenon is shown in wire-bar heat-treating baskets and is process-dependent. As a result of the stresses, carburizing and salt-bath heat treating cause cracks to form at the surface and propagate toward the center, and these cracks are visible. On the other hand, neutral hardening will show just the opposite. Cracks will form in the center and give no indication that anything is wrong until the entire bar breaks.

There are several ways to minimize this phenomenon.

- Design flexible or loose fixtures such as serpentine grids (Fig. 4) with thin sections.
- Pinned joints may also be employed.
- Use thinner sections to lessen the effect of non-uniform heating and cooling. In wire-bar baskets, size reduction from 5/8-inch-diameter rod to 0.5 inch diameter has alleviated many instances of thermal fatigue cracking (Fig. 5).
- Employing finer-grain materials and alloys more resistant to grain growth will result in fixturing that is more ductile and resistant to such cracking.

Just as important as fatigue is thermal expansion. One point that design engineers often fail to consider is that heat transfer is not uniform. Should thermal expansion be restrained, stresses will result from the restraint. When these stresses exceed the yield point of any piece of metal, it will buckle, bend or crack. Therefore, it is important to understand how all parts will heat up and make sure that there is adequate room for expansion and contraction.

Other Factors

Some less common factors (which will not be treated in this writing) that sometimes require consideration include sulfidation, exposure to molten metal, galling and proper maintenance. When considering a heat-resistant alloy for a new application, it is wise to contact a supplier with a metallurgical staff that can provide all data necessary for a design engineer to confidently specify a material, knowing that he/she has considered all potential factors. IH

Apendix A and additional tables can be seen in the slideshow above.

For more information: Contact Marc Glasser at Rolled Alloys, 125 West Sterns Road, Temperance, MI; tel: 800-521-0332, e-mail: metallurgical-help@rolledalloys.com; web: www.rolledalloys.com.

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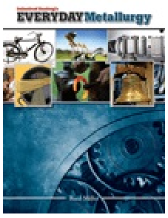

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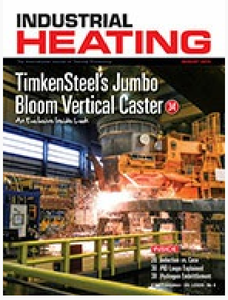

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