HAYNES International

HIGH-TEMPERATURE ALLOYS

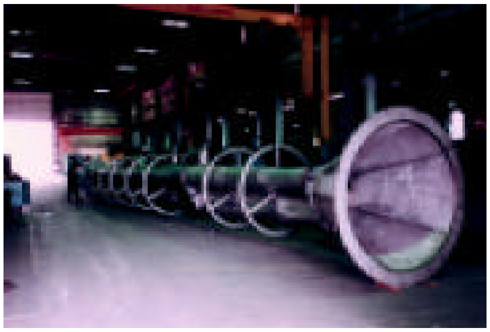
HAYNES® HR-160® alloy

A solid-solution-strengthened, high-temperature corrosion-resistant alloy that provides excellent resistance to sulfidation and chloride attack in both reducing and oxidizing atmospheres with exceptionally good resistance to oxidation, hot corrosion, carburization, metal dusting, and nitridation.

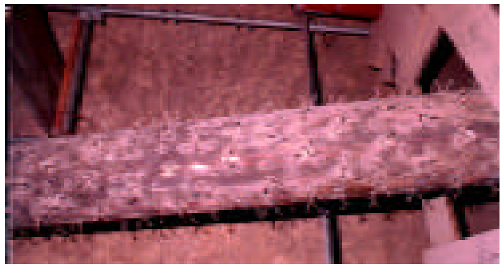
Contents

H-3129A

APPLICATIONS

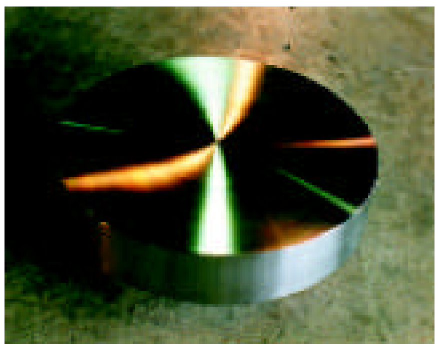


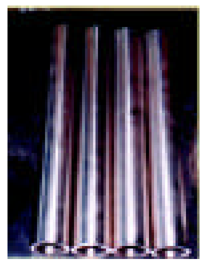
Afterburner retort for processing hazardous waste.

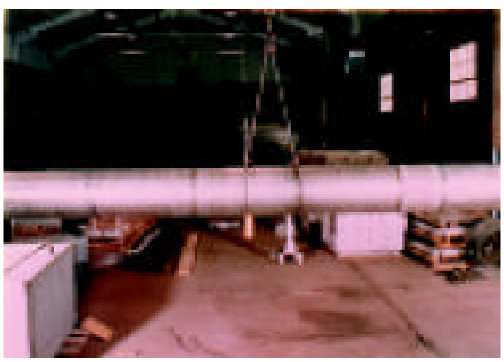


Refractory anchors used in waste incinerator operating between 1300-1700°F (704-927°C) burning agri-wastes. HR-160 alloy showed the most resistance in the environment containing high levels of sulfur and chlorine. Original material was 309SS.

HR-160® alloy components in petroleum refinery process.







Calciner tube made of HR-160 alloy for use in processing high sulfur feedstocks at 2000°F (1093°C). HR-160 alloy was selected after intensive field rack testing.

PRINCIPAL FEATURES

Resistance to High-Temperature Corrosion

HAYNES® HR-160® alloy is a solid-solution-strengthened nickel-cobalt-chromium-silicon alloy with outstanding resistance to various forms of high-temperature corrosion attack. HR-160 alloy has excellent resistance to sulfidation and chloride attack in both reducing and oxidizing atmospheres. The alloy also has exceptionally good resistance to oxidation, hot corrosion, carburization, metal dusting, nitridation and corrosion attack by low melting point compounds such as those formed by phosphorus, vanadium, and other impurities. The alloy is especially suited for applications in high temperature corrosive environments generated by combustion of low-grade fuels or processing of chemical feedstocks with corrosive contaminants such as sulfur, chlorine, fluorine, vanadium, phosphorus, and others. The alloy is capable of withstanding temperatures up to 2200°F (1204°C).

Ease of Fabrication

HAYNES HR-160 alloy has excellent forming and welding characteristics. It may be forged or otherwise hot-worked, providing it is held at 2050°F (1121°C) for time sufficient to bring the entire piece to temperature. As a consequence of its good ductility, HR-160 alloy is also readily formed by cold working. Cold- or hot-worked parts should be annealed and rapidly cooled in order to restore the best balance of properties.

HR-160 alloy can be welded by a variety of techniques, including gas tungsten arc (TIG), gas metal arc (MIG), and resistance welding.

Heat-Treatment

HR-160 alloy is furnished in the solution annealed condition, unless otherwise specified. The alloy is solution annealed at 2050°F (1121°C) and rapidly cooled for optimum properties. Intermediate annealing, if required during fabrication and forming operations, can be performed at temperatures as low as 1950°F (1066°C).

Available in Practical Product Forms

HAYNES HR-160 alloy is available in the form of plate, sheet, strip, billet, bar, wire, pipe and tubing.

Applications

HAYNES HR-160 alloy combines properties which make it highly useful for service in severe high-temperature corrosive environments. Applications include a variety of fabricated components in municipal, industrial, hazardous, and nuclear waste incinerators. It is widely used in recuperators, heat exchangers and waste heat recovery systems. HR-160 alloy is also suitable for utility boilers, sulfur plants, high-temperature furnaces, kilns, calciners, resource recovery units, cement kilns, pulp and paper recovery boilers, coal gasification systems, and fluidized-bed combustion systems.

Applicable Specifications

The UNS number for Haynes HR-160 alloy is N12160.

ASME Vessel Code

HAYNES HR-160 alloy is covered by ASME Vessel Code case No. 2162 for Section VIII Division 1 construction to 1500°F (816°C).

Nominal Chemical Composition, Weight Percent

Ni	Co	Cr	Fe	Si	Mn	Ti	C	W	Mo	Cb
37[a]	30	28	3.5*	2.75	0.5	0.5	0.05	1*	1*	1*

[a] As Balance * Maximum

HIGH TEMPERATURE CORROSION RESISTANCE

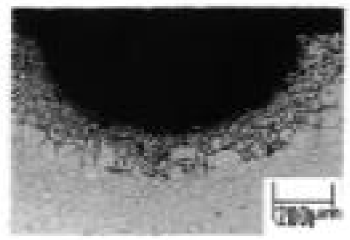
Sulfidation in Reducing Atmospheres

Ar-5%H_2-5%CO-1%CO_2-0.15%H_2S (Vol. %)
(PO_2= 3 x 10^{-19} atm, PS_2 = 0.9 x 10^{-6} atm)

1600°F (871°C) / 215 hours

HR-160® alloy

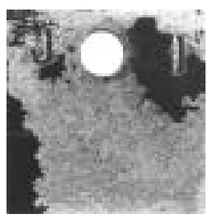
556™ alloy



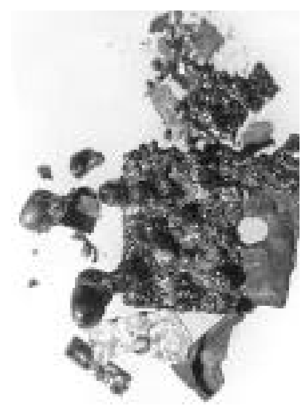
Alloy 800H

Top edge of the photograph represents the original sample surface. The specimens were tested and then cathodically descaled to remove the corrosion products prior to mounting for metallography.

1600°F (871°C) / 500 hours



HR-160 alloy



RA330 alloy

1600°F (871°C) / 500 hours

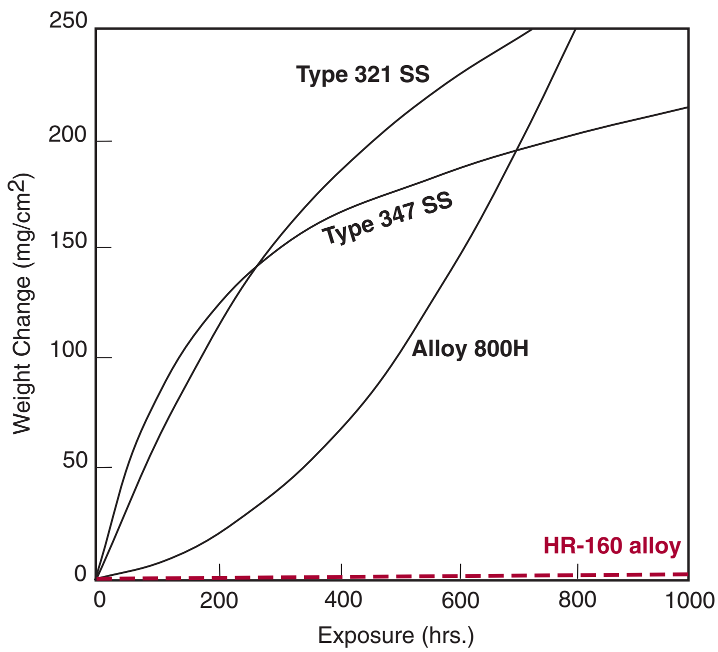
Alloy	% Cobalt	Metal Loss, Mils	Metal Loss, (mm)	Average Depth of Attack Mils	Average Depth of Attack (mm)	Max. Depth of Attack Mils	Max. Depth of Attack (mm)
alloy 6B	57	0.3	(0.008)	3.1	(0.08)	3.3	(0.08)
HR-160 alloy	30	0.2	(0.005)	4.7	(0.12)	5.2	(0.13)
alloy 25	51	4.1	(0.10)	8.4	(0.21)	14.6	(0.37)
alloy 188	39	7.6	(0.10)	14.9	(0.38)	23.6	(0.60)
alloy 150	50	10.3	(0.26)	22.1	(0.56)	28.3	(0.72)
556 alloy	18	20.6	(0.52)	31.9	(0.81)	35.6	(0.90)

Note: 1) Nickel alloys (e.g. 600, 601) consumed in 215 hours (0.044-inch thick samples)
2) 310SS suffered 14 mils of attack in 215 hours
3) 800H suffered 19 mils of attack in 215 hours

Sulfidation in Reducing Atmospheres

Alloy	H_2-46%CO-0.8%CO_2-1.7%H_2S Total Depth of Attack 1100°F (593°C) mpy	(mm/y)	1300°F (704°C) mpy	(mm/y)
HR-160®	14.4	(0.37)	27.3	(0.70)
6B	23.6	(0.60)	264.4	(6.72)
150	37.7	(0.96)	108.8	(2.76)
25	94.1	(2.39)	188.5	(4.79)
188	150.5	(3.82)	292.6	(7.43)
556	121.1	(3.08)	345.8	(8.78)

H_2-7%CO-1.5%H_2O-0.6%H_2S
(PO_2= 1 x 10^{-23} atm, PS_2 = 1 x 10^{-9} atm, a_c = 0.3-0.4 at 1292°F (700°C))



Note: HR-160 alloy exhibited about 1.0 mg/cm² of weight gain after 1000 hours of exposure.

Sulfate-Induced Sulfidation in Combustion Atmospheres

Laboratory Hot Corrosion Burner Rig Testing - Specimens were exposed to a combustion stream generated in a burner rig fired with No. 2 fuel oil with a constant injection of 50 ppm (by weight) salt (mostly sodium chloride) into the combustion stream. Specimens were also subjected to thermal cycling by cycling them out of the test chamber once every hour and rapid fan cooling to less than 390°F (199°C) for two minutes.

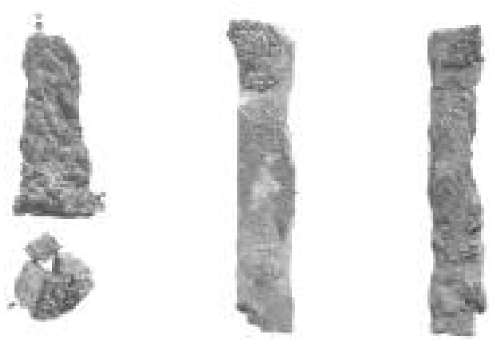
No. 2 fuel oil with 0.4% sulfur
1650°F (899°C)

310SS	RA330 alloy	alloy 800H	alloy 625	HR-160® alloy

1000 hours	476 hours	1000 hours	940 hours	1000 hours

No. 2 fuel oil with 1.0% sulfur
1650°F (899°C) for 500 hours

253 MA® alloy **RA330 alloy** **RA85H® alloy**



alloy 800H **556 alloy** **HR-160 alloy**

OXIDATION RESISTANCE

Oxidation in Air

Laboratory tests were conducted in flowing air at 1800 to 2200°F (982 to 1204°C) for 1008 hours, with specimens cycled to room temperature once every 168 hours.

	1800°F (982°C)		2000°F (1093°C)	
Alloy	Metal Loss, Mils*	Average Metal Affected, Mils*	Metal Loss Mils*	Average Metal Affected, Mils*
HR-160® alloy	0.6	5.9	1.7	10.3
800HT® alloy	0.0	3.9	6.1	12.0
253 MA alloy	1.3	2.9	0.7	8.2
RA85H alloy	0.5	8.2	2.9	25.9

	2100°F (1149°C)		2200°F (1204°C)	
Alloy	Metal Loss, Mils*	Average Metal Affected, Mils*	Metal Loss Mils*	Average Metal Affected, Mils*
HR-160 alloy	2.7	13.0	4.1	24.2
800HT alloy	12.3	18.8	19.4	>58*
253 MA alloy	8.4	16.4	18.6	29.2
RA85H alloy	3.7	>59**	3.9	>59**

* To convert mils to mm, divide by 40
** Internal oxidation through thickness

Long-Term Oxidation in Air

Laboratory tests were conducted at 2000°F (1093°C) in still air (box furnace), with specimens being cycled to room temperature once every 30 days.

	Weight Loss (mg/cm²)							
Alloy	30 days	90 days	150 days	210 days	300 days	360 days	Metal Loss* Mils	Average Metal* Affected, Mils
HR-160 alloy	10.4	23.2	34.6	46.8	60.1	73.1	3.6	29.0
alloy 601	4.6	15.8	28.2	46.1	82.0	110.5	5.4	45.1
800HT alloy	4.6	203.3	379.7	529.2	746.7	893.9	44.3	51.0
RA85H alloy	6.3	46.5	103.8	144.9	210.5	348.1	17.9	80.3

* 360 days

CHLORIDATION RESISTANCE

High Temperature Chloride Vapor Corrosion

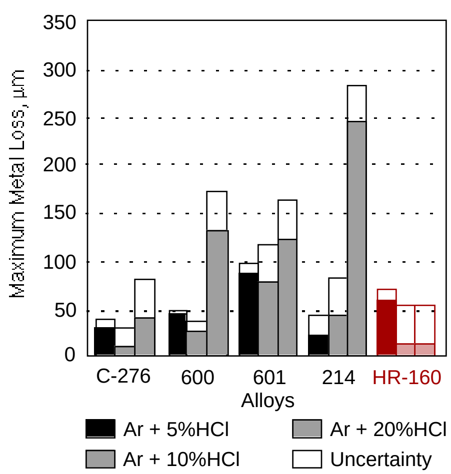
Ar-20%0_2-2%H_2O-0.05%NaCl (Vol.%)
1830°F (999°C) for 75 hours

Alloy	Total Depth of Attack, Mils	(mm)
214™ alloy	11.5	(0.29)
HR-160® alloy	12.0	(0.31)
alloy 800H	>62.0 (complete penetration)	

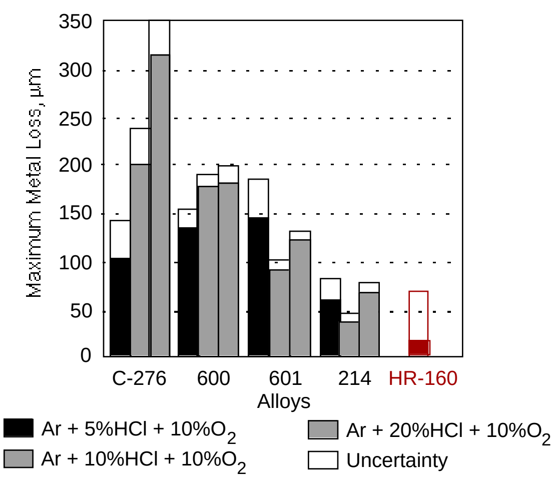
Field tests were conducted by exposing specimens to air containing vapors of sodium chloride, potassium chloride and barium chloride at 1600°F (871°C) for 173 hours.

HR-160 alloy **alloy 188** **Type 310 SS**

Chlorination Resistance



Maximal loss of sound metal per side.
Laboratory tests in chlorinating atmospheres
at 1112°F (600°C) for 500 hours.*



Maximal loss of sound metal per side.
Laboratory tests in oxychlorinating atmospheres
at 1112°F (600°C) for 500 hours.*

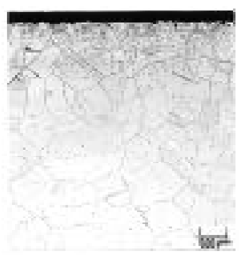
* Data from "Corrosion Studies and Recommendation of Alloys for an Incinerator of Glove-Boxes Wastes" by F. Devisme and N. H. Garnier, Presented at the 11th International Incineration Conference 1992, May 11-15, 1992, Albuquerque, New Mexico

CARBURIZATION RESISTANCE

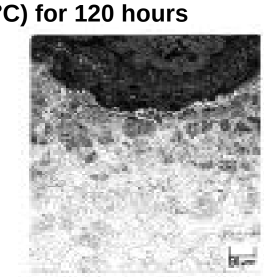
Laboratory pack carburization testing in graphite at 1800°F (982°C) for 500 hours

Alloy	Carbon Absorption (mg/cm^2)	Depth of Carburization Mils	(mm)
HR-120™ alloy	0.0	0	
556 alloy	0.0	0	
HR-160® alloy	0.3	0	
800HT alloy	0.3	0.9	(0.02)
alloy 601	1.0	18.0	(0.46)
RA330 alloy	1.9	70.6	(1.79)
310SS	7.7	84.2	(2.14)
253 MA alloy	11.6	92.1	(2.34)

Field tests conducted in a carbon bed during manufacturing of activated carbon at 1650°F (899°C) for 120 hours



HR-160 alloy



Type 316 SS

Ar-5%H_2-1%CH_4 (Vol.%)
1800°F (982°C) for 55 hours

Alloy	Carbon Absorption (mg/cm^2)
HR-160 alloy	2.9
alloy 601	3.2
alloy 800H	3.6
alloy 600	7.3
HR-120 alloy	7.9
556 alloy	7.9
RA330 alloy	9.2
253 MA alloy	9.4
310SS	10.0

NITRIDATION RESISTANCE

HAYNES® HR-160® alloy is also very resistant to nitridation attack. Tests were performed in flowing ammonia or nitrogen at various temperatures for 168 hours. Nitrogen absorption was determined by chemical analysis of samples before and after exposure and knowledge of the exposed specimen area.

Ammonia (NH_3)
168 hours

	Nitrogen Absorption (mg/cm^2)		
Alloy	**1200°F (649°C)**	**1800°F (982°C)**	**2000°F (1093°C)**
HR-160 alloy	0.9	2.2	3.0
alloy 601	1.1	1.2	2.6
RA330 alloy	4.7	3.9	3.1
alloy 800H	4.3	4.0	5.5
304SS	9.8	7.3	3.5
316SS	6.9	6.0	3.3
310SS	7.4	7.7	9.5
446SS	28.8	12.9	4.5
253 MA alloy	-	3.3	6.3

Nitrogen (N_2)
2000°F (1093°C), 168 hours

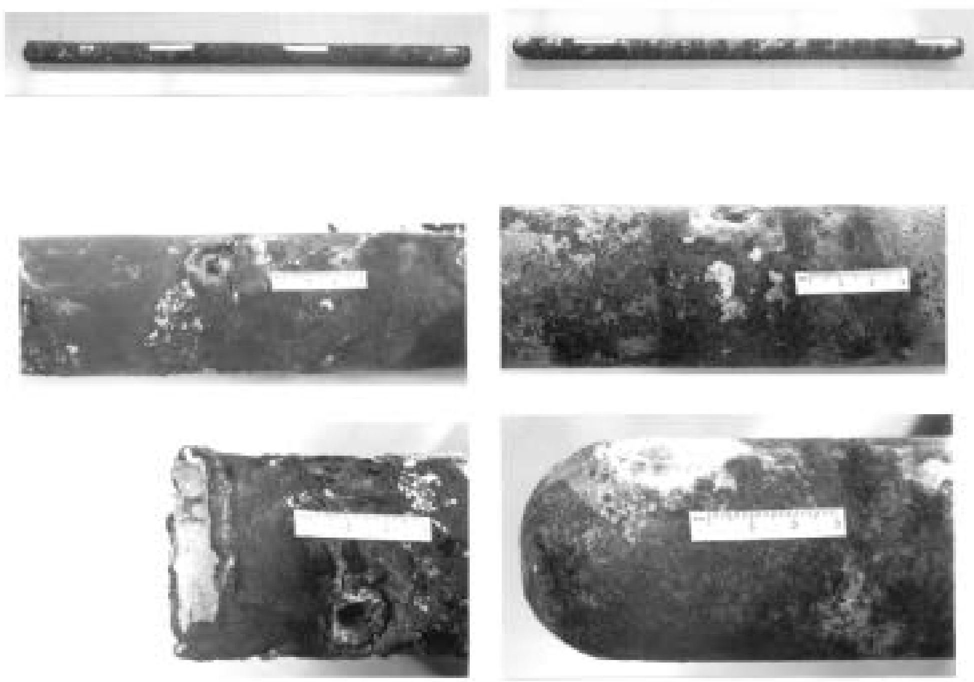
Alloy	Nitrogen Absorption (mg/cm^2)
HR-160 alloy	3.9
alloy 601	7.2
RA330 alloy	6.6
RA85H alloy	8.5
253 MA alloy	10.0
alloy 800H	10.3
alloy 800HT	11.4
310SS	12.3

WASTE INCINERATION ENVIRONMENTS

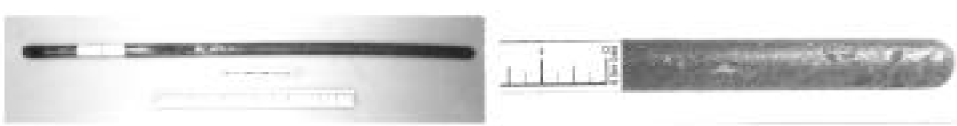
Incineration of municipal, industrial and hazardous wastes generates very corrosive environments which typically contain such corrosive constituents as SO_2, HCl and sometimes HF, along with vapors/deposits of chlorides and sulfates. The following examples demonstrate the relative improvements resulting from upgrading to HR-160® alloy.

Soot blowers in a municipal waste incinerator
1400°F (760°C) for 75 days

Type 446 SS | **HR-160 alloy**



Thermowell in municipal waste incinerator
1800-2100°F (982-1149°C) for 180 days

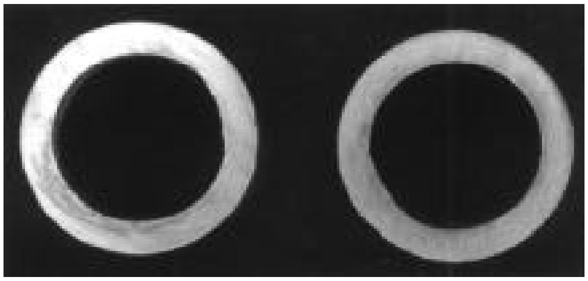


HR-160 alloy

Waste Incineration Environments

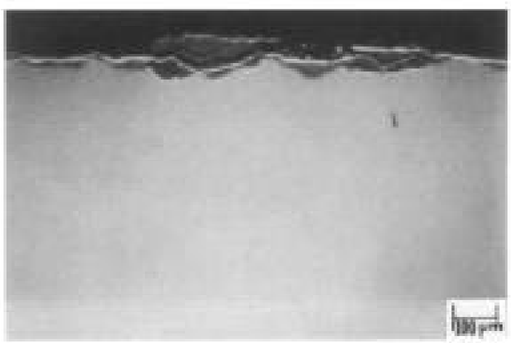
HAYNES® HR-160® thermowell in a municipal waste incinerator for 170 days at 1850-1950°F (1010-1066°C)

Unexposed end | Exposed end

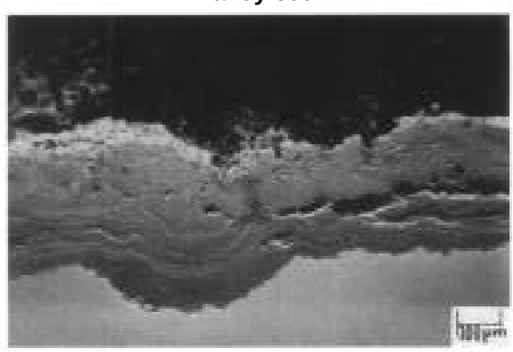


Field testing in a chemical waste incinerator showed little scaling or metal wastage for HR-160 alloy when exposed to the flue gas stream which contained SO_2, HCl and HF for 5800 hours at 900°F (482°C)

HR-160 alloy



alloy 600



TYPICAL TENSILE PROPERTIES

Tensile Data (plate)*

Test Temperature		Ultimate Tensile Strength		Yield Strength at 0.2% Offset		Elongation in 1.340 in. (34.0 mm)	Reduction of Area
°F	(°C)	Ksi	MPa	Ksi	MPa	%	%
70	(21)	111.2	767	45.6	314	68	73
200	(93)	104.0	717	40.4	279	69	74
400	(204)	97.9	675	33.8	233	71	74
600	(316)	91.9	634	27.6	190	74	70
800	(427)	87.7	605	26.0	179	76	68
1000	(538)	81.8	564	25.5	176	76	69
1200	(649)	75.8	523	25.7	177	70	67
1400	(760)	62.1	428	24.7	170	73	64
1600	(871)	38.3	264	22.1	152	85	84
1800	(982)	20.4	140	10.8	74	90	98
2000	(1093)	10.8	74	5.0	34	88	98
2100	(1149)	6.0	41	2.3	16	113	94
2200	(1204)	4.4	30	1.6	11	110	94

* Hot-Rolled and Solution-Annealed

Tensile Data (Sheet)*

Test Temperature		Ultimate Tensile Strength		Yield Strength at 0.2% Offset		Elongation in 2 in. (50.8 mm)
°F	(°C)	Ksi	MPa	Ksi	MPa	%
70	(21)	110.0	758	51.2	353	63
1000	(538)	82.5	569	32.7	225	73
1200	(649)	75.3	519	31.2	215	62
1400	(760)	61.1	421	30.7	212	47
1600	(871)	34.9	241	15.9	110	41
1800	(982)	18.7	129	9.5	66	51
2000	(1093)	9.8	68	4.7	32	53
2100	(1149)	6.6	46	2.8	19	107
2200	(1204)	4.8	33	2.0	14	91

* Solution-Annealed

CREEP AND STRESS-RUPTURE STRENGTHS

Plate - 2050°F (1121°C) Solution Anneal

Temperature °F	(°C)	Creep Percent	Approximate Initial Stress, Ksi (MPa) to Produce Specified Creep in 100 Hours		1000 Hours		10,000 Hours		100,000 Hours*	
1100	593	1.0	29.4	(203)	20.4	(141)	14.4*	(100)	-	-
		Rupture	45.5	(315)	32.2	(223)	22.9	(158)	16.3	(113)
1200	649	1.0	18.9	(131)	13.1	(91)	9.3*	(64)	-	-
		Rupture	32.2	(223)	22.4	(154)	15.6	(108)	11.0	(76)
1300	704	1.0	12.5	(86)	8.7	(60)	6.2*	(43)	-	-
		Rupture	22.9	(158)	15.7	(108)	10.8	(75)	7.4	(51)
1400	760	1.0	8.5	(59)	6.0	(41)	4.2*	(29)	-	-
		Rupture	16.4	(113)	11.0	(76)	7.4	(51)	5.0	(34)
1500	816	1.0	5.9	(41)	4.1	(28)	2.9*	(20)	-	-
		Rupture	11.7	(81)	7.7	(53)	5.1	(35)	3.4	(23)
1600	871	1.0	4.2	(29)	2.9	(20)	2.1*	(14)	-	-
		Rupture	8.4	(58)	5.5	(38)	3.6	(25)	2.4	(17)
1700	927	1.0	3.0	(21)	2.1	(14)	1.5*	(10)	-	-
		Rupture	6.1	(42)	3.9	(27)	2.5	(17)	1.6	(11)
1800	982	1.0	2.2	(15)	1.5	(10)	1.1*	(8)	-	-
		Rupture	4.4	(30)	2.8	(19)	1.8	(12)	1.2	(8)

* Extrapolation

Comparative Stress-Rupture Strengths

Temperature °F	(°C)	10,000 Hours Rupture Strenths (Ksi*) HR-160	RA333®	800HT	RA330	253 MA	RA85H	309	310
1200	649	15.6	16.5	17.5	11.0	14.0	12.0	16.0	9.3
1300	704	10.8	12.0	11.0	-	8.5	-	-	-
1400	760	7.4	9.2	7.3	4.3	5.2	5.0	5.45	3.9
1500	816	5.1	5.7	5.2	-	3.75	-	-	-
1600	871	3.6	3.1	3.5	1.7	2.5	2.1	1.86	1.65
1700	927	2.5	1.8	1.9	-	1.65	-	-	-
1800	982	1.8	1.05	1.2	0.63	1.15	0.9	0.63	0.69

Temperature °F	(°C)	100,000 Hours Rupture Strenths (Ksi*) HR-160**	RA333	800HT	RA330	253 MA	RA85H	309	310
1200	649	11.0	11.5	13.0	7.6	8.7	8.0	11.6	6.5
1300	704	7.4	8.4	8.0	-	4.6	-	-	-
1400	760	5.0	6.5	5.3	2.7	3.9	3.2	3.8	2.6
1500	816	3.4	3.7	3.7	-	2.1	-	-	-
1600	871	2.4	1.9	2.5	1.0	1.45	1.3	1.25	1.06
1700	927	1.6	1.05	1.2	-	0.97	-	-	-
1800	982	1.2	0.58	0.8	0.33	0.7	0.5	0.41	0.42

* Ksi can be converted to MPa (megapascals) by multiplying by 6.895
** Extrapolation

TYPICAL PHYSICAL PROPERTIES

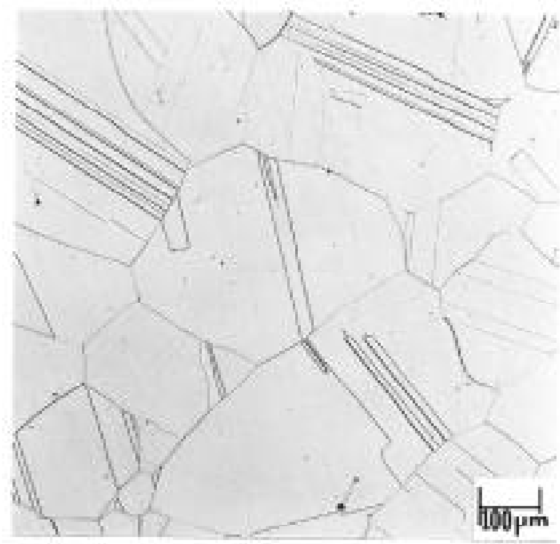
	Temp., °F	British Units	Temp., °C	Metric Units
Density	Room	0.292 lb/in.^{3}	Room	8.08 g/cm.^{3}
Melting Temperature	2360-2500		1293-1370	
Electrical Resistivity	Room	43.8 microhm-in.	Room	111.2 microhm-cm
	200	44.3 microhm-in.	100	112.8 microhm-cm
	400	45.2 microhm-in.	200	114.7 microhm-cm
	600	46.1 microhm-in.	300	116.7 microhm-cm
	800	46.9 microhm-in.	400	118.6 microhm-cm
	1000	47.8 microhm-in.	500	120.6 microhm-cm
	1200	48.3 microhm-in.	600	122.4 microhm-cm
	1400	48.6 microhm-in.	700	123.1 microhm-cm
	1600	48.9 microhm-in.	800	123.8 microhm-cm
	1800	49.3 microhm-in.	900	124.5 microhm-cm
	2000	49.6 microhm-in.	1000	125.2 microhm-cm
	2200	49.9 microhm-in.	1100	125.9 microhm-cm
			1200	126.7 microhm-cm
Thermal Diffusivity	Room	4.6 x 10^{-3} in.^{2}/sec.	Room	29.4 x 10^{-3} cm^2/sec.
	212	4.8 x 10^{-3} in.^{2}/sec.	100	30.8 x 10^{-3} cm^2/sec.
	392	5.2 x 10^{-3} in.^{2}/sec.	200	33.6 x 10^{-3} cm^2/sec.
	572	5.7 x 10^{-3} in.^{2}/sec.	300	37.0 x 10^{-3} cm^2/sec.
	752	6.3 x 10^{-3} in.^{2}/sec.	400	40.6 x 10^{-3} cm^2/sec.
	932	6.9 x 10^{-3} in.^{2}/sec.	500	44.3 x 10^{-3} cm^2/sec.
	1112	7.1 x 10^{-3} in.^{2}/sec.	600	45.6 x 10^{-3} cm^2/sec.
	1292	7.3 x 10^{-3} in.^{2}/sec.	700	47.2 x 10^{-3} cm^2/sec.
	1472	7.5 x 10^{-3} in.^{2}/sec.	800	48.6 x 10^{-3} cm^2/sec.
	1652	7.5 x 10^{-3} in.^{2}/sec.	900	48.7 x 10^{-3} cm^2/sec.
	1832	7.9 x 10^{-3} in.^{2}/sec.	1000	50.9 x 10^{-3} cm^2/sec.
	2012	8.4 x 10^{-3} in.^{2}/sec.	1100	54.1 x 10^{-3} cm^2/sec.
	2192	8.7 x 10^{-3} in.^{2}/sec.	1200	56.1 x 10^{-3} cm^2/sec.
Thermal Conductivity	Room	75 Btu-in./ft.^{2} hr.-°F	Room	10.9 W/m-K
	200	82 Btu-in./ft.^{2} hr.-°F	100	12.0 W/m-K
	400	95 Btu-in./ft.^{2} hr.-°F	200	13.6 W/m-K
	600	108 Btu-in./ft.^{2} hr.-°F	300	15.4 W/m-K
	800	126 Btu-in./ft.^{2} hr.-°F	400	17.6 W/m-K
	1000	144 Btu-in./ft.^{2} hr.-°F	500	19.9 W/m-K
	1200	162 Btu-in./ft.^{2} hr.-°F	600	21.8 W/m-K
	1400	178 Btu-in./ft.^{2} hr.-°F	700	24.7 W/m-K
	1600	185 Btu-in./ft.^{2} hr.-°F	800	26.1 W/m-K
	1800	196 Btu-in./ft.^{2} hr.-°F	900	26.9 W/m-K
	2000	213 Btu-in./ft.^{2} hr.-°F	1000	28.7 W/m-K
	2200	228 Btu-in./ft.^{2} hr.-°F	1100	31.1 W/m-K
			1200	32.9 W/m-K

Typical Physical Properties

	Temp., °F	British Units	Temp., °C	Metric Units
Specific Heat	Room	0.110 Btu/lb.-°F	Room	462 J/Kg-K
	200	0.116 Btu/lb.-°F	100	487 J/Kg-K
	400	0.121 Btu/lb.-°F	200	506 J/Kg-K
	600	0.125 Btu/lb.-°F	300	521 J/Kg-K
	800	0.131 Btu/lb.-°F	400	542 J/Kg-K
	1000	0.136 Btu/lb.-°F	500	562 J/Kg-K
	1200	0.151 Btu/lb.-°F	600	597 J/Kg-K
	1400	0.159 Btu/lb.-°F	700	653 J/Kg-K
	1600	0.164 Btu/lb.-°F	800	672 J/Kg-K
	1800	0.167 Btu/lb.-°F	900	689 J/Kg-K
	2000	0.171 Btu/lb.-°F	1000	704 J/Kg-K
	2200	0.175 Btu/lb.-°F	1100	719 J/Kg-K
			1200	732 J/Kg-K
Dynamic Modulus of Elasticity	Room	30.6 x 10^6 psi	Room	211 GPa
	100	30.5 x 10^6 psi	40	210 GPa
	200	30.1 x 10^6 psi	90	208 GPa
	300	29.6 x 10^6 psi	150	204 GPa
	400	29.1 x 10^6 psi	205	201 GPa
	500	28.6 x 10^6 psi	260	197 GPa
	600	27.8 x 10^6 psi	315	192 GPa
	700	27.1 x 10^6 psi	370	187 GPa
	800	26.5 x 10^6 psi	425	183 GPa
	900	26.1 x 10^6 psi	480	180 GPa
	1000	25.6 x 10^6 psi	540	177 GPa
	1100	25.1 x 10^6 psi	595	173 GPa
	1200	24.4 x 10^6 psi	650	168 GPa
	1300	23.7 x 10^6 psi	705	163 GPa
	1400	22.9 x 10^6 psi	760	158 GPa
	1500	22.4 x 10^6 psi	815	154 GPa
	1600	21.7 x 10^6 psi	870	150 GPa
	1700	21.1 x 10^6 psi	925	145 GPa
	1800	19.8 x 10^6 psi	980	137 GPa
Mean Coefficient of Thermal Expansion	78-200	7.2 microinches/in.-°F	25-95	13.0 10^{-6}m/m-°C
	78-400	7.6 microinches/in.-°F	25-205	13.7 10^{-6}m/m-°C
	78-600	7.9 microinches/in.-°F	25-315	14.0 10^{-6}m/m-°C
	78-800	8.1 microinches/in.-°F	25-425	14.4 10^{-6}m/m-°C
	78-1000	8.3 microinches/in.-°F	25-540	14.9 10^{-6}m/m-°C
	78-1200	8.6 microinches/in.-°F	25-600	15.5 10^{-6}m/m-°C
	78-1400	8.9 microinches/in.-°F	25-700	15.7 10^{-6}m/m-°C
	78-1600	9.2 microinches/in.-°F	25-800	16.6 10^{-6}m/m-°C
	78-1800	9.5 microinches/in.-°F	25-900	17.1 10^{-6}m/m-°C

PHYSICAL METALLURGY

	Plate/Bar	Sheet
Typical Grain Size	1 1/2 - 2 1/2	3 1/2 - 4
Average Hardness	Rb 88	Rb 87



Annealed Microstructure

The alloy has a stable austenitic structure and exhibits no sigma or mu phases after long-term aging. Aging at 1200, 1400 and 1600°F (649, 760 and 871°C) for 4000 hours, for example, resulted in the precipitation of $Cr_{23}C_6$ and G phase ($Ni_{16}Ti_6Si_7$). The morphology of G phase is quite similar to that of $Cr_{23}C_6$. Thus, G phase is not considered to be more detrimental than carbides in causing the ductility to drop upon long-term aging. The alloy is non-magnetic in annealed and cold-worked conditions.

THERMAL STABILITY

Room-Temperature Tensile Properties

Thermal Exposure Condition*	Ultimate Tensile Strength Ksi	Ultimate Tensile Strength MPa	Yield Strength at 0.2% Offset Ksi	Yield Strength at 0.2% Offset MPa	Elongation in 2 in. (50.8 mm) %	Reduction Area %
Annealed	112.2	774	46.5	321	66	73
Aged at 1200°F/1000 hrs	117.8	812	49.5	341	40	33
Aged at 1200°F/4000 hrs	121.5	838	51.3	354	38	31
Aged at 1200°F/8000 hrs	122.2	843	51.2	353	34	28
Aged at 1400°F/1000 hrs	115.0	793	46.4	320	36	28
Aged at 1400°F/4000 hrs	117.3	809	46.6	321	26	23
Aged at 1400°F/8000 hrs	116.0	800	46.2	319	26	19
Aged at 1600°F/1000 hrs	101.6	701	42.9	295	28	23
Aged at 1600°F/4000 hrs	98.0	676	43.1	297	24	20
Aged at 1600°F/8000 hrs	91.7	632	42.0	290	20	16

* Plate

Thermal Stability

Condition	Room-Temperature V-Notch Impact Strength ft.-lb.	Joules
Annealed	264	358
Aged at 1200°F/1000 hrs	43	58
Aged at 1200°F/4000 hrs	34	46
Aged at 1200°F/8000 hrs	31	42
Aged at 1400°F/1000 hrs	27	37
Aged at 1400°F/4000 hrs	18	24
Aged at 1400°F/8000 hrs	15	20
Aged at 1600°F/1000 hrs	16	22
Aged at 1600°F/4000 hrs	13	18
Aged at 1600°F/8000 hrs	11	15

AQUEOUS CORROSION RESISTANCE

Stress Corrosion Cracking

U-Bend Specimens
45% $MgCl_2$, 154°C (309°F)

Alloy	Time to Failure, hours	
HR-160® alloy	1000	No cracking
C-22™ alloy	1000	No cracking
alloy 825	150	Cracked
316LSS	24	Cracked

Uniform Corrosion

	Average Corrosion Rate Per Year, mils*		
	HR-160	625	316L
3% HCl + 59% HNO_3, 80°C	2	20	-
1% HF + 20% HNO_3, 80°C	35	123	>400
50% H_2SO_4 + 10% HNO_3, Boiling	20	-	-
60% H_2SO_4 + 5% HNO_3, Boiling	50	105	-
65% HNO_3, Boiling	9	20	12
G-28A, Boiling 50% H_2SO_4 + 42 g/l $Fe_2(SO_4)_3$	9	24	38
25% H_2SO_4 + 5% HNO_3 + 4% NaCl, Boiling	3	713	-
1% HCl, Boiling	469	0.9	524
1% HCl + 1% H_2SO_4 + 1% HF, 79°C	107	120	245

*To convert mils per year (mpy) to mm per year, divide by 40.

WELDING

HAYNES® HR-160® alloy is readily weldable by Gas Tungsten Arc (TIG) and Gas Metal Arc (MIG) welding processes. Many of the alloy's welding characteristics are similar to those for the HASTELLOY® alloys and the same precautions apply. Submerged arc welding is not recommended as this process is characterized by high heat input which could result in distortion and hot cracking. HR-160 filler metal is prone to start/stop cracking. The filler metal may be prone to hot cracking when welding heavy plate (e.g. greater than 1/2 inch thick) under highly restrained conditions. Any localized cracking should be removed by grinding prior to further welding. Do not attempt to remelt or "wash-out" welding cracks.

Base Metal Preparation

The joint surface and adjacent area should be thoroughly cleaned before welding. All grease, oil, crayon marks, sulfur compounds and other foreign matter should be removed. It is preferable, but not mandatory, that the alloy be in the solution-annealed condition when welded.

Filler Metal Selection

Matching composition filler metal is recommended for joining HR-160 alloy. When dissimilar base metals are to be jointed, such as HR-160 alloy to a stainless steel, HAYNES 556 filler metal is recommended.

Preheating, Interpass Temperatures and Post-Weld Heat Treatment

Preheat should not be used so long as the base metal to be welded is above 32°F (0°C). Interpass temperatures should be less than 200°F (93°C). Auxiliary cooling methods may be used between weld passes, as needed, providing that such methods do not introduce contaminants. Post-weld heat treatment is not normally required for HR-160 alloy.

Nominal Welding Parameters

Nominal welding parameters are provided as a guide for performing typical operations. These are based on welding conditions used in our laboratory and should be considered only as a guideline. For further information, please consult Haynes publication H-3159.

Manual Gas Tungsten Arc Welding

V- or U-Groove - All Thicknesses 0.125" (3.2 mm) or greater

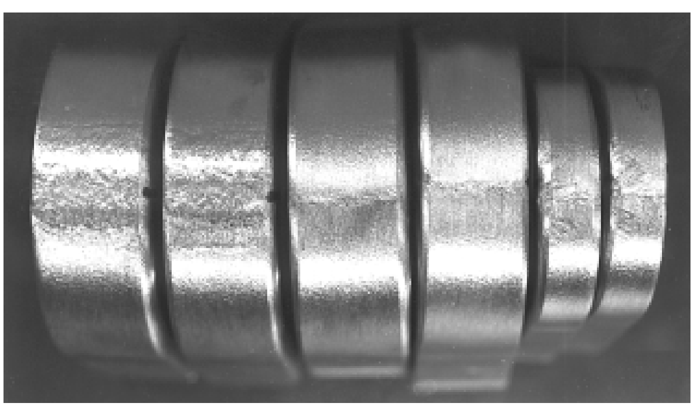
Technique	-	Stringer Bead
Current (DCEN), amperes	-	120 root, 150 fill
Voltage	-	10 to 14
Filler Metal	-	0.125" (3.2 mm) diameter. HR-160 wire
Travel Speed, ipm (mm/min)	-	4 to 6 (100-150)
Electrode Size-EWTH-2, in (mm)	-	0.125 (3.2)
Electrode Shape	-	30° included angle
Cup Size	-	#8 or larger
Shielding Gas, 100% Ar CFH (l/min.)	-	30 to 35
Backup Gas, 100% Ar CFH (l/min.)	-	10 CFH
Preheat	-	Ambient
Interpass Temperature	-	<200°F (93°C)

Gas Metal Arc Welding

Short Circuiting Transfer Mode
All Thicknesses 0.125" (3.2 mm) or greater

Technique	-	Stringer or slight weave
Current (DCEN), amperes	-	100 to 140
Voltage	-	18 to 21
Wire Feed Rate, ipm (m/min)	-	170 to 190 (4.3 to 4.8)
Stickout, in (mm)	-	0.5 to 0.75 (12.7 to 19)
Filler Metal	-	0.045" (1.1 mm) diameter HR-160 wire
Travel Speed, ipm (mm/min	-	8 to 14 (203 to 356)
Shielding Gas Flow, CFH (l/min.)	-	50 (23.7)
Gas	-	Argon - 25% Helium

Large Welded retort fabricated from 0.375 inch (9.5 mm) HR-160® plate



Typical face, root and side bends for HR-160 alloy. The plate thickness was 0.5 inch (12.7 mm) and the bend radius 1.0 inch (25 mm) (2T radius)

MACHINING

HAYNES® HR-160® alloy is similar in machining characteristics to other solid-solution-strengthened nickel-base alloys. These alloys as a group are classified as moderate to difficult to machine; however, it should be emphasized that they can be machined using conventional methods at satisfactory rates. As these alloys will work-harden rapidly, the keys to successful machining are to use lower speeds and feeds, and to take heavier cuts than would be used for machining stainless steels. See Haynes International publication H-3159 for more detailed information.

Normal Roughing (Turning / Facing)

Use carbide C-2 / C-3 grade tool

Speed: 90 surface feet / minute
Feed: 0.010 in. / revolution
Depth of cut: 0.150 in.

Negative rake square insert, 45° SCEA[1] 1/32 in. nose radius. Tool holder: 5° negative back and side rakes.

Lubricant: Dry[2], oil[3] or water-base[4,5].

Finishing (Turning / Facing)

Use carbide C-2 / C-3 grade tool

Speed: 95-110 surface feet / minute
Feed: 0.005-0.007 in. / revolution
Depth of cut: 0.040 in.

Positive rake square insert, if possible, 45° SCEA[1] 1/32 in. nose radius. Tool holder: 5° positive back and side rakes.

Lubricant: Dry or water-base.

Drilling

Use high speed steel M-33 / M-40 series[6]/ or T-15 grades*

Speed: 10-15 surface feet / minute (200 RPM maximum for 1/4 in. diameter or smaller)

Lubricant: oil or water-base. Use coolant feed drills if possible.

Short, heavy-web drills with 135° crank shaft point. Thinning of web at point may reduce thrust.

Feed:
0.001 in. rev. 1/8 in. dia.
0.002 in. rev. 1/4 in. dia.
0.003 in. rev. 1/2 in. dia.
0.005 in. rev. 3/4 in. dia.
0.007 in. rev. 1 in. dia.

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*Carbide drills not recommended, but may be used in some set-ups. See Haynes International publication H-3159 for details.

Notes:
1 SCEA - Side cutting edge angle, or lead angle of the tool.

2 At any point where dry cutting is recommended, an air jet directed on the tool may provide substantial tool life increases. A water-base coolant mist may also be effective.

3 Oil coolant should be a premium quality, sulfochlorinated oil with extreme pressure additives. A viscosity at 100°F of from 50 to 125 SSU is standard.

4 Water-base coolant should be a 15:1 mix of water with either a premium quality, sulfochlorinated water soluble oil or a chemical emulsion with extreme pressure additives.

5 Water-base coolants may cause chipping or rapid failure of carbide tools in interrupted cuts.

6 M-40 series High Speed Steels include M-41 through M-46 at time of writing, others may be added, and should be equally suitable.

HEALTH AND SAFETY

Those involved with the welding industry are obligated to provide safe working conditions and be aware of the potential hazards associated with welding fumes, gases, radiation, electrical shock, heat, eye injuries, burns, etc. Various local, municipal, state and federal regulations (OSHA, for example) relative to the welding and cutting processes must be considered.

The operation and maintenance of welding and cutting equipment should conform to the provisions of American National Standard ANSI Z49.1-88, "Safety in Welding and Cutting". Attention is especially called to Section 4 (Protection of Personnel), Section 5 (Ventilation) and Section 7 (Confined Spaces) of that document. Adequate ventilation is required during all welding and cutting operations. Specific requirements are included in Section 5 for natural ventilation versus mechanical ventilation methods. When welding in confined spaces, ventilation shall also be sufficient to assure adequate oxygen for life support.

The following precautionary warning is supplied with all welding products. It should be provided to and fully understood by all employees involved with welding.

CAUTION: "Welding may produce fumes and gases hazardous to health. Avoid breathing these fumes and gases. Use adequate ventilation. See ANSI/AWS Z49.1-88, "Safety in Welding and Cutting" published by the American Welding Society.

EXPOSURES: Maintain all exposures below the limits shown in the Material Safety Data Sheet, and the product label. Use industrial hygiene air monitoring to ensure compliance with the recommended exposure limits. ALWAYS USE EXHAUST VENTILATION.

RESPIRATORY PROTECTION: Be sure to use a fume respirator or air supplied respirator when welding in confined spaces or where local exhaust or ventilation does not keep exposures below the PEL and TLV limits.

WARNING: Protect yourself and others. Be sure the label is read and understood by the welder. FUMES and GASES can be dangerous to your health. Overexposure to fumes and gases can result in LUNG DAMAGE. ARC RAYS can injure eyes and burn skin. ELECTRIC SHOCK can kill.

Acknowledgements

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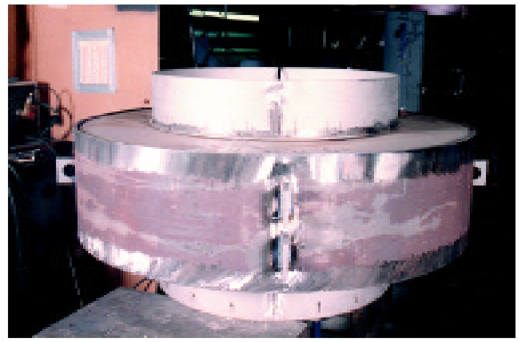
APPLICATIONS

Cross-section of HR-160® flue-gas stack annubar flow monitoring device for waste incineration and chemical process industries.



Lining (inner cylinder) of exhaust ducting in pulp and paper recovery boiler made from HR-160 alloy. Outer shell is carbon steel.

Many waste incineration and chemical process facilities have used HR-160 thermocouple protection tubes with outstanding success. Life extensions greater than 10X compared to Ni-Cr alloys and stainless steels are common.

HR-160 tube shields are considered the premier superheater tube shield material for municipal and industrial waste incineration systems. The use of HR-160 alloy has resulted in greatly improved life in municipal waste incinerators where high temperature corrosion and fly ash erosion are major considerations.

STANDARD PRODUCTS

HAYNES International

By Brand or Alloy Designation:

HASTELLOY® Family of Corrosion-Resistant Alloys

B-2, B-3™, C-4, C-22™, C-276, D-205™, G-3, G-30®, G-50®, H-9M™ and N

HASTELLOY Family of Heat-Resistant Alloys

S, W, and X

HAYNES® Family of Heat-Resistant Alloys

25, 31, R-41, 75, HR-120™, 150, 188, 214™, 230™, 230-W™, 242™, 263, 625, 718, X-750, MULTIMET® and WASPALOY

HAYNES Family of High-Temperature-Corrosion-Resistant Alloys

HR-160® and 556™

Corrosion-Wear Resistant Alloy

ULTIMET®

Wear-Resistant Alloy

6B

Super Stainless Steel

FERRALIUM® 255

HAYNES Titanium Alloy Tubular

Ti-3Al-2.5V

Standard Forms:

Bar, Billet, Remelt Materials, Plate, Sheet, Strip, Coils, Seamless or Welded Pipe & Tubing, Welding Wire and Coated Electrodes

Properties Data:

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