

HASTELLOY® C-4 alloy

Principal Features

A versatile Ni-Cr-Mo alloy with extremely high resistance to HAZ sensitization

HASTELLOY® C-4 alloy (UNS N06455) is the most (microstructurally) stable of the widely used nickel-chromium-molybdenum materials, which are well known for their resistance to many aggressive chemicals, in particular hydrochloric acid, sulfuric acid, and chlorides. This stability means that the alloy can be welded without fear of sensitization, i.e. the nucleation and growth of deleterious, second phase precipitates in the grain boundaries of the weld heat-affected zone (HAZ).

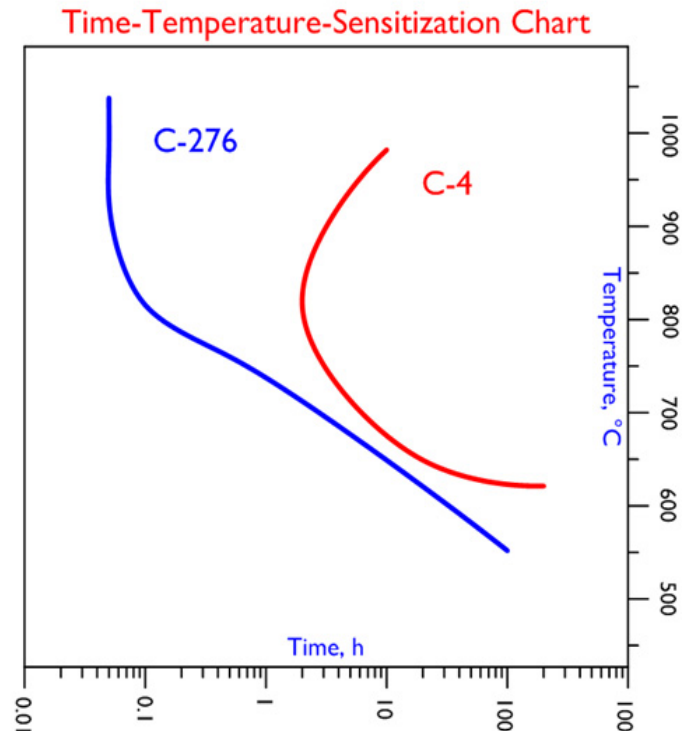
Like other nickel alloys, it is ductile, easy to form and weld, and possesses exceptional resistance to stress corrosion cracking in chloride-bearing solutions (a form of degradation to which the austenitic stainless steels are prone). With its high chromium and molybdenum contents, it is able to withstand both oxidizing and non-oxidizing acids, and is resistant to pitting and crevice attack in the presence of chlorides and other halides.

Nominal Composition

Weight %

Nickel:	65 Balance
Cobalt:	2 max.
Chromium:	16
Molybdenum:	16
Iron:	3 max.
Manganese:	1 max.
Titanium:	0.7 max.
Silicon:	0.08 max.
Carbon:	0.01 max.
Copper:	0.5 max.

Thermal Stability (T-T-S Chart)

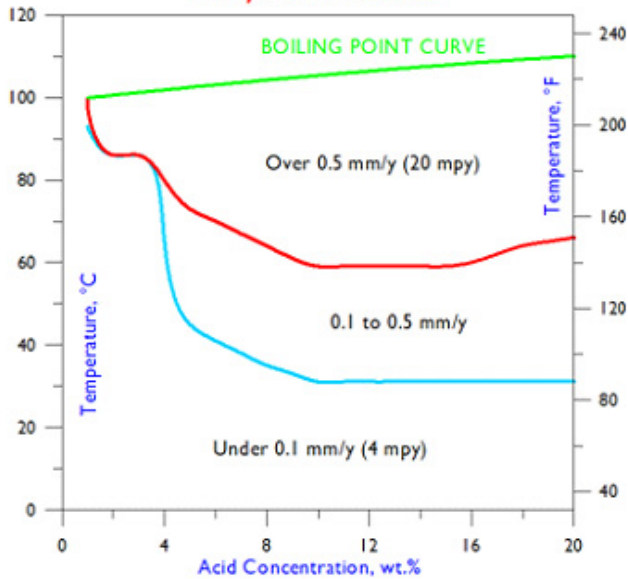


The above chart illustrates the large difference between the grain boundary precipitation kinetics of C-4 and C-276 alloys. It indicates that C-4 alloy must be held at the most critical temperature (825°C) for 2 hours before grain boundary precipitation is sufficient to cause preferential grain boundary attack of a significant nature, that is to a depth of 0.05 mm in the ASTM G 28A test solution (50% H₂SO₄ + 42 g/l Fe₂(SO₄)₃ at the boiling point). On the other hand, C-276 alloy is prone to significant grain boundary attack in this boiling solution after just 3 minutes at temperatures in the approximate range 925°C to 1050°C. This means that, during welding, heat input is important in the case of C-276 alloy, but of little consequence in the case of C-4 alloy.

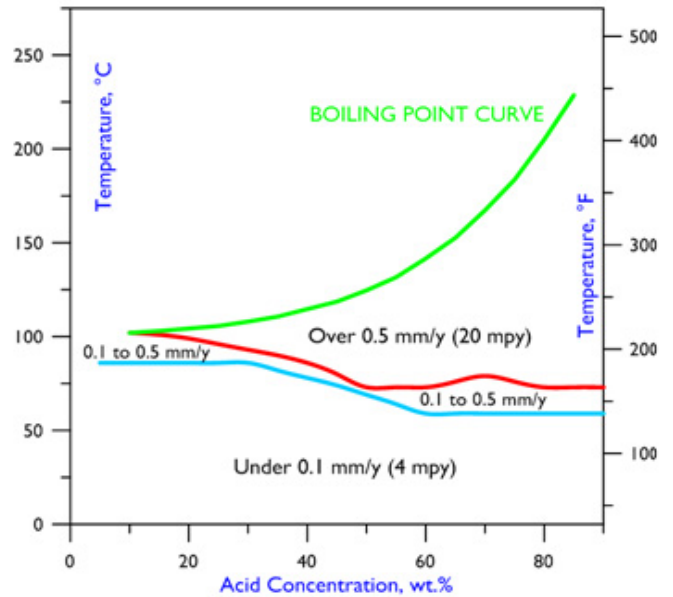
ISO-Corrosion Diagrams

Each of these iso-corrosion diagrams was constructed using numerous corrosion rate values, generated at different acid concentrations and temperatures. The blue line represents those combinations of acid concentration and temperature at which a corrosion rate of 0.1 mm/y (4 mils per year) is expected, based on laboratory tests in reagent grade acids. Below the line, rates under 0.1 mm/y are expected. Similarly, the red line indicates the combinations of acid concentration and temperature at which a corrosion rate of 0.5 mm/y (20 mils per year) is expected. Above the line, rates over 0.5 mm/y are expected. Between the blue and red lines, corrosion rates are expected to fall between 0.1 and 0.5 mm/y.

Iso-Corrosion Diagram for C-4 Alloy
in Hydrochloric Acid



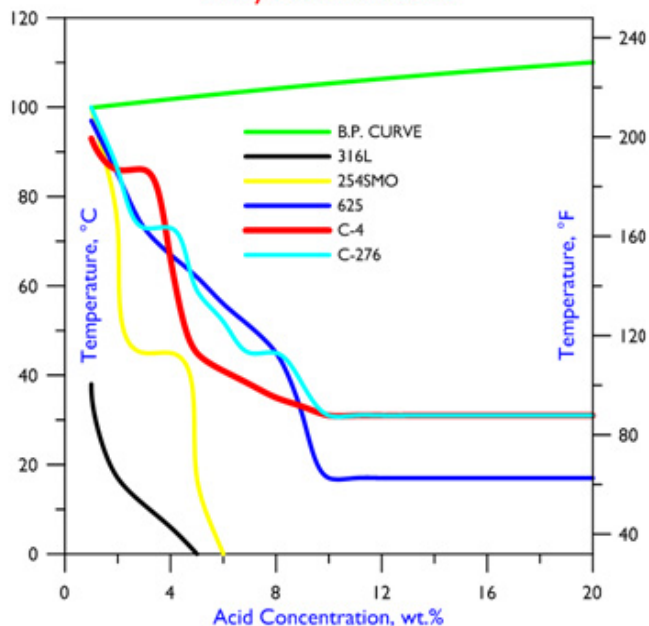
Iso-Corrosion Diagram for C-4 Alloy
in Sulfuric Acid



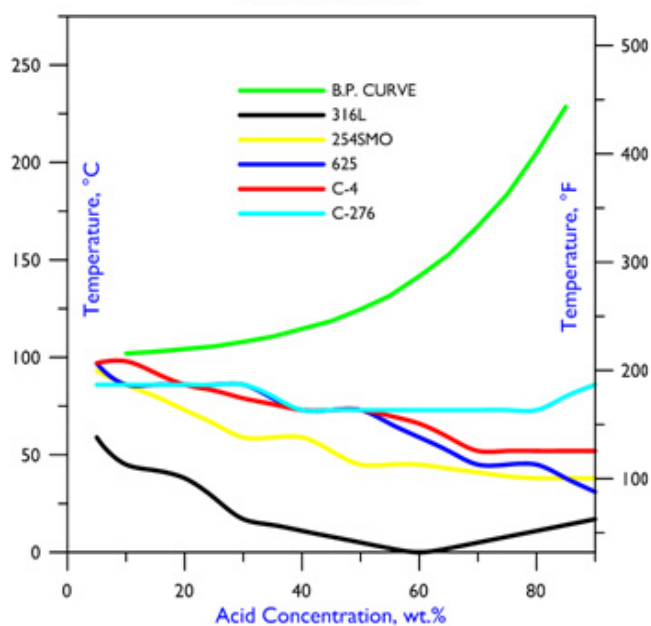
Comparative 0.1 mm/y Line Plots

To compare the performance of HASTELLOY® C-4 alloy with that of other materials, it is useful to plot the 0.1 mm/y lines. In the following graphs, the lines for C-4 alloy are compared with those of two popular, austenitic stainless steels (316L and 254SMO), a lower-molybdenum nickel alloy (625), and C-276 alloy in hydrochloric and sulfuric acids. At hydrochloric acid concentrations above about 5%, C-4 alloy provides a quantum improvement over the stainless steels, and offers greater resistance to higher concentrations of both acids than alloy 625. The concentration limit of 20% hydrochloric acid is the azeotrope, beyond which high temperature corrosion tests are less reliable.

Comparison of 0.1 mm/y Lines in Hydrochloric Acid



Comparison of 0.1 mm/y Lines in Sulfuric Acid



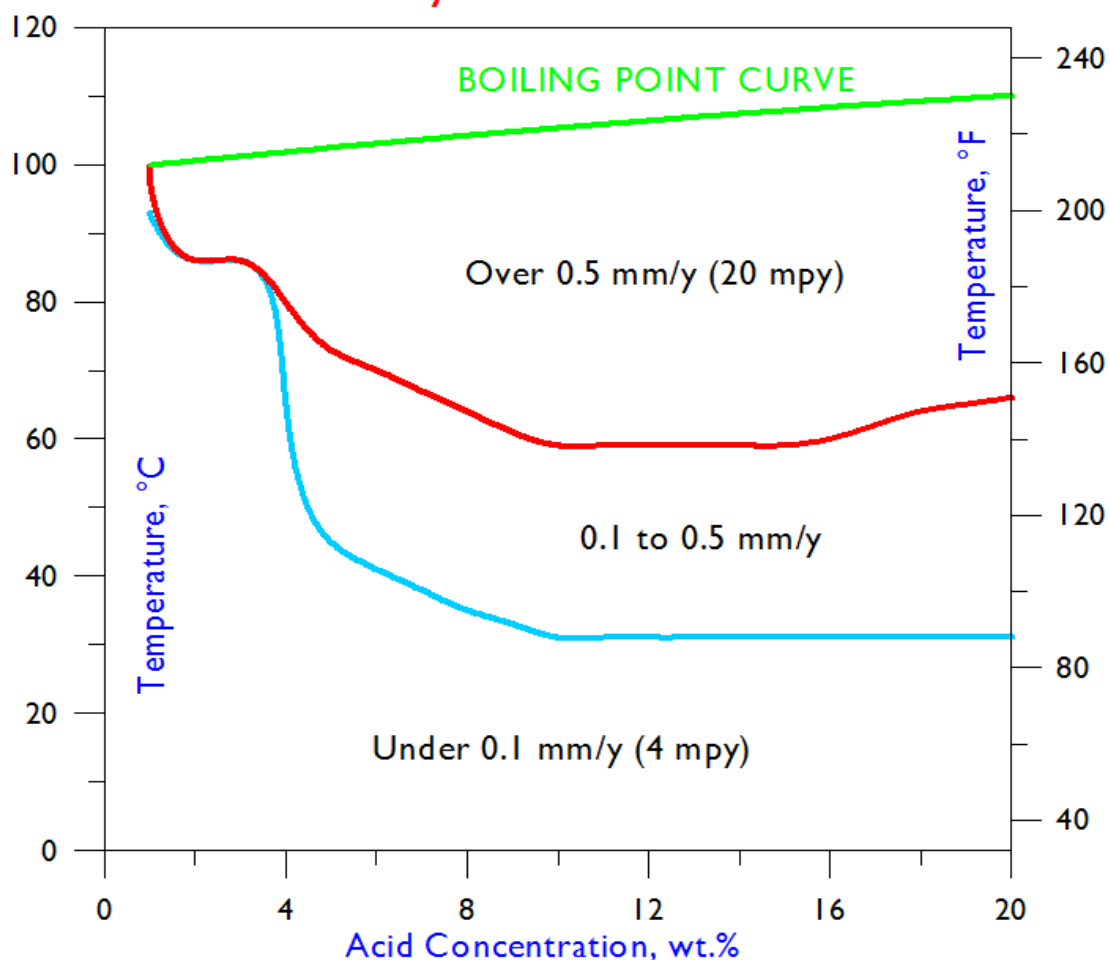
Selected Corrosion Data

Hydrochloric Acid

Conc. Wt.%	50°F	75°F	100°F	125°F	150°F	175°F	200°F	225°F	Boiling
	10°C	24°C	38°C	52°C	66°C	79°C	93°C	107°C	
1	-	-	<0.01	-	<0.01	<0.01	0.1	-	0.48
1.5	-	-	-	-	-	-	-	-	-
2	-	-	-	-	0.01	0.03	-	-	1.99
2.5	-	-	-	-	-	-	-	-	-
3	-	-	-	-	0.02	0.04	-	-	-
3.5	-	-	-	-	-	-	-	-	-
4	-	-	-	-	-	-	-	-	-
4.5	-	-	-	-	-	-	-	-	-
5	-	-	<0.01	0.27	0.42	0.98	-	-	4.37
7.5	-	-	-	-	-	-	-	-	-
10	-	0.06	0.19	0.3	0.57	1.11	-	-	6.91
15	-	0.06	0.18	0.39	0.57	1.33	2.33	-	6.35
20	-	0.05	0.14	0.27	0.55	1.12	2.19	-	5.72

All corrosion rates are in millimeters per year (mm/y); to convert to mils (thousandths of an inch) per year, divide by 0.0254. Data are from Corrosion Laboratory Jobs 2-74 and 73-96. All tests were performed in reagent grade acids under laboratory conditions; field tests are encouraged prior to industrial use.

Iso-Corrosion Diagram for C-4 Alloy in Hydrochloric Acid



Selected Corrosion Data Continued

Sulfuric Acid

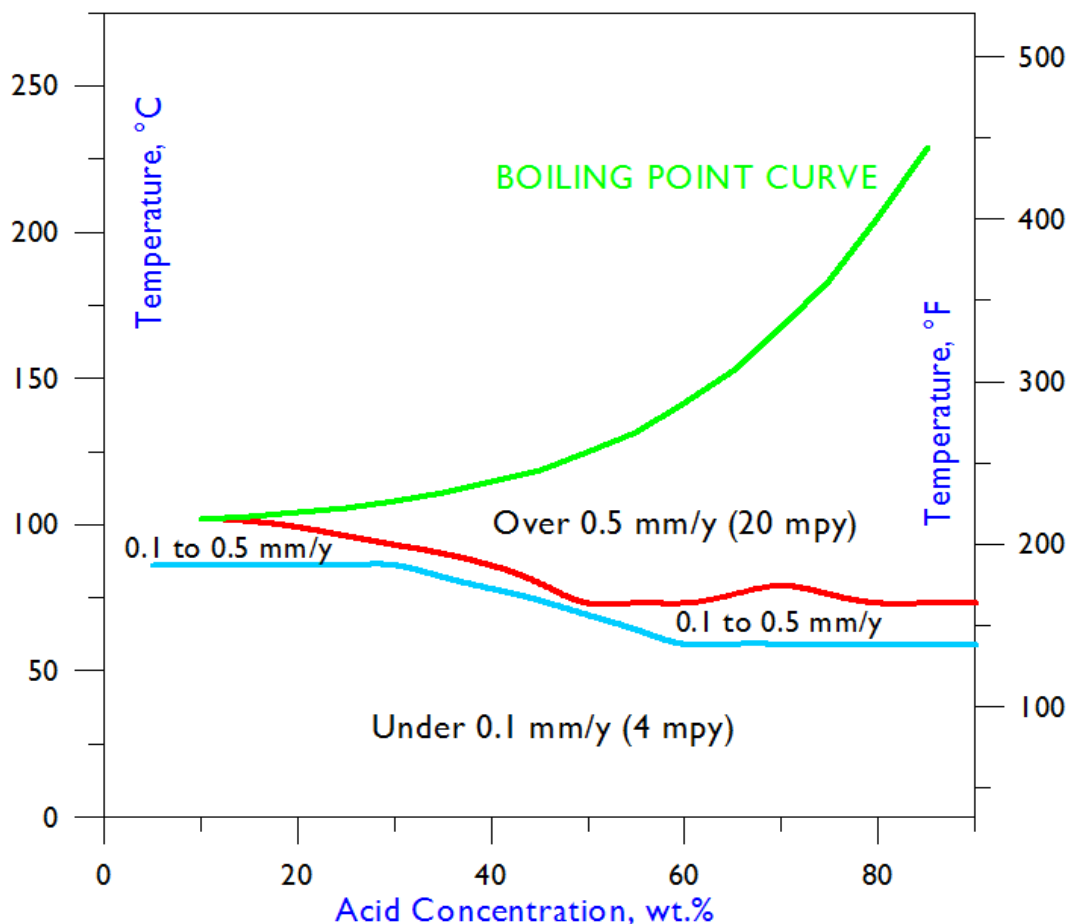
Conc. Wt.%	75°F	100°F	125°F	150°F	175°F	200°F	225°F	250°F	275°F	300°F	350°F	Boiling
	24°C	38°C	52°C	66°C	79°C	93°C	107°C	121°C	135°C	149°C	177°C	
1	-	-	-	-	-	-	-	-	-	-	-	-
2	-	-	-	-	-	-	-	-	-	-	-	-
3	-	-	-	-	-	-	-	-	-	-	-	-
4	-	-	-	-	-	-	-	-	-	-	-	-
5	-	-	-	0.01	0.02	-	-	-	-	-	-	0.41
10	-	<0.01	-	0.01	0.03	0.19	-	-	-	-	-	0.43
20	-	-	-	0.01	0.05	0.38	-	-	-	-	-	0.89
30	-	<0.01	-	0.02	0.07	0.54	-	-	-	-	-	1.85
40	-	-	<0.01	0.03	0.38	0.87	-	-	-	-	-	3.63
50	-	0.02	0.01	0.03	0.63	0.99	-	-	-	-	-	9.96
60	-	-	0.03	0.15	0.67	1.24	-	-	-	-	-	-
70	-	0.04	0.06	0.14	0.46	0.94	-	-	-	-	-	-
80	-	-	0.04	0.13	1.1	2.47	-	-	-	-	-	-
90	-	0.04	0.05	0.19	0.71	2.63	-	-	-	-	-	-
96	-	-	-	-	-	-	-	-	-	-	-	-

All corrosion rates are in millimeters per year (mm/y); to convert to mils (thousandths of an inch) per year, divide by 0.0254.

Data are from Corrosion Laboratory Jobs 19-73, 24-94, and 68-96.

All tests were performed in reagent grade acids under laboratory conditions; field tests are encouraged prior to industrial use.

Iso-Corrosion Diagram for C-4 Alloy in Sulfuric Acid



Selected Corrosion Data (Reagent Grade Solutions, mm/y)

Chemical	Concentration	100°F	125°F	150°F	175°F	200°F	Boiling
	wt.%	38°C	52°C	66°C	79°C	93°C	
Hydrobromic Acid	2.5	-	-	<0.01	-	<0.01	0.08
	5	-	-	<0.01	0.01	0.76	-
	7.5	-	-	0.03	0.18	0.76	-
	10	-	<0.01	0.37	0.53	-	-
	15	<0.01	0.24	0.37	0.56	-	-
	20	0.15	0.24	0.35	0.51	-	-
	30	0.1	0.16	0.23	0.41	0.67	-
	40	-	0.11	0.17	0.28	0.44	-
Hydrochloric Acid	1	<0.01	-	<0.01	<0.01	0.1	0.48
	2	-	-	0.01	0.03	-	1.99
	3	-	-	0.02	0.04	-	-
	5	<0.01	0.27	0.42	0.98	-	-
	10	0.19	0.3	0.57	1.11	-	-
	15	0.18	0.39	0.57	1.33	-	-
	20	0.14	0.27	0.55	1.12	-	-
Hydrofluoric Acid*	5	-	-	-	0.59	-	-
Sulfuric Acid	10	<0.01	-	0.01	0.03	0.19	0.43
	20	-	-	0.01	0.05	0.38	0.89
	30	<0.01	-	0.02	0.07	0.54	1.85
	40	-	<0.01	0.03	0.38	0.87	-
	50	0.02	0.01	0.03	0.63	0.99	-
	60	-	0.03	0.15	0.67	1.24	-
	70	0.04	0.06	0.14	0.46	0.94	-
	80	-	0.04	0.13	1.1	2.47	-
	90	0.04	0.05	0.19	0.71	2.63	-

*Hydrofluoric acid can also induce internal attack of nickel alloys; these values represent only external attack.

Resistance to Pitting & Crevice Corrosion

HASTELLOY® C-4 alloy exhibits high resistance to chloride-induced pitting and crevice attack, forms of corrosion to which the austenitic stainless steels are particularly prone. To assess the resistance of alloys to pitting and crevice attack, it is customary to measure their Critical Pitting Temperatures and Critical Crevice Temperatures in acidified 6 wt.% ferric chloride, in accordance with the procedures defined in ASTM Standard G 48. These values represent the lowest temperatures at which pitting and crevice attack are encountered in this solution, within 72 hours. For comparison, the values for 316L, 254SMO, 625, and C-4 alloys are as follows:

Alloy	Critical Pitting Temperature in Acidified 6% FeCl ₃		Critical Crevice Temperature in Acidified 6% FeCl ₃	
	°F	°C	°F	°C
-				
316L	59	15	32	0
254SMO	140	60	86	30
625	212	100	104	40
C-4	212	100	122	50

Other chloride-bearing environments, notably Green Death (11.5% H₂SO₄ + 1.2% HCl + 1% FeCl₃ + 1% CuCl₂) and Yellow Death (4% NaCl + 0.1% Fe₂(SO₄)₃ + 0.021M HCl), have been used to compare the resistance of various alloys to pitting (using tests of 24 hours duration). In Green Death, the lowest temperature at which pitting has been observed in C-4 alloy is 85°C. In Yellow Death, C-4 alloy has not exhibited pitting at temperatures up to 120°C (the maximum to which C-4 alloy has been exposed).

Resistance to Stress Corrosion Cracking

One of the chief attributes of the nickel alloys is their resistance to chloride-induced stress corrosion cracking. A common solution for assessing the resistance of materials to this extremely destructive form of attack is boiling 45% magnesium chloride (ASTM Standard G 36), typically with stressed U-bend samples. As is evident from the following results, the two nickel alloys, C-4 and 625, are much more resistant to this form of attack than the comparative, austenitic stainless steels. The tests were stopped after 1,008 hours (six weeks).

Alloy	Time to Cracking
316L	2 h
254SMO	24 h
625	No Cracking in 1,008 h
C-4	No Cracking in 1,008 h

Physical Properties

Physical Property	British Units		Metric Units	
Density	RT	0.312 lb/in ³	RT	8.64 g/cm ³
Electrical Resistivity	RT	49.1 μohm.in	RT	1.25 μohm.m
	200°F	49.1 μohm.in	100°C	1.25 μohm.m
	400°F	49.6 μohm.in	200°C	1.26 μohm.m
	600°F	50.0 μohm.in	300°C	1.27 μohm.m
	800°F	50.5 μohm.in	400°C	1.28 μohm.m
	1000°F	51.3 μohm.in	500°C	1.29 μohm.m
	-	-	600°C	1.32 μohm.m
Thermal Conductivity	RT	70 Btu.in/h.ft ² .°F	RT	10.1 W/m.°C
	200°F	79 Btu.in/h.ft ² .°F	100°C	11.4 W/m.°C
	400°F	92 Btu.in/h.ft ² .°F	200°C	13.2 W/m.°C
	600°F	105 Btu.in/h.ft ² .°F	300°C	15.0 W/m.°C
	800°F	119 Btu.in/h.ft ² .°F	400°C	16.7 W/m.°C
	1000°F	133 Btu.in/h.ft ² .°F	500°C	18.4 W/m.°C
	-	-	600°C	20.5 W/m.°C
Mean Coefficient of Thermal Expansion	68-200°F	6.0 μin/in.°F	24-100°C	10.9 μm/m.°C
	68-400°F	6.6 μin/in.°F	24-200°C	11.8 μm/m.°C
	68-600°F	7.0 μin/in.°F	24-300°C	12.5 μm/m.°C
	68-800°F	7.2 μin/in.°F	24-400°C	12.9 μm/m.°C
	68-1000°F	7.4 μin/in.°F	24-500°C	13.2 μm/m.°C
	68-1200°F	7.5 μin/in.°F	24-600°C	13.4 μm/m.°C
Specific Heat	32°F	0.097 Btu/lb.°F	0°C	406 J/kg.°C
	200°F	0.102 Btu/lb.°F	100°C	427 J/kg.°C
	400°F	0.107 Btu/lb.°F	200°C	448 J/kg.°C
	600°F	0.111 Btu/lb.°F	300°C	465 J/kg.°C
	800°F	0.115 Btu/lb.°F	400°C	477 J/kg.°C
	1000°F	0.118 Btu/lb.°F	500°C	490 J/kg.°C
	-	-	600°C	502 J/kg.°C
Dynamic Modulus of Elasticity	RT	30.8 x 10 ⁶ psi	RT	212 GPa
	200°F	30.2 x 10 ⁶ psi	100°C	208 GPa
	400°F	29.3 x 10 ⁶ psi	200°C	202 GPa
	600°F	28.3 x 10 ⁶ psi	300°C	196 GPa
	800°F	27.3 x 10 ⁶ psi	400°C	190 GPa
	1000°F	26.2 x 10 ⁶ psi	500°C	183 GPa
	1200°F	25.0 x 10 ⁶ psi	600°C	176 GPa

RT= Room Temperature

Impact Strength

Test Temperature		Impact Strength	
°F	°C	ft-lbf	J
RT	RT	281	381
-320	-196	215	292

Limited data

Impact strengths were generated using Charpy V-notch samples, machined from mill annealed plate.

Tensile Strength & Elongation

Form	Test Temperature		Thickness		0.2% Offset Yield Strength		Ultimate Tensile Strength		Elongation
	°F	°C	in	mm	ksi	MPa	ksi	MPa	%
Sheet	RT	RT	0.065	1.7	60.3	416	111.4	768	52
Sheet	400	204	0.065	1.7	58.5	403	102.4	706	49
Sheet	600	316	0.065	1.7	53.8	371	97.9	675	52
Sheet	800	427	0.065	1.7	46.4	320	95.2	656	64
Sheet	RT	RT	0.125	3.2	61	421	116.2	801	54
Sheet	400	204	0.125	3.2	46.4	320	98.3	678	54
Sheet	600	316	0.125	3.2	43.9	303	97.5	672	59
Sheet	800	427	0.125	3.2	43.9	303	93.4	644	62
Sheet	1000	538	0.125	3.2	43.4	299	93.5	645	55
Sheet	RT	RT	0.156	4	53	365	113.5	783	55
Sheet	400	204	0.156	4	39.9	275	99.9	689	55
Sheet	600	316	0.156	4	36.1	249	95.3	657	61
Sheet	800	427	0.156	4	36.2	250	95.1	656	68
Plate	RT	RT	0.25	6.3	48.8	336	111.3	767	58
Plate	400	204	0.25	6.3	42.8	295	104	717	54
Plate	600	316	0.25	6.3	40.8	281	103.3	712	55
Plate	800	427	0.25	6.3	37	255	99	683	60
Plate	RT	RT	0.375	9.5	51.6	356	114.7	791	59
Plate	400	204	0.375	9.5	43.6	301	105.4	727	56
Plate	600	316	0.375	9.5	39.1	270	102.1	704	59
Plate	800	427	0.375	9.5	37.4	258	96.3	657	62
Plate	1000	538	0.375	9.5	33	228	93.3	643	52
Plate	RT	RT	0.5	12.7	48.6	335	116.8	805	63
Plate	400	204	0.5	12.7	38.3	264	105.2	725	61
Plate	600	316	0.5	12.7	35.8	247	102.5	707	65
Plate	800	427	0.5	12.7	34.2	236	99.8	688	66
Plate	1000	538	0.5	12.7	29.8	205	92.1	635	71

RT= Room Temperature

Hardness

Form	Hardness, HRBW	Typical ASTM Grain Size
Sheet	92	6 - 7.5
Plate	90	4 - 6

All samples tested in solution-annealed condition.

HRBW = Hardness Rockwell "B", Tungsten Indentor.

Welding & Fabrication

HASTELLOY® C-4 alloy is very amenable to the Gas Metal Arc (GMA/MIG), Gas Tungsten Arc (GTA/TIG), and Shielded Metal Arc (SMA/Stick) welding processes. Matching filler metals (i.e. solid wires and coated electrodes) are available for these processes, and welding guidelines are given in our "Welding and Fabrication" brochure.

Wrought products of HASTELLOY® C-4 alloy are supplied in the Mill Annealed (MA) condition, unless otherwise specified. This solution annealing procedure has been designed to optimize the alloy's corrosion resistance and ductility. Following all hot forming operations, the material should be re-annealed, to restore optimum properties. The alloy should also be re-annealed after any cold forming operations that result in an outer fiber elongation of 7% or more. The annealing temperature for HASTELLOY® C-4 alloy is 1066°C (1950°F), and water quenching is advised (rapid air cooling is feasible with structures thinner than 10 mm (0.375 in)). A hold time at the annealing temperature of 10 to 30 minutes is recommended, depending on the thickness of the structure (thicker structures need the full 30 minutes). More details concerning the heat treatment of HASTELLOY® C-4 alloy are given in our "Welding and Fabrication" brochure.

HASTELLOY® C-4 alloy can be hot forged, hot rolled, hot upset, hot extruded, and hot formed. However, it is more sensitive to strain and strain rates than the austenitic stainless steels, and the hot working temperature range is quite narrow. For example, the recommended start temperature for hot forging is 1177°C (2150°F) and the recommended finish temperature is 954°C (1750°F). Moderate reductions and frequent re-heating provide the best results, as described in our "Welding and Fabrication" brochure. This reference also provides guidelines for cold forming, spinning, drop hammering, punching, and shearing. The alloy is stiffer than most austenitic stainless steels, and more energy is required during cold forming. Also, HASTELLOY® C-4 alloy work hardens more readily than most austenitic stainless steels, and may require several stages of cold work, with intermediate anneals.

While cold work does not usually affect the resistance of HASTELLOY® C-4 alloy to general corrosion, and to chloride-induced pitting and crevice attack, it can affect resistance to stress corrosion cracking. For optimum corrosion performance, therefore, the re-annealing of cold worked parts (following an outer fiber elongation of 7% or more) is important.

Specifications & Codes

Specifications

HASTELLOY® C-4 alloy (N06455, W86445)	
Sheet, Plate & Strip	SB 575/B 575 P= 43
Billet, Rod & Bar	SB 574/B 574 P= 43
Coated Electrodes	SFA 5.11/A 5.11 (ENiCrMo-7) DIN 2.4612 (EL-NiMo15Cr15Ti) F= 43
Bare Welding Rods & Wire	SFA 5.14/ A 5.14 (ERNiCrMo-7) DIN 2.4611 (SG-NiMo16Cr16Ti) F= 43
Seamless Pipe & Tube	SB 622/B 622 P= 43
Welded Pipe & Tube	SB 619/B 619 SB 626/B 626 P= 43
Fittings	SB 366/B 366 P= 43
Forgings	-
DIN	17744 No. 2.4610 NiMo16Cr16Ti
TÜV	Werkstoffblatt 424 Kennblatt 2666 Kennblatt 2667 Kennblatt 2665
Others	NACE MR0175 ISO 15156

Codes

HASTELLOY® C-4 alloy (N06455, W86445)				
ASME	Section I	-		
	Section III	Class 1	-	
		Class 2	-	
		Class 3	-	
	Section VIII	Div. 1	PSBfWs-800°F (427°C) Blt-800°F (427°C)	
		Div. 2	PSBWs-800°F (427°C) Blt-800°F (427°C)	
	Section XII	PSBfWs-650°F (343°C) Blt-800°F (427°C)		
	B16.5	PFf-800°F (427°C) Blt		
	B16.34	PBFs-800°F (427°C) Blt		
	B31.1	-		
B31.3	PSBfWs 800°F (427°C)			
VdTÜV (doc #)		PSBFs- 752°F (400°C), #424		

¹Approved material forms: Plate, Sheet, Bar, fittings, welded pipe/tube, seamless pipe/tube, bolting

²Approved material forms: Plate, Sheet, Bar, welded pipe/tube, seamless pipe/tube

³Approved material forms: Bolting

⁴Approved material forms: Plate, Bar, Forgings, seamless pipe/tube, bolting

⁵Approved material forms: Plate, Sheet, Bar, fittings, welded pipe/tube, seamless pipe/tube

⁶Approved material forms: Plate, Sheet, Bar, Forgings, seamless pipe/tube

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