product/data

Bulletin No. S-21c
Armco 15-5 PH VAC CE

Armco 15-5 PH VAC CE or ESR AMS 5659 - II Precipitation-Hardening Stainless Steel

(XM-12, UNS S15500)

Bar, Wire and Forging Billets

Armco 15-5 PH VAC CE is a precipitation-hardening stainless steel that offers a unique combination of high strength and hardness, good corrosion resistance plus excellent transverse toughness and good forgeability.

Armco 15-5 PH stainless is produced by consumable electrode vacuum arc remelting (designated VAC CE) to meet the stringent mechanical property and cleanliness requirements of the space and nuclear industries. Besides lowering gas content, VAC CE adds other advantages to Armco 15-5 PH VAC CE stainless. It reduces and disperses inclusions, and minimizes alloy segregation during solidification.

EXCELLENT TRANSVERSE PROPERTIES

These factors, coupled with the elimination of delta ferrite, combine to give Armco 15-5 PH VAC CE stainless excellent transverse mechanical properties in any test location. Consequently, it has good transverse notch-toughness and forgeability. In severe upset forging or hot flattening operations where splitting or rupturing are encountered with high strength steels, Armco 15-5 PH VAC CE stainless offers valuable advantages. Its forgeability is superior to Armco 17-4 PH stainless steel.

READILY FABRICATED

Fabrication practices for Armco 15-5 PH VAC CE stainless are generally the same as those established for Armco 17-4 PH stainless steel. Most techniques are similar to those recommended for the regular grades of stainless steel. Hardening heat treatments require temperatures of only 900 F (482 C) to 1150 F (621 C), depending on the properties desired. As a result, scaling and distortion difficulties are virtually eliminated. Armco 15-5 PH VAC CE stainless has good machining properties. Excellent surface finish can be produced with conventional tooling.

The information and data in this bulletin are accurate to the best of our knowledge and belief, but are intended for general information only. Applications suggested for the materials are described only to help the reader make his own evaluation and decision, and are neither guarantees nor to be construed as express or implied warranties of suitability for these or other applications.

Data referring to mechanical properties and chemical analyses are the result of tests performed on specimens obtained from specific locations of the products in accordance with prescribed sampling procedures; any warranty thereof is limited to the values obtained at such locations and by such procedures. There is no warranty with respect to values of the materials at other locations.

AK Steel s.r.l.
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ARMCO

COMPOSITION

	%		
Carbon	0.07 max	Silicon	1.00 max
Manganese	1.00 max	Chromium	14.00-15.50
Phosphorus	0.04 max	Nickel	3.50-5.50
Sulfur	0.03 max	Copper	2.50-4.50
		Columbium plus Tantalum	0.15-0.45

AVAILABLE FORMS

Armco 15-5 PH VAC CE stainless steel is produced in the form of billets, plate, bar and wire. It is usually supplied in the solution treated Condition A ready for fabrication and subsequent hardening by the user. However, it can be supplied in certain hardened conditions if so desired. Material for forging should be ordered in the overaged condition. Wire for cold heading should be ordered overaged, coated and cold drawn.

Conditions Available from Mill

1) Condition A (Solution treated)	Material for fabrication and heat treatment by the user. If severe cold forming is required use Condition H 1150 or H 1150-M.
2) Condition H 1075	Precipitation-hardened condition. Machines as well as Condition A.
3) Condition H 1150	Precipitation-hardened condition. More readily fabricated than Condition A. No further heat treatment necessary where no severe cold working is involved.
4) Overaged for forging	Allows hot forging of all sections without thermal cracking.
5) Overaged, copper coated and cold drawn for cold heading	Maximum softness for cold heading. Materials in this condition will not respond to aging treatments without first solution treating.
6) Other Conditions	Inquire for availability.

APPLICATIONS

Armco 15-5 PH VAC CE stainless steel is currently used in applications requiring high strength and toughness in all directions. Typical applications include forgings, pump and valve parts for high pressure systems requiring good corrosion resistance, pressure transducers, aircraft components and transversely loaded plate applications.

SPECIFICATIONS

Armco 15-5 PH bar, wire, forgings and forging stock is covered by the following specifications. It is suggested that the issuing agency be contacted for the latest revision of the specification. Armco 15-5 PH is listed as Grade XM-12 (UNS S15500) in:

ASTM A 564 Hot-Finished or Cold-Finished Age Hardening Stainless and Heat-Resisting Steel Bars and Shapes

ASTM A 693 Plate, Sheet and Strip

ASTM A 705 Age Hardening and Heat-Resisting Steel Forgings

AMS 5659 Consumable Electrode Melted Bars, Forgings and Rings

STANDARD HEAT TREATMENTS

Armco 15-5 PH VAC CE stainless steel can be heat treated at different temperatures to develop a wide range of properties. Fully hardened 15-5 PH VAC CE stainless, Condition H 900, will have a minimum ultimate tensile strength of 190,000 psi (1310 MPa) and minimum yield strength of 170,000 psi (1172 MPa). Typical properties for the standard conditions are shown in Tables IV and V.

15-5 PH VAC CE HEAT TREATMENTS

Condition A
Solution Treated
1900 F ±25 F
(1036 C ±14 C)
Oil or Air Cool
below 90 F (32 C)

Condition	Heat to ±15 F (±9 C)	Hold for Hours	Cool
H 900	900 F (482 C)	1	Air
H 925	925 F (495 C)	4	Air
H 1025	1025 F (552 C)	4	Air
H 1075	1075 F (579 C)	4	Air
H 1100	1100 F (593 C)	4	Air
H 1150	1150 F (621 C)	4	Air
H 1150-M (Double Overaged)	1400 F (760 C)	2	Air
	1150 F (621 C)	Followed by 4	Air

Armco 15-5 PH VAC CE stainless exhibits useful mechanical properties in Condition A, and tests in progress at Kure Beach for more than seven years show excellent stress corrosion cracking resistance. Condition A material can be used successfully in numerous applications without subsequent heat treating.

However, in critical applications, Armco 15-5 PH VAC CE stainless should be used in the precipitation-hardened condition, rather than Condition A. Heat treating to the hardened conditions, especially at the higher end of the temperature range, stress relieves the structure and may provide more reliable resistance to stress corrosion cracking than Condition A.

In applications where the use of 15-5 PH VAC CE stainless in Condition A is being considered, it is suggested that Armco be contacted for technical assistance.

Heat-Treating Cycle for Forging

If 15-5 PH VAC CE stainless is to be forged, it is supplied "overaged for forging." Overaging consists of heat treatment at the mill in the temperature range of 1150 to 1200 F (621 to 648 C). Such treatment eliminates the possibility of cracking during the heating and forging operation. Material in this condition will not respond to hardening treatments without first solution treating.

METRIC PRACTICE

The values shown in this bulletin were established in U.S. customary units. The metric equivalents of U.S. customary units shown may be approximate. Conversion to the metric system, known as the International System of Units (SI), has been accomplished in accordance with the American Iron and Steel Institute Metric Practice Guide, 1978.

The newton (N) has been adopted by the SI as the metric standard unit of force as discussed in the AISI Metric Practice Guide. The term for force per unit of area (stress) is the newton per square metre (N/m^2). Since this can be a large number, the prefix mega is used to indicate 1,000,000 units and the term meganewton per square metre (MN/m^2) is used. The unit (N/m^2) has been designated a pascal (Pa). The relationship between the U.S. and the SI units for stress is: 1000 pounds/in² (psi) = 1 kip/in² (ksi) = 6.8948 meganewtons/m² (MN/m^2) = 6.8948 megapascals (MPa). Other units are discussed in the Metric Practice Guide.

Orientation and Location of Test Specimens

Armco 15-5 PH VAC CE stainless is needed in many applications requiring excellent mechanical properties in the long transverse and short transverse directions, as well as in the longitudinal direction (direction of rolling). Orientation and location of the test specimen and product section size are receiving more emphasis in the determination of design values. The data included in this bulletin are identified regarding (1) orientation of specimen, (2) specimen location, and (3) section size from which the test specimens were taken. Orientation and location of test specimens are shown in the following sketches. Unless otherwise stated, data represents longitudinal direction — intermediate location.

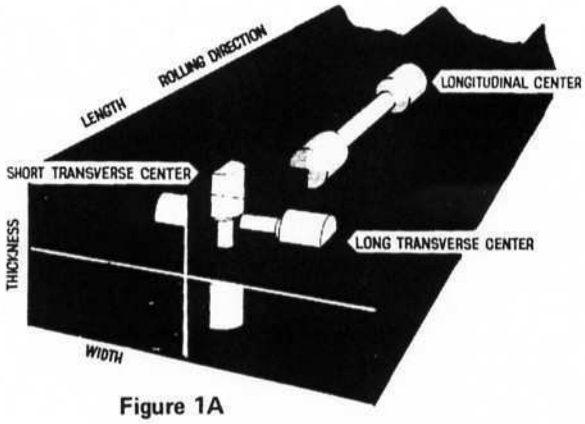


Figure 1A

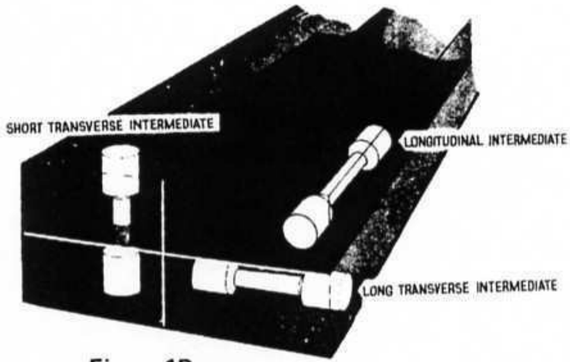


Figure 1B

Sketches showing the orientation and location of test specimens in a typical bar section. Fig. 1A shows specimens located at the center or along the axes of the respective bar dimensions. Fig. 1B illustrates the location of test specimens to determine properties at intermediate locations.

(1) Transverse properties cannot be determined if bar dimensions are under 3" (76.2 mm) in the test direction.

(2) In rounds, squares, and hexagon bars, no short transverse direction exists.

Properties Acceptable for Material Specifications

Table I
Maximum Hardness or Tensile Strength in Condition A

Rounds, Hexagons and Squares			Flats
1/8" (3.18 mm) and Smaller	Over 1/8" to 1/2" Incl (3.18 mm to 12.7 mm Incl)	Over 1/2" (12.7 mm)	Over 1/2" (12.7 mm)
175,000 psi (1207 MPa) max	R_C 38 max	BHN 363 max	BHN 363

Table II
Minimum Properties (Suitable for Specifications)
Longitudinal Direction — Intermediate Location (up to 12" [304.8 mm] section)

	Condition						
	H 900	H 925	H 1025	H 1075	H 1100	H 1150	H 1150-M
Ultimate Tensile Strength, ksi (MPa)	190 (1310)	170 (1172)	155 (1069)	145 (1000)	140 (965)	135 (931)	115 (793)
0.2% Yield Strength, ksi (MPa)	170 (1172)	155 (1069)	145 (1000)	125 (862)	115 (793)	105 (724)	75 (517)
Elongation, % in 2" (50.8 mm) or 4 x D	10.0	10.0	12.0	13.0	14.0	16.0	18.0
Reduction of Area, %	35.0	38.0	45.0	45.0	45.0	50.0	55.0
Hardness Brinell Rockwell	388/448 C40/47	375/438 C38/45	331/401 C35/42	302/375 C32/39	294/364 C31/38	277/352 C28/37	255/293 C24/30
Impact, Charpy V-Notch, ft-lbs (J)	•	5 (6.8)	15 (20)	20 (27)	25 (34)	30 (41)	55 (75)

Table III
Minimum Properties (Suitable for Specifications)
Transverse Direction (up to 12" [304.8 mm] section)

Property	Condition						
	H 900	H 925	H 1025	H 1075	H 1100	H 1150	H 1150-M
Ultimate Tensile, Strength, ksi (MPa)	190 (1310)	170 (1172)	155 (1069)	145 (1000)	140 (965)	135 (931)	115 (793)
0.2% Yield Strength, ksi (MPa)	170 (1172)	155 (1069)	145 (1000)	125 (862)	115 (793)	105 (724)	75 (517)
Elongation, % in 2" (50.8 mm) or 4 x D	6.0	7.0	8.0	9.0	10.0	11.0	14.0
Reduction of Area, %	15.0	20.0	27.0	28.0	29.0	30.0	35.0
Hardness Brinell	388/448	375/438	331/401	302/375	311/364	277/352	255/293
Rockwell	C40/47	C38/45	C35/42	C31/39	C32/38	C28/37	C24/30
Impact, Charpy V-Notch, ft-lbs (J) Intermediate Location	*	*	10 (14)	15 (20)	15 (20)	20 (27)	35 (47)

*Minimum impact properties cannot be accepted in this condition. If toughness is a design criteria, this heat treatment should be used with caution.

Typical Properties

Table IV
Typical Mechanical Properties**
Longitudinal Direction — Intermediate Location

Property	Condition						
	H 900	H 925	H 1025	H 1075	H 1100	H 1150	H 1150-M
Ultimate Tensile Strength, ksi (MPa)	200 (1379)	190 (1310)	170 (1172)	165 (1138)	150 (1034)	145 (1000)	125 (862)
0.2% Yield Strength, ksi (MPa)	185* (1276)	175 (1207)	165 (1138)	150 (1034)	135 (931)	125 (862)	85 (586)
Elongation, % in 2" (50.8 mm) or 4 x D	14.0	14.0	15.0	16.0	17.0	19.0	22.0
Reduction of Area, %	50.0	54.0	56.0	58.0	58.0	60.0	68.0
Hardness Brinell	420	409	352	341	332	311	277
Rockwell	C44	C42	C38	C36	C34	C33	C27
Impact, Charpy V-Notch, ft-lbs (J)	15 (20)	25 (34)	35 (47)	40 (54)	45 (61)	50 (68)	100 (136)

*Compressive yield strength for Condition H 900 is 178,000 psi (1227 MPa).
**Typical data represent average values of qualification tests for production orders.

Table V
Typical Mechanical Properties**
Transverse Direction — Intermediate and Center Location

Property	H 900		H 925		H 1025		H 1075		H 1100		H 1150		H 1150-M	
	I*	C*	I*	C*	I*	C*	I*	C*	I*	C*	I*	C*	I*	C*
Ultimate Tensile Strength, ksi (MPa)	200 (1379)	200 (1379)	190 (1310)	190 (1310)	170 (1172)	170 (1172)	165 (1138)	165 (1138)	150 (1034)	150 (1034)	145 (1000)	145 (1000)	125 (862)	125 (862)
0.2% Yield Strength, ksi (MPa)	185 (1276)	185 (1276)	175 (1207)	175 (1207)	165 (1138)	165 (1138)	150 (1034)	150 (1034)	135 (931)	135 (931)	125 (862)	125 (862)	85 (586)	85 (586)
Elongation, % in 2" (50.8 mm) or 4 x D	10.0	10.0	11.0	11.0	12.0	12.0	13.0	13.0	14.0	14.0	15.0	15.0	18.0	18.0
Reduction of Area, %	30.0	30.0	35.0	35.0	42.0	42.0	43.0	43.0	44.0	44.0	45.0	45.0	50.0	50.0
Hardness Brinell	420	420	409	409	352	352	341	341	332	332	311	311	277	277
Rockwell	C44	C44	C42	C42	C38	C38	C36	C36	C34	C34	C33	C33	C27	C27
Impact, Charpy V-Notch, ft-lbs (J)														
Notch Axis Longitudinal	7 (9.5)		17 (23)		27 (37)		30 (41)		30 (41)		50 (68)		100 (136)	
Notch Axis Transverse	8 (11)		12 (16)		25 (34)		25 (34)		25 (34)		45 (61)		70 (95)	

*I — Intermediate Location C — Center Location

** — Typical data represent average values of qualification tests for production orders.

Shear Strength

Table VI
Shear Strength In Double Shear

Condition	UTS ksi (MPa)	Shear Strength ksi (MPa)	Shear/Tensile Ratio %
H 900	205.6 (1418)	124.0 (855)	60.7
H 925	189.1 (1304)	116.0 (800)	61.8
H 1025	164.7 (1136)	104.2 (718)	63.2
H 1100	154.7 (1067)	99.1 (683)	63.0
H 1150-M	134.9 (930)	89.3 (616)	66.2

*Data developed on 1/4" (6.35 mm) round wire. Average of five tests on one heat.

Table VII
Fatigue Strength — Unnotched*
Tension — Tension

Maximum Stress, ksi (MPa)	Cycles to Failure**				
	Condition A	Condition H 1025	Condition H 1100	Condition H 1150	Condition H 1150-M
160.0 (1103)	—	32,900	—	—	—
155.0 (1069)	—	322,800	—	—	—
150.0 (1034)	—	38,800	55,100	—	—
150.0 (1034)	—	99,200	—	130	—
145.0 (1000)	—	—	—	38,200	—
140.0 (965)	61,200	125,600	95,000	—	—
140.0 (965)	—	358,600	—	38,400	—
137.5 (948)	—	—	96,100	—	—
137.5 (948)	—	—	97,400	72,100	—
135.0 (931)	—	80,700	3,696,000	—	—
135.0 (931)	—	162,600	7,096,000	—	—
135.0 (931)	—	2,032,000	—	78,200	—
132.5 (914)	—	—	127,100	—	—
132.5 (914)	—	—	219,900	92,700	—
130.0 (896)	190,400	118,700	4,860,000	—	—
130.0 (896)	—	8,044,800	—	—	—
130.0 (896)	—	8,720,100	—	99,600	—
127.5 (879)	—	—	7,300,000	11,911,200	—
125.0 (862)	224,400	—	3,907,000	4,053,800 (Discontinued)	5,000
125.0 (862)	—	—	6,031,000	9,877,100	—
120.0 (827)	214,900	—	—	—	64,500
115.0 (793)	4,792,000 (Discontinued)	—	—	—	124,600
110.0 (758)	3,433,600 (Discontinued)	—	—	—	138,900
105.0 (724)	—	—	—	—	4,453,600 (Discontinued)
102.5 (707)	—	—	—	—	—
102.5 (707)	—	—	—	—	381,700
100.0 (690)	—	—	—	—	399,200
100.0 (690)	—	—	—	—	4,910,900
97.5 (672)	—	—	—	—	898,000
95.0 (655)	—	—	—	—	8,265,400
90.0 (621)	5,152,200 (Discontinued)	—	—	—	10,982,700 (Discontinued)
90.0 (621)	10,100,000 (Discontinued)	—	—	—	4,453,600 (Discontinued)

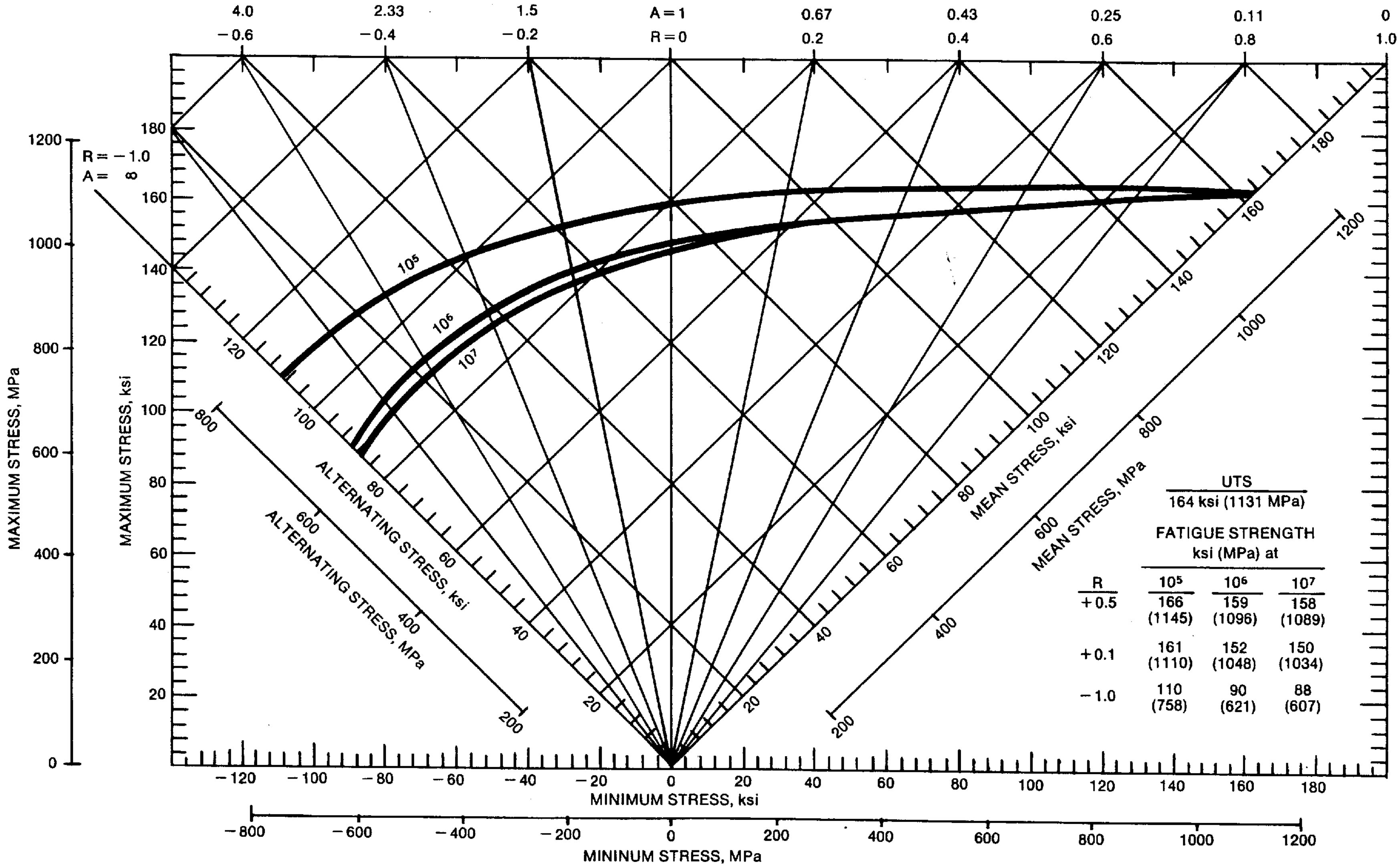
Table VIII
Fatigue Strength — Notched (k_t = 3.0)
Tension — Tension*

Maximum Stress, ksi (MPa)	Cycles to Failure**			
	Condition A	Condition H 1025	Condition H 1100	Condition H 1150
70.0 (483)	—	—	—	128,100
65.0 (448)	—	—	107,000	113,500
62.5 (431)	—	111,500	—	305,200
60.0 (414)	—	105,200	—	—
60.0 (414)	—	150,400	232,600	225,000
57.5 (396)	—	262,200	—	—
57.5 (396)	—	6,966,400	—	131,100
55.0 (379)	—	225,700	332,000	—
55.0 (379)	—	1,678,300	332,000	—
55.0 (379)	—	3,004,000	5,529,400	439,300
52.5 (362)	—	—	23,300,000 (Discontinued)	2,608,900
52.5 (362)	—	10,164,000 (Discontinued)	10,000,000 (Discontinued)	10,516,800 (Discontinued)
50.0 (345)	88,200	—	10,017,000 (Discontinued)	10,183,900 (Discontinued)
50.0 (345)	299,200	—	—	—
45.0 (310)	350,000	—	—	—
45.0 (310)	10,826,000 (Discontinued)	—	—	—
42.5 (293)	255,500	—	—	—
42.5 (293)	10,110,500 (Discontinued)	—	—	—
40.0 (276)	10,563,800 (Discontinued)	—	10,200,000 (Discontinued)	—
40.0 (276)	10,565,000 (Discontinued)	—	—	—

*Transverse specimens prepared from 2" (51 mm) x 6" (152 mm) hot forged bar.

$R = \frac{\text{minimum stress}}{\text{maximum stress}}$ = 0.1, speed = 30 hertz, uniaxial loading

**Data represent individual tests from one heat.



UTS
164 ksi (1131 MPa)

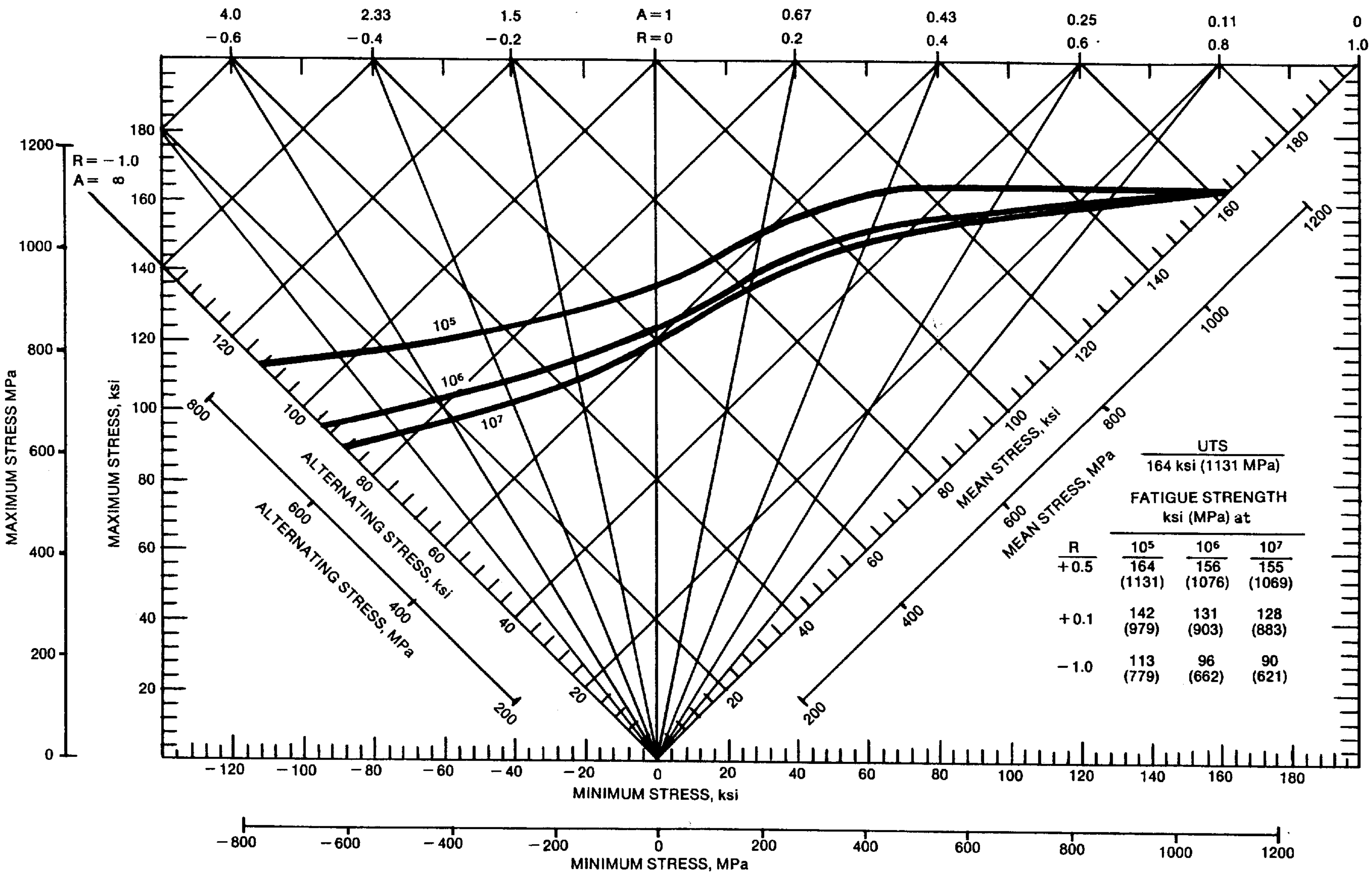
FATIGUE STRENGTH ksi (MPa) at

R	10^5	10^6	10^7
+0.5	166 (1145)	159 (1096)	158 (1089)
+0.1	161 (1110)	152 (1048)	150 (1034)
−1.0	110 (758)	90 (621)	88 (607)

FIGURE 2

CONSTANT LIFE DIAGRAM*
AXIAL LOADED 15-5 PH, CONDITION H 1025
UNNOTCHED LONGITUDINAL SPECIMENS
2" × 6" (50.8 × 152.4 mm) SECTION

*DIAGRAM CONSTRUCTED FROM S-N CURVES DEVELOPED FROM ONE HEAT USING STRESS RATIO OF +0.5, +0.1 AND −1.0. RAW DATA AVAILABLE UPON REQUEST.



R	10^5	10^6	10^7
+0.5	164 (1131)	156 (1076)	155 (1069)
+0.1	142 (979)	131 (903)	128 (883)
−1.0	113 (779)	96 (662)	90 (621)

FIGURE 3

CONSTANT LIFE DIAGRAM*
AXIAL LOADED 15-5 PH, CONDITION H 1025
UNNOTCHED TRANSVERSE SPECIMENS
2″ × 6″ (50.8 × 152.4 mm) SECTION

*DIAGRAM CONSTRUCTED FROM S-N CURVES DEVELOPED FROM ONE HEAT USING STRESS RATIO OF +0.5, +0.1 AND −1.0. RAW DATA AVAILABLE UPON REQUEST.

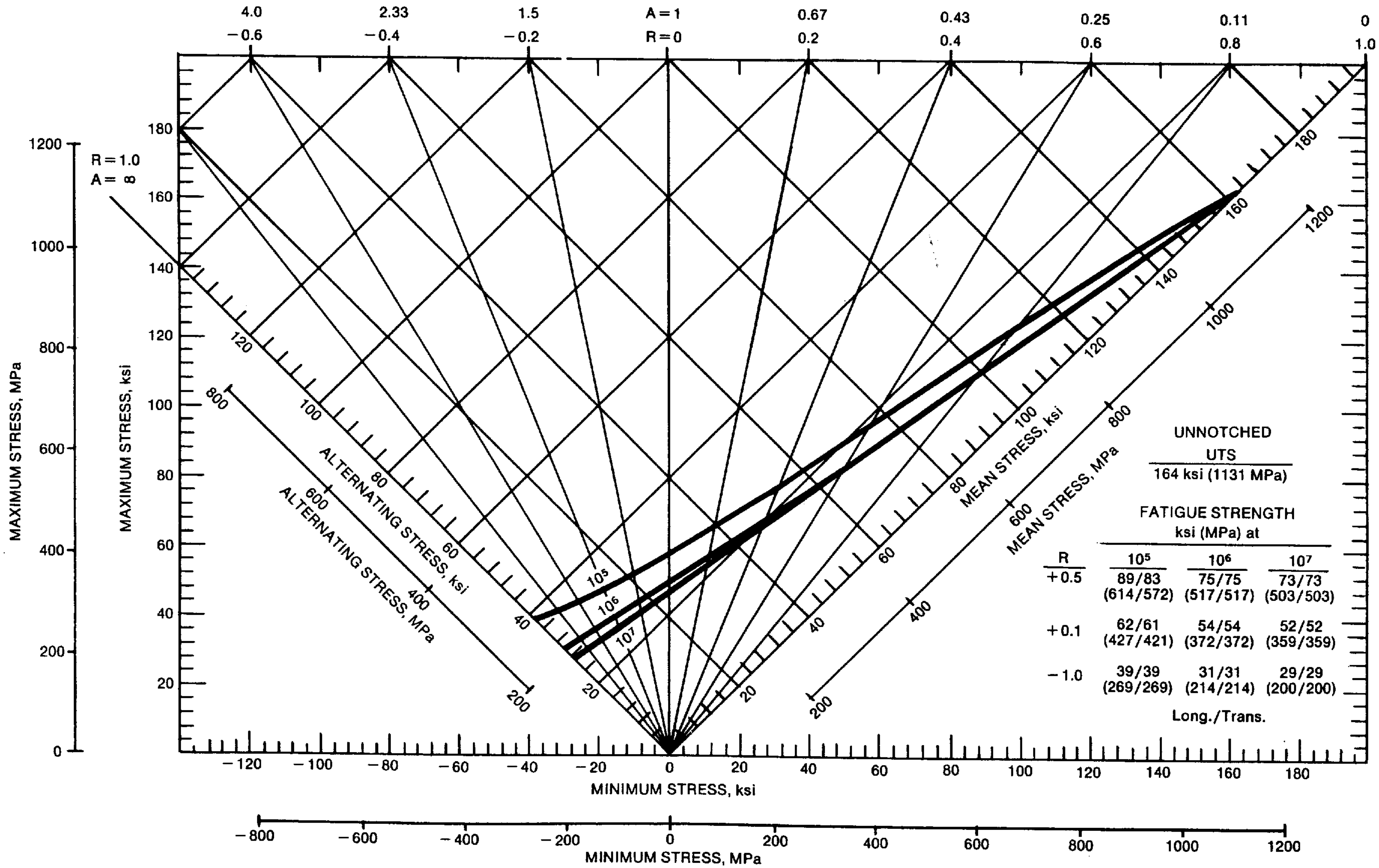


FIGURE 4

CONSTANT LIFE DIAGRAM *
AXIAL LOADED 15-5 PH, CONDITION H 1025
NOTCHED (K_t = 3.0) LONGITUDINAL AND TRANSVERSE SPECIMENS
2" × 6" (50.8 × 152.4 mm) SECTION

* DIAGRAM CONSTRUCTED FROM S-N CURVES DEVELOPED FROM ONE HEAT USING STRESS RATIO OF +0.5, +0.1 AND -1.0.
RAW DATA AVAILABLE UPON REQUEST.

Modulus of Elasticity

Table IX

	Condition*			
	H 900	H 1025	H 1075	H 1150
Modulus in Tension, psi (MPa)	28.5×10^6 (196×10^3)	—	—	—
Modulus in Torsion, psi (MPa)	11.2×10^6 (77×10^3)	11.0×10^6 (76×10^3)	10.0×10^6 (69×10^3)	10.0×10^6 (69×10^3)

*Data represent average of two tests from one heat.

The modulus of elasticity of 15-5 PH VAC CE stainless at elevated temperature can be conveniently expressed as % of room temperature modulus. At temperatures ranging from room to 600 F (315 C) this material showed the following:

Temperature F (C)	Modulus of Elasticity* (% of Room Temp. Modulus)
72 (22)	100.0
100 (38)	99.6
200 (93)	97.8
300 (149)	96.3
400 (204)	94.7
500 (260)	93.0
600 (315)	91.4

Poisson's Ratio in all hardened conditions is 0.272.
*Data represent average of two tests from one heat.

Table X
Torsional and Tensile Data
Armco 15-5 PH VAC CE Stainless Bar Stock*

Condition	Torsional Shear Modulus, psi (MPa)	Torsional Proportional Limit, ksi (MPa)	0.2% Torsional Yield Strength, ksi (MPa)		Modulus of Rupture ksi (MPa)	UTS, ksi (MPa)	0.2% YS, Offset, ksi (MPa)	Torsional YS (√) / Tension YS	Torsional YS (ε) / Tension YS	Modulus of Rupture / UTS
			√**	ε**						
Annealed	9.95×10^6 (69×10^3)	62.8 (433)	84.8 (576)	93.5 (644)	120.7 (832)	154.4 (1065)	122.6 (845)	0.69	0.76	0.78
H 900	10.79×10^6 (75×10^3)	89.3 (616)	117.6 (811)	126.3 (871)	163.7 (1129)	190.1 (1311)	170.2 (1174)	0.69	0.74	0.86
H 925	11.07×10^6 (76×10^3)	92.3 (636)	114.7 (790)	123.1 (849)	155.5 (1074)	182.0 (1255)	168.3 (1160)	0.68	0.73	0.85
H 1025	10.93×10^6 (75×10^3)	90.8 (627)	107.7 (743)	114.2 (787)	137.1 (946)	161.0 (1110)	157.3 (1084)	0.68	0.73	0.85
H 1100	10.66×10^6 (74×10^3)	80.1 (553)	99.0 (683)	105.3 (726)	127.0 (876)	150.0 (1034)	145.2 (1002)	0.68	0.73	0.85
H 1150	10.76×10^6 (74×10^3)	57.7 (398)	86.2 (594)	93.3 (643)	125.1 (863)	141.8 (977)	128.1 (887)	0.67	0.73	0.88
H 1150-M	9.56×10^6 (65×10^3)	38.0 (262)	59.4 (409)	67.5 (465)	113.4 (782)	132.0 (910)	90.9 (627)	0.65	0.74	0.86

* Average of two tests from one heat — specimens machined from 1" (25.4 mm) bar stock.
** √ — Offset determined by shearing strain (√) = 0.002.
ε — Offset determined by normal strain (ε) =0.002.
Reference: Test Method described in paper, "Mechanical Properties of Shafting and Valve Stem Materials," by John N. Macadam, published in *Proceedings of the American Society for Testing and Materials,* Vol. 64, page 765.

Elevated Temperature Properties

Table XI
Short-Time Tensile Properties*

Property and Condition	Temperature, F (C) 75 (24)	400 (204)	600 (315)	800 (426)	1000 (538)	1200 (648)
UTS, ksi (MPa)						
H 925	191 (1317)	168 (1158)	159 (1096)	149 (1027)	110 (758)	58 (400)
H 1025	166 (1145)	147 (1014)	139 (958)	133 (917)	105 (724)	54 (372)
H 1100	155 (1069)	138 (951)	132 (910)	123 (848)	96 (662)	—
H 1150-M	130 (896)	111 (765)	104 (717)	98 (676)	80 (552)	—
0.2% YS, ksi (MPa)						
H 925	176 (1213)	152 (1048)	140 (965)	126 (869)	92 (634)	46 (317)
H 1025	161 (1110)	139 (958)	131 (903)	119 (820)	91 (627)	41 (283)
H 1100	150 (1034)	134 (924)	126 (869)	114 (786)	88 (607)	—
H 1150-M	104 (717)	100 (689)	96 (662)	88 (607)	67 (462)	—
Elong, % in 4 x D						
H 925	16	15	14	15	17	26
H 1025	17	15	14	15	18	28
H 1100	19	16	14	14	18	—
H 1150-M	23	20	19	17	20	—
Reduction of Area, %						
H 925	59	54	59	60	70	83
H 1025	64	58	57	60	70	83
H 1100	67	62	57	60	71	—
H 1150-M	75	64	70	69	74	—

*Data represent average of four tests consisting of duplicate tests on each of two heats: one on 1" (25.4 mm) diameter bar and the other on 1-1/4" (31.8 mm) diameter bar.

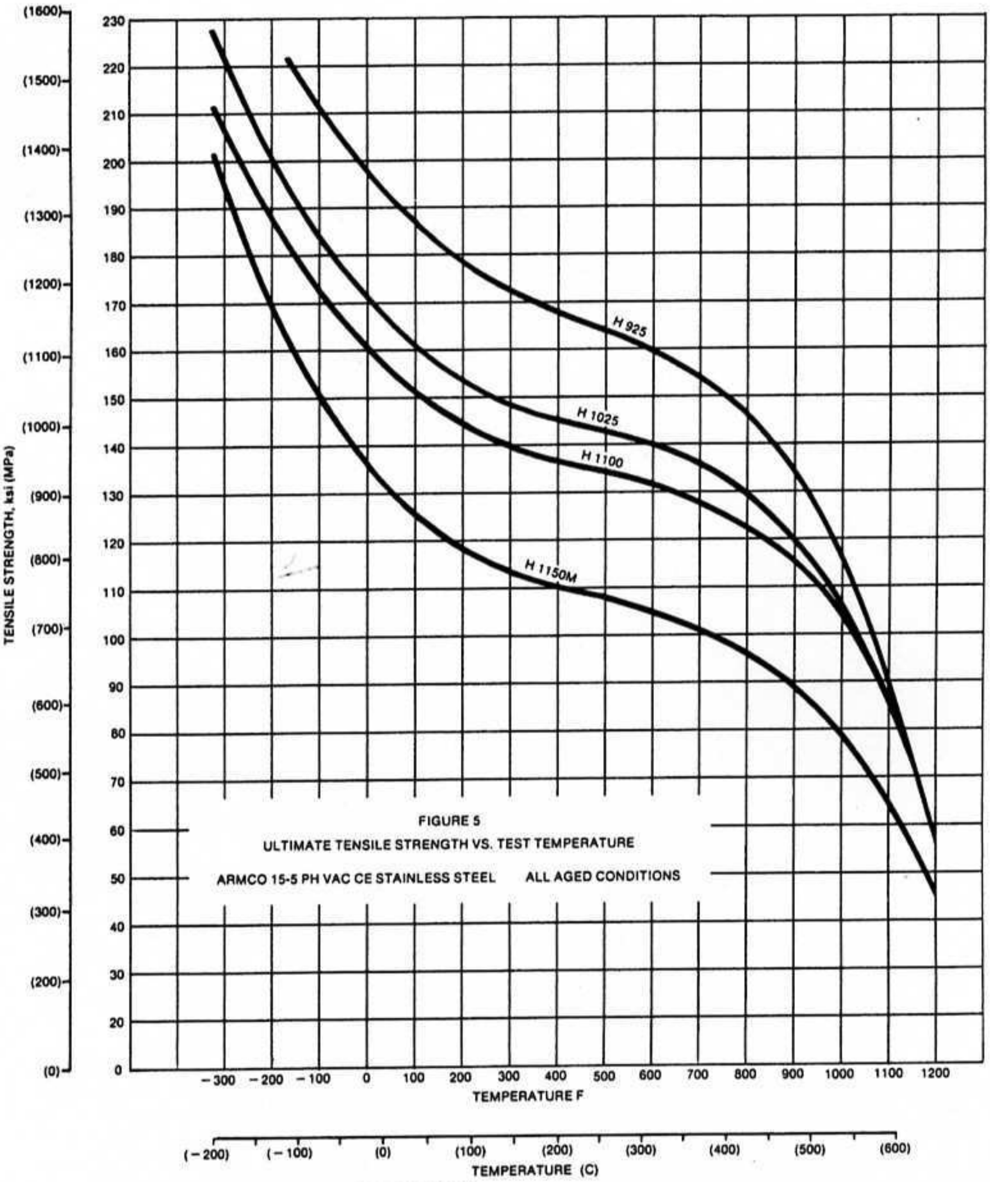


FIGURE 5
ULTIMATE TENSILE STRENGTH VS. TEST TEMPERATURE
ARMCO 15-5 PH VAC CE STAINLESS STEEL ALL AGED CONDITIONS

*THESE CURVES CONSTRUCTED USING DATA FROM DUPLICATE TESTS ON 2 HEATS

Sub-Zero Mechanical Properties

Armco 15-5 PH VAC CE stainless steel maintains good ductility at sub-zero temperatures. This property makes it an ideal material for applications such as valves and aircraft parts that must operate at low temperatures. No general statement can be made regarding preferred heat treatment for cryogenic applications because much depends on design requirements. However, many engineers have approved Armco 15-5 PH VAC CE stainless to the following temperature limits:

Condition H 925 — Down to 0 F (-18 C) for general use. For non-impact applications it is useful at temperatures as low as -320 F (-196 C). For example, valve seats.

Condition H 1025 — Down to -50 F (-46 C). Design with caution when using large diameter bars.

Condition H 1100 — Down to -110 F (-79 C). Design with caution when using large diameter bars.

Condition H 1150-M — Down to -320 F (-196 C).

Table XII
Short-Time Tensile Properties*

Property and Condition	Temperature, F (C) -320 (-196)	-100 (-73)	75 (23.8)
UTS, ksi (MPa)			
H 925	*	212 (1462)	191 (1317)
H 1025	226 (1558)	184 (1269)	166 (1145)
H 1100	210 (1448)	172 (1186)	155 (1069)
H 1150-M	201 (1386)	151 (1041)	130 (896)
0.2% YS, ksi (MPa)			
H 925	*	199 (1372)	176 (1213)
H 1025	221 (1524)	179 (1234)	161 (1110)
H 1100	205 (1413)	166 (1145)	150 (1034)
H 1150-M	146 (1007)	107 (738)	104 (717)
Elong, % in 4 x D			
H 925	*	17	16
H 1025	15	18	17
H 1100	18	19	19
H 1150-M	27	25	23
Reduction of Area, %			
H 925	*	61	59
H 1025	55	67	64
H 1100	60	66	67
H 1150-M	65	74	75

*Data represent average of four tests consisting of duplicate tests on each of two heats: one on 1" (25.4 mm) diameter bar and the other on 1-1/4" (31.8 mm) diameter bar.

Table XIII
Impact at Sub-Zero Temperatures*
V-Notch Charpy Impact, Foot-Pounds (J)

Condition	Temperature F (C) 75 (23.8)	+10 (-12)	-40 (-40)	-110 (-79)	-320 (-196)
H 925	58 (79)	28 (38)	16 (22)	7 (9)	—
H 1025	84 (114)	46 (62)	23 (31)	9 (12)	2 (2.7)
H 1100	96 (130)	80 (108)	54 (73)	27 (37)	3.5 (4.7)
H 1150-M	174 (236)	172 (233)	167 (226)	152 (206)	33 (45)

*Data represent average of four tests consisting of duplicate tests of two heats: one on 1" (25.4 mm) diameter bar and the other on 1-1/4" (31.8 mm) diameter bar.

Table XIV
Impact at Sub-Zero Temperatures*
Precracked Charpy Impact, in-lbs/in^2 (mm•N/mm^2)

Condition	Temperature F (C) 75 (23.8)	+10 (-12)	-40 (-40)	-110 (-79)	-320 (-196)
H 925	2,650 (464)	750 (131)	300 (53)	200 (35)	—
H 1025	5,100 (893)	1,900 (333)	900 (158)	350 (61)	—
H 1100	6,900 (1,208)	4,150 (727)	2,150 (377)	850 (149)	—
H 1150-M	12,250 (2,145)	11,900 (2,084)	11,400 (1,997)	9,900 (1,734)	1,100 (193)

*Data represent average of four tests consisting of duplicate tests of two heats: one on 1" (25.4 mm) diameter bar and the other on 1-1/4" (31.8 mm) diameter bar.

Table XV
Typical Sub-Zero V-Notch Charpy Impact*
6" x 6" (150 mm x 150 mm) Section
Longitudinal — Intermediate
Condition H 1150-M

Test Temperature, F (C)	Charpy V-Notch, ft-lbs (J)
Room	100 (136)
-110 (-79)	75 (102)
-175 (-115)	40 (54)
-320 (-196)	20 (27)

*Data represent average of duplicate tests on one heat.

PHYSICAL PROPERTIES

Table XVI

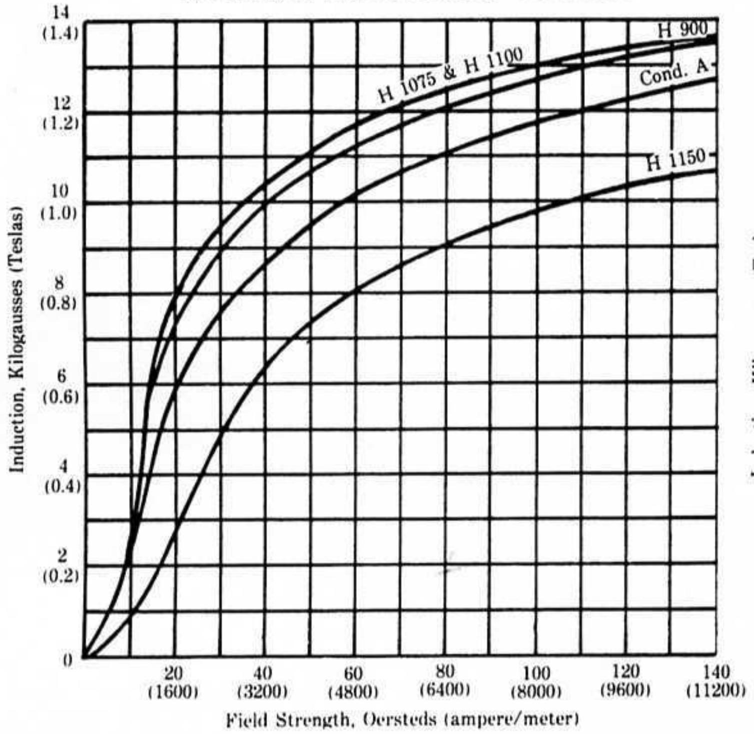
	Condition*			
	A	H 900	H 1075	H 1150
Density, gm/cm³	7.78	7.80	7.81	7.82
lbs/in³	0.281	0.282	0.282	0.283
Electrical Resistivity, microhm-cm	98	77	—	—
Mean Coefficient of Thermal Expansion in/in/°F (μm/m•K)				
-100/70 F (-73/21 C)	—	5.8 x 10^{-6} (10.4)	—	6.1 x 10^{-6} (11.0)
70/200 F (21/93 C)	6.0 x 10^{-6} (10.8)	6.0 x 10^{-6} (10.8)	6.3 x 10^{-6} (11.3)	6.6 x 10^{-6} (11.9)
70/400 F (21/204 C)	6.0 x 10^{-6} (10.8)	6.0 x 10^{-6} (10.8)	6.5 x 10^{-6} (11.7)	6.9 x 10^{-6} (12.4)
70/600 F (21/315 C)	6.2 x 10^{-6} (11.2)	6.3 x 10^{-6} (11.3)	6.6 x 10^{-6} (11.9)	7.1 x 10^{-6} (12.8)
70/800 F (21/426 C)	6.3 x 10^{-6} (11.3)	6.5 x 10^{-6} (11.7)	6.8 x 10^{-6} (12.2)	7.2 x 10^{-6} (13.0)
70/900 F (21/482 C)	—	—	—	7.3 x 10^{-6} (13.1)
Thermal Conductivity BTU/hr/ft²/in/°F (W/m•K)				
300 F (149 C)	—	124 (17.9)	—	—
500 F (260 C)	—	135 (19.5)	—	—
860 F (460 C)	—	156 (22.5)	—	—
900 F (482 C)	—	157 (22.6)	—	—
Specific Heat BTU/lb/°F (J/kg•K)				
32/212 F (0/100 C)	0.11 (460)	0.10 (418)	—	—

*Data represent one test from one heat.

Magnetic Properties

Normal induction and hysteresis curves are shown in Figures 6 and 7. There is little difference in the magnetic properties of material heat treated to Conditions H 900 and H 1075. However, magnetic properties of material heated to Condition H 1150 are significantly lower.

NORMAL INDUCTION CURVES*



HYSTERESIS CURVES*

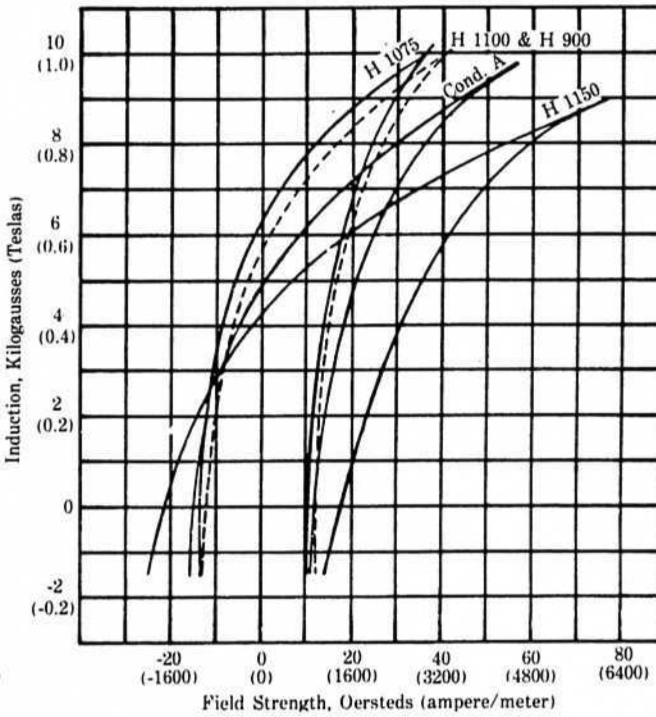


Figure 6 *Data represent single tests from three heats. **Figure 7**

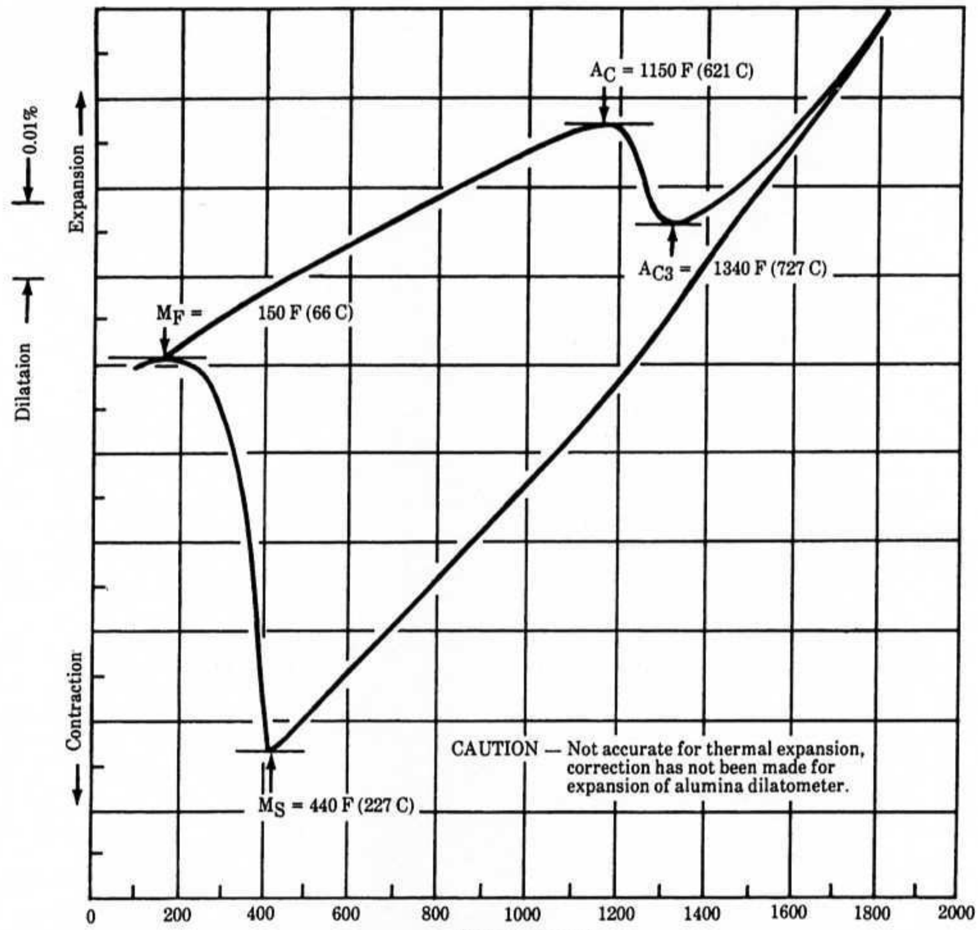


Figure 8
Dilatometer Curve of Armco 15-5 PH

CORROSION RESISTANCE

The general level of corrosion resistance of Armco 15-5 PH VAC CE stainless steel exceeds that of Types 410 and 431, and is approximately equal to that of Armco 17-4 PH stainless steel. This is indicated by laboratory tests in both strongly oxidizing and reducing media, as well as by atmospheric exposures. In all heat-treated conditions, Armco 15-5 PH VAC CE stainless exhibits very little rusting after 500 hours' exposure to 5% salt fog at 95 F (35 C). When exposed to seacoast atmosphere for long periods of time, Armco 15-5 PH VAC CE stainless gradually develops a superficial overall layer of rust like other precipitation-hardening stainless steels. The general level of corrosion resistance of Armco 15-5 PH VAC CE stainless is best in the fully hardened condition, and decreases slightly as the aging temperature is increased.

Stress Corrosion Resistance

The following data were obtained on .052" (1.3 mm) strip samples of Armco 15-5 PH VAC CE stainless steel from two heats exposed in triplicate on a location 80 feet (24 m) from the ocean at Kure Beach, North Carolina.

Condition	Applied Stress(1) ksi (MPa)	Results(2)
A (Heat 1)	133.2 (918.1)	3 NF
	99.9 (688.6)	3 NF
H 900 (Heat 1)	172.5 (1189.0)	3 - 21 days
	129.4 (892.0)	2 - 21 days; 1 - 28 days
H 900 (Heat 2)	180.0 (1240.7)	3 - 22 days
	135.0 (930.6)	3 - 22 days
H 925 (Heat 1)	165.8 (1142.9)	3 - 23 days
	124.4 (857.5)	3 - 23 days
H 925 (Heat 2)	171.8 (1184.2)	2 - 22 days; 1 - 266 days
	128.9 (888.5)	2 - 22 days; 1 - 109 days
H 975 (Heat 1)	159.0 (1096.0)	3 NF
	119.3 (822.3)	3 NF
H 975 (Heat 2)	162.3 (1118.7)	3 NF
	121.7 (838.9)	3 NF
H 1025 (Heat 2)	159.1 (1096.7)	3 NF
	119.3 (822.3)	3 NF

(1) Applied stresses were 100% and 75% of the 0.2% yield strength, using smooth bent beam specimens in the longitudinal direction.

(2) NF indicates NO FAILURE to date. Tests were begun June 5, 1973, for Heat 1 and June 3, 1971, for Heat 2, and are still continuing.

These data indicate Armco 15-5 PH VAC CE stainless steel is highly resistant to stress corrosion cracking in marine atmosphere in Condition A and when aged at temperatures of 975 F (523 C) and higher. Heat treating to the hardened conditions, especially at the higher end of the temperature range, stress-relieves the structure and may provide more reliable resistance to stress corrosion cracking than Condition A.

FABRICATION

Heat Treatment

For maximum hardness and strength, material in the solution-treated condition is heated for one hour at 900 ± 15 F (482 ± 8 C) and air cooled to room temperature. If material purchased in the solution-treated condition (Condition A) is hot worked, it must be solution-treated after such working and before hardening.

All surfaces should be free of cutting lubricants and other foreign matter before any heat-treating operation is performed.

Where ductility in the hardened condition is especially important, better toughness can be obtained by raising the temperature of the hardening heat treatment. Unlike regular hardenable materials which require a hardening plus a tempering or stress-relieving treatment, Armco 15-5 PH VAC CE stainless steel can be hardened to the final desired properties in one operation. By heat treating at temperatures from 900 to 1150 F (482 to 621 C), a wide range of properties can be attained. A heat treatment of 4 hours is generally used for all hardenening heat treatments except 900 F (482 C), for which a one-hour treatment is used.

If Armco 15-5 PH VAC CE stainless is not ductile enough in any given hardened condition, it can be reheat-treated at a higher temperature to increase impact strength and elongation. This retreatment can be made without a solution treatment prior to the final heat treatment. However, if the material is not hard enough or strong enough it must be resolution treated, and then hardened at a lower temperature.

For material hot worked or forged, or castings, a solution treatment at 1875 to 1925 F (1022 to 1050 C) for 1/2 hour, followed by cooling to at least 90 F (32 C) must be done prior to hardening. Oil quenching rather than air cooling may be used on small, simple sections. This treatment will refine the grain size and make hardened material more uniform.

On hardening Armco 15-5 PH VAC CE stainless steel, a dimensional change will take place. Typical dimensional changes are shown below. They can vary from heat to heat.

Table XVII
Contraction From Heat Treatment*

H 900		.00045 in/in (mm/mm)
H 925		.00051 in/in (mm/mm)
H 1025		.00053 in/in (mm/mm)
H 1100		.0009 in/in (mm/mm)
H 1150		.0022 in/in (mm/mm)
H 1150-M	1400→	.00037 in/in (mm/mm)
	1150→	.00206 in/in (mm/mm)
	∴ 1400 + 1150→	.00243 in/in (mm/mm)

*Data represent single tests from one heat.

Importance of Cooling to 90 F (32 C) in Fabricating and Heat Treating Armco 15-5 PH VAC CE Stainless Steel

In fabricating Armco 15-5 PH VAC CE stainless, it is important to keep in mind the low temperatures at which the start of transformation to martensite (M_S) and the finish of the martensite transformation (M_f) occur. These temperatures are approximately 270 F (132 C) and 90 F (32 C), respectively.

Because of this characteristic, it is necessary to cool parts in process at least to 90 F (32 C) prior to applying subsequent heat treatments if normal final properties are to be obtained. This practice is essential to assure grain refinement, and to assure the product will have the good ductility of which this alloy is capable. Examples of situations where cooling to 90 F (32 C) is an important step follow:

1) Cool a forged part to 90 F (32 C) after final forging before solution treating.
2) Cool to 90 F (32 C) after heat treating at 1400 F (760 C) prior to aging at 1150 F (621 C) in the H 1150-M treatment.
3) Cool to 90 F (32 C) after solution treating prior to applying any of the precipitation-hardening treatments.

Surface Hardening

Armco 15-5 PH VAC CE stainless steel can be nitrided when increased resistance to galling and wear is required. An advantage obtained in using Armco 15-5 PH VAC CE stainless rather than a standard chromium or chromium-nickel stainless steel is that the core is simultaneously strengthened and toughened during the nitriding treatment.

Using the gas-phase method, case hardnesses of approximately Rockwell C67 have been obtained to a depth of 0.004" to 0.006" (0.1 mm to 0.15 mm). This method of nitriding utilizes a temperature of about 1050 F (565 C) and results in a tough core with a hardness of about Rockwell C36. However, nitriding considerably decreases the corrosion resistance of Armco 15-5 PH VAC CE stainless (as it does with any stainless steel). Nitrided Armco 15-5 PH VAC CE stainless should be used only in mildly corrosive applications.

Forging

Forging is an excellent method of forming intricate shapes of Armco 15-5 PH VAC CE stainless steel. Forging blanks should be heated uniformly to 2150 to 2200 F (1176 to 1204 C) and held at temperature at least 15 minutes before forging. On large sections over 3/4" (19 mm) diameter or thickness, it is recommended the material be heated for 1/2 hour per inch (25.4 mm) of thickness at 2150 to 2200 F (1176 to 1204 C) and held for one-half to one hour at temperature prior to forging. Heating above 2200 F (1204 C) may cause undesirable grain coarsening. The material should be reheated in the furnace when this temperature is reached. After forging, the material should be cooled below 90 F (32 C) to assure complete transformation. To secure optimum toughness in the final hardened condition, forged parts must first be put into Condition A by reheating to 1875 to 1925 F (1022 to 1050 C) and air cooling (or oil quenching small simple parts).

Complete forging practices for Armco 15-5 PH VAC CE stainless steel are similar to those found in the Fabricating Data Bulletin covering the forging and heat treating of Armco 17-4 PH and 17-7 PH billets, bars and forgings.

In critical types of upset forgings and hot flattening operations, Armco 17-4 PH stainless steel may split and rupture. Armco 15-5 PH VAC CE stainless will perform better because it has no delta ferrite, and minimal directionality.

Welding

Sound joints can easily be produced in Armco 15-5 PH VAC CE stainless with proper welding practice. Properties comparable to those of the parent metal can be secured in the weld by postweld heat treatment. Procedures employed for welding are similar to those ordinarily used for the austenitic types, even though the composition of Armco 15-5 PH VAC CE stainless and its structure more closely resemble that of a martensitic stainless steel. Any of the arc and resistance welding processes used on the regular grades of stainless steel are suitable for Armco 15-5 PH VAC CE stainless steel. The most outstanding welding property of this steel is its ability to withstand welding operations without requiring preheating.

Favorable composition accounts for the good performance of Armco 15-5 PH VAC CE stainless in welding. The very low carbon content is an important feature because it restricts the hardness of rapidly cooled material and avoids the formation of cracks in the weld metal and the heat-affected zone of the base metal. This eliminates the need for pre-heating. While the Armco 15-5 PH VAC CE stainless base metal shows no susceptibility to spontaneous underbead cracking from weld hardening, it does not possess the high ductility and toughness of austenitic Cr-Ni steels. Therefore, it should not be subjected to high levels of biaxial or triaxial stress from severely restrained weldments or exposed to notched conditions. Weldment design should be given the same attention required for any high-strength alloy steel to avoid the concentration of residual welding stress or reaction stress at square corners, unfused notches and sharp threads.

In fusion welding, it is important that consideration be given to proper control of the weld deposit composition. Fillerless fusion welds such as are possible with the gas tungsten arc, plasma arc and electron beam processes represent a borderline condition with respect to producing best metallurgical structures for hot crack resistance. Even with such a borderline condition, no instances of hot cracking have been reported in either the laboratory or field welding of Armco 15-5 PH Stainless Steel. While confidence that crack-free welds can be made is high, it is still conceivable that changes in product and/or weld procedures could cause cracking to occur. Cracking of this type, if it were to occur, can be detected easily at the time of welding.

In fusion weld processes, where fillers can be added and mechanical properties equivalent to those of the parent metal are needed, the use of W17-4 PH Stainless Steel electrodes or fillers is suggested. When the weld deposit is not required to have a strength level equivalent to that of the parent metal, a Type 308L stainless steel electrode or filler may be used. The information found in the Fabricating Data Bulletin on welding Armco 17-4 PH Stainless Steel will be helpful in welding Armco 15-5 PH VAC CE Stainless Steel.

Machining

Armco 15-5 PH VAC CE stainless steel can be machined in either the solution-treated or any of the heat-treated conditions. One of the important advantages of the alloy is it can be finish machined in Condition A, then heat treated. Because the final hardening temperatures are low, there is no harmful scaling or distortion. Design allowance can be made for the predictable contraction on hardening.

Machining rates for Armco 15-5 PH VAC CE stainless steel in Condition A are similar to those for Types 302 and 304 stainless steels. In the hardened condition (H 900) this material should be machined at 60% of the rate used for Condition A. Surface finishes in either condition are excellent. Best tool life is achieved from Condition H 1150-M; however, higher cutting forces may be encountered.

Cutting

In general, the cutting procedures commonly used for the standard chromium-nickel types also apply to Armco 15-5 PH VAC CE stainless steel.

Cold sawing is recommended for cutting bars and forging billets. Hot cutting or abrasive wheel cutting with a large volume of coolant has been used successfully. However, it should be noted that abrasive wheel cutting can cause small surface cracks on the cut face.

Torch cutting Armco 15-5 PH VAC CE stainless steel requires a process suited for cutting stainless steel, such as plasma-arc, powder cutting, oxy-arc or arc-air methods. Since the heat-affected zones of Armco 15-5 PH VAC CE stainless are not significantly hardened or embrittled by the localized heat of welding or torch cutting, this alloy offers good possibilities for oxygen or air torch cutting. Armco 15-5 PH VAC CE stainless bars can be torch cut by flux-injection or iron powder processes.

Descaling

The hardening treatments for Armco 15-5 PH Stainless Steel produce only a light heat tint on the surfaces. The presence of this film may degrade the corrosion resistance of the alloy. The heat tint can be removed easily either by mechanical means, such as wet grit blasting, or by light pickling for several minutes in 10% nitric acid — 2% hydrofluoric acid (by volume) solution at 110-140 F (43-60 C). Prolonged exposure to this solution should be avoided to minimize surface etching and the possibility of hydrogen embrittlement. Where pickling is undesirable, the heat tint may be removed by light electropolishing. The latter two treatments also passivate or clean the surfaces for maximum corrosion resistance.

The most satisfactory method of removing scale resulting from the solution treatment or forging is grit blasting. This should be followed by immersion in 10% nitric acid-2% hydrofluoric acid (by volume) solution at 110-140 F (43-60 C) for several minutes to remove any debris that may have been embedded in the surface by the blasting operation. Again, prolonged exposure to this solution should be avoided to minimize the possibility of hydrogen embrittlement.