11
Materials

11.1. Types of Materials

Steel & Alloys

1.0 Ferrous >50% Fe

- A. Carbon Steel
  - Low <.3% C
  - Medium .35 – .55% C
  - High .6 – 1.5% C
- B. Low Alloy (Chrome and Cr-Mo)
  - <5% addition of alloy, i.e. Mn, Ni, Cr, etc.
  - Examples are Cr-Mo, C-1/2 Mo, etc.
- C. High Alloy
  - >10% addition of alloy compostion
  - Stainless Steels
    - a. Ferritic
    - b. Martensitic
    - c. Austenitic
      - 1. Stabilized
      - 2. Low Carbon
      - 3. High carbon
    - d. Duplex
- D. Cast Iron >1.5% C
  - 1. Ductile
  - 2. Malleable
  - 3. White
  - 4. Gray

2.0 Non-Ferrous <50% Fe

- Copper
- Nickel
- Aluminum
- Magnesium
- Titanium
- Brass
- Bronze

2.1 Common names for Non-Ferrous Alloys

- Inconel
- Incoloy
- Monel
- Carpenter 20
- Cupronickel
- Aluminum Bronze

Table 11-1
Material specifications

Matl	Plate	Pipe	Tube	Bar	Figs	Fittings
Nick 200	SB-162	SB-161	SB-163	SB-160	SB-160	B-366-WPN
Monel 400	SB-127	SB-165	SB-163	SB-164	SB-164	B-366-WPNC
Inco 600	SB-443	SB-444	SB-163	SB-446	SB-166	B-366-WPNCI
Incoloy 825	SB-424	SB-423	SB-163	SB-425	SB-408	–
Hast C-4	SB-575	SB-619	SB-622	SB-574	SB-622	–
Carp 20	SB-463	SB-464	SB-468	SB-473	SB-462	–
SST	SA-240	SA-312	SA-213	SA-276	SA-182	SA-403
			SA-269	SA-479		
CS	SA-516	SA-106-B	SA-179	SA-306	SA-105	SA-234-WPB
Titanium	SB-265	SB-337	SB-338	SB-348	SB-381	SB-363
Alum 6061	SB-209	SB-241	SB-210	SB-211	SB-247	
Chrome	SA-387	SA-335	SA-213	SA-739	SA-182	SA-234
T-405 12 Cr			Use SST Designations			
T-410 13 Cr			Use SST Designations			
T-430 17 Cr			Use SST Designations			
3½ Ni	SA-203-D	SA-333-3	SA-334-3		SA-350-LF3	SA-420-WPL3
Hast G-30	SB-582	SB-622	SB-622	SB-581	SB-581	
Nitronic 50 (UNS) 20910	SA-240-XM19	SA-312-XM19	SA-213-XM19	SA-479-XM19	SA-182-XM19	SA-403-XM19
Inco 800	SB-409	SB-407	SB-407	SB-408	SB-408	B-366

- Hastelloy
- Waspalloy
- E-brite

2.2 Clad materials: A combination of base material and some alloy cladding or weld overlay (WOL)

- Methods of manufacture;
  1. Roll bonded
  2. Explosion bonded
  3. Weld overlay (WOL)
- ASTM/ASME material specifications for clad plate are as follows;

  SA-263: Specification for stainless chromium steel - clad plate

  SA-264: Specification for stainless chromium Nickel steel-clad plate

  SA-265: Specification for nickel and nickel base alloy-clad steel plate

- Terms and definitions for cladding/weld overlay (WOL);

  Integral Bonded Cladding: A composite material produced by roll bonding or explosion welding (EXW).

  Weld Overlay (WOL): Produced by weld depositing a dissimilar material on a base metal surface.

  Back Cladding: A localized WOL operation between two integrally clad or weld overlayed sections. This process is also known as "clad restoration".

  Total Depth: Total thickness of WOL or back cladding

  Effective Depth: The thickness of WOL or back cladding having the specified chemical composition

  Sleeve Lining: The installation of a cylindrical sleeve of alloy material on the inside diameter of a connection.

Table 11-2
Properties of commonly used pressure vessel materials

	Material	Mechanical Properties			Chemical Properties %							
	Designation	UTS	YS	Elong	C max	Si	Mn	P max	S max	Ni	Cr	Mo
PLATE	SA-36	58–80	36	23	0.25			0.04	0.05			
	SA-285-C	55–75	30	27	0.28		0.9	0.035	0.04			
	SA-515-55	55–75	30	27	0.20	0.15–0.40	0.9	0.035	0.04			
	SA-515-60	60–80	32	25	0.24	0.15–0.40	0.9	0.035	0.04			
	SA-515-70	70–90	38	21	0.31	0.15–0.40	1.2	0.035	0.04			
	SA-516-55	55–75	30	27	0.18	0.15–0.40	0.6–0.9	0.035	0.04			
	SA-516-60	60–80	32	23	0.21	0.15–0.40	0.6–0.9	0.035	0.04			
	SA-516-70	70–90	38	21	0.27	0.15–0.40	0.85–1.2	0.035	0.04			
	SA-204-B	70–90	40	21	0.2	0.15–0.40	0.9	0.035	0.04			0.45–0.60
	SA-302-B	80–100	50	18	0.2	0.15–0.40	1.15–1.5	0.035	0.04			0.45–0.60
	SA-387-11-2	75–100	45	22	0.17	0.5–0.8	0.40–0.65	0.035	0.04			
	SA-203-A	65–85	37	19	0.17	0.15–0.40	0.7	0.035	0.04	2.1–2.5		
	SA-203-D	65–85	37	19	0.17	0.15–0.40	0.7	0.035	0.04	3.25–3.75		
	SA-240-304	75	30	40	0.08	1.0	2.0	0.045	0.03	8–10.5	18–20	
	SA-240-316	75	30	40	0.08	1.0	2.0	0.045	0.03	10–14	16–18	2–3
PIPE	SA-53	60	35		0.3		1.2	0.05	0.06			
	SA-106-B	60	35	30	0.3	0.1	0.29–1.06	0.048	0.058			
	SA-333-3	65	35	30	0.19	0.18–0.37	0.31–0.64	0.05	0.05	3.18–3.82		
	SA-333-6	60	35	30	0.3	0.1	0.29–1.06	0.048	0.058			
	SA-335-P1	55	30	30	0.1–0.2	0.1–0.5	0.3–0.8	0.045	0.045			0.44–0.65
	SA-335-P11	60	30	30	0.15	0.50–1.0	0.3–0.6	0.03	0.03		1–1.5	0.44–0.65
	SA-312-304	75	30	35	0.08	0.75	2	0.04	0.03	8–11	18–20	
	SA-312-316	75	30	35	0.08	0.75	2	0.04	0.03	11–14	16–18	2–3
FORGINGS	SA-105	70	36	22	0.35	0.35	0.60–1.05	0.04	0.05			
	SA-350-LF2	70–95	36	22	0.3	0.15–0.30	1.35	0.035	0.04			
	SA-350-LF3	70–95	37.5	22	0.2	0.20–0.35	0.9	0.035	0.04	3.25–3.75		
	SA-182-F1	70	40	25	0.28	0.15–0.35	0.8–0.9	0.045	0.045			0.44–0 65
	SA-182-F11	70	40	20	0.1–0.2	0.50–1.0	0.3–0.8	0.04	0.04		1.0–1.5	0.44–0.65
	SA-182-304	75	30	30	0.08	1.0	2	0.04	0.03	8–11	18–20	
	SA-182-316	75	30	30	0.08	1.0	2	0.04	0.03	10–14	16–18	
MISC.	SA-234-WPB	60	35		0.3	0.1	0.29–1.06	0.05	0.058			
	SA-193-B7	125	105	16	0.37–0.49	0.15–0.35	0.85–1.1	0.04	0.04		0.75–1.2	0.15–0.25
	SA-193-B16	125	105	18	0.36–0.44	0.15–0.35	0.45–0.70	0.04	0.04		0.80–1.15	0.50–0.65
	SA-320-L7	125	105	16	0.38–0.46	0.15–0.35	0.75–1.0	0.035	0.04		0.80–1.1	0.15–0.25

Table 11-3
Stainless steel

	TYPE	CHEMICAL COMPOSITION				MECH PROPERTIES			REMARKS
		Cr	Ni	C (Max)	Other (Max)	Tensile KSI	Yield KSI	Elong (%)	
AUSTENITIC	201	16-18	3.5-5.5	0.15	Mn 5.5-7.5 N .25	115	55	55	Low Ni Version of 301
	202	17-19	4-6	0.15	Mn 7.5-10 N .25	105	55	55	Low Ni Version of 302
	203EZ	16-18	5-6	0.07	Mn 5.5-6.5 Cu 1.75-2.15 S.18-.35	90	40	50	Free machining grade
	216	19.75	6	0.08	Mn 8.25 Mo 2.5 N.37	100	55	45	Similar to 316 w/ better high strength properties
	301	16-18	6-8	0.15	Mn 2 Si 1	110	40	60	High work hardening, structural grade
	302	17-19	8-10	0.15	Mn 2 Si 1	90	40	55	General purpose SST
	303	17-19	8-10	0.15	Mn 2 Si 1 P .2 Mo .6 S .15 Min	90	35	50	Free machining version of 302
	303SE	17-19	8-10	0.15	Mn 2 Si 1 Se .15 Min P .2 S .06	90	35	50	Better surface finish than 303
	303PB	17-19	8-10	0.15	Mn 2 Si 1 Mo .6 Pb .12-.3	90	35	50	Leaded version of 303 for high volume machining
	304	18-20	8-10	0.08	Mn 2 Si 1	85	35	55	Low carbon variation of 302
	304L	18-20	8-10	0.03	Mn 2 Si 1	80	30	55	Extra low carbon 304
	305	17-19	10-13	0.12	Mn 2 Si 1	85	35	55	Low work hardening. Good spinning and deep drawing
	309	22-24	12-15	0.2	Mn 2 Si 1	95	40	45	High temperature applications
	310	24-26	19-22	0.25	Mn 2 Si 1.5	95	45	50	Excel corrosion resistance
	316	16-18	10-14	0.08	Mn 2 Si 1 Mo 2-3	85	35	60	Best corrosion resistance of standard SST's. High temperature strength
	316L	16-18	10-14	0.03	Mn 2 Si 1Mo 2-3	78	30	55	Extra low carbon 316
	317	18-20	11-15	0.08	Mn 2 Si 1Mo 3-4	90	40	50	316 w/ better creep resistance
	321	17-19	9-12	0.08	Mn 2 Si 1 P.04 S .03 Ti 5 x C Min	85	35	55	Stabilized w/ Ti
	347	17-19	9-12	0.08	Mn 2 Si 1Cb-Ta 10 x C Min	95	40	50	Stabilized w/ Cb
MARTENSITIC	403	11.5-13	0	0.15	Mn 1 Si .5	75	40	35	Turbine quality for highly stresed parts
	405	11.5-14.5	0	0.08	Mn 1 Si 1 Al .1-.3	70	40	30	Variation of 410 w/ limited hardenability
	410	11.5-12.5	0	0.15	Mn 1 Si 1	75	40	35	Low cost, general purpose, heat treatable SST
	414	11.5-13.5	1.25-2.5	0.15	Mn .6 P .04 S .03 Si .5 V .15 Al .015	110	85	18	Modified 410 w/ 2% Ni
	416	12-14	0	0.15	Mn 1.25 Si 1 S .15 Min	75	40	30	Free machining version of T-410
	440A	16-18	0	0.75	Mo .75 Mn 1 Si 1	105	60	20	High Carbon variety. Can be heat treated for high strength.
	440B	16-18	0	0.95	Mo .75 Mn 1 Si 1	107	62	18	
	440C	16-18	0	1.2	Mo .75 Mn 1 Si 1	110	65	14	
	501	4-6	0	0.15	Mo .45-.65 Mn .3-.6 Si .5	70	30	28	Economical. Cr & Mo added for mild corrosion resistance and elevated temperature service
	502	4-6	0	0.1	Mo .45-.65 Mn .3-.6 Si .5	70	30	30	
FERRITIC	409	10.5-11.75	0.5	0.08	Mn 1 P .045 S .045 Si 1 Ti 6xC Min	70	40	30	Economical. Easy to fabricate.
	430	14-18	0	0.12	Mn 1 Si 1	75	45	30	Most widely used non-hardenable type. Good heat resistance & mechanical properties
	430F	14-18	0	0.12	Mn 1.25 Si 1 P .06 S .15 Min	80	55	25	Free machining version of 430
	446	23-27	0	0.2	Mn 1.5 Si 1 N .25	80	50	25	Good oxidation resistance in sulfuric atmospheres
SPECIAL	A286	15	26	0.05	Mn 1.4 Si .4 Mo 1.25 Ti 2.15 V .3 Al .2 B .03 Fe Bal	93	27	48	An austenitic alloy w/ exceptionally high strength at elevated temperatures
	AM350	16.5	4.3	0.1	Mn .8 Si .25 Mo 2.75 N .1 Fe Bal	145	60	40	These austenitic varieties are heat treatable, superior corrosion resistance. Provided in annealed condition and age hardened.
	AM355	15.5	4.3	0.13	Mn .95 Si .25 Mo 2.75 N .1 Fe Bal	186	55	29.5	
	PH13-8Mo	12.25-13.25	7.5-8.5	0.05	Mn .1 P .01 S .008 Si .1 Al 1.35 Mo 2.5 N .01	160	100	0.15	
	15-5PH	14-15.5	3.5-5.5	0.07	Mn 1 P .04 S .03 Si 1 Cu 4.5 Cb Ta .45	150	110	10	
	PH15-7Mo	14-16	6.5-7.75	0.09	Mn 1 Si 1 P .04 S .03 Al .75-1.5 Mo 2-3	130	55	35	
	17-4PH	15.5-17.5	3-5	0.07	Mn 1 Si 1 Cu 3-5 Fe Bal	150	110	10	
	17-7PH	16-18	6.5-7.75	0.09	Mn 1 Si 1 Al .75-1.5 Fe Bal	130	40	35	

TABLE 11-4
Nickel Alloys

Item	Common Name	% Ni	Other Major Ingredients
1	Nickel 200	99.5	None
2	Duranickel 301	94	4.5% Al, .5% Ti
3	Monel 400	66	32% Cu
4	Inconel 600	78	15% Cr, 7% Fe
5	Incoloy 800	32.5	46% Fe, 21% Cr
6	Carpenter 20	32-38	20% Cr, 3% Mo, 3% Cu
7	Hastelloy C-22	55	21% Cr, 13% Mo, 2.5% Co
8	Hastelloy G-30	36	30% Cr, 5% Mo, 5% Co, 15% Fe
9	Hastelloy C-276	55	15.5% Cr, 16% Mo, 2.5% Co, 4% W
10	E-Brite	73	26% Cr, 1% Mo
11	Waspalloy	55	14% Co, 19% Cr, 4.3% Mo, 2% Fe, 3% Ti
12	Nimonic 75	75	19% Cr
13	Nimonic 90	57	19.5% Cr, 16.5% Co
14	Cupronickel	30	70% Cu

11.2. Properties of Materials

1. Physical Properties
   a. Density
   b. Melting point
   c. Boiling point
   d. Specific heat
   e. Latent heat of fusion
   f. Thermal conductivity
   g. Anisotropy
   h. Thermal expansion
   i. Viscosity
   j. Solidus/liquidus
   k. Vapor pressure
   l. Specific gravity
2. Mechanical Properties
   a. Brittle fracture
   b. Fatigue
   c. Endurance limit
   d. Creep
   e. Hardness
   f. Abrasion resistance
   g. Impact resistance
   h. Strength/ductility/toughness
      1. Tensile
      2. Yield
      3. Elongation
      4. Proportional limit
      5. Modulus of elasticity
      6. Compression
      7. Shear
      8. Reduction of area
3. Fabrication Properties
   a. Weldability
   b. Machinability
   c. Formability
   d. Hardenability
4. Special Properties
   a. Coefficient of friction
   b. Water absorption
   c. Thixotropy
   d. Light transmittance, reflectivity, emissivity
5. Chemical Properties
   a. Corrosion properties
   b. Galvanic series
   c. Acid/base
   d. Graphitization
   e. Alloy chemistry
6. Electrical Properties
   a. Resistivity
   b. Conductivity
   c. Magnetic
   d. Piezoelectric
   e. Photoconductivity
   f. Thermoelectric
   g. Dielectric strength

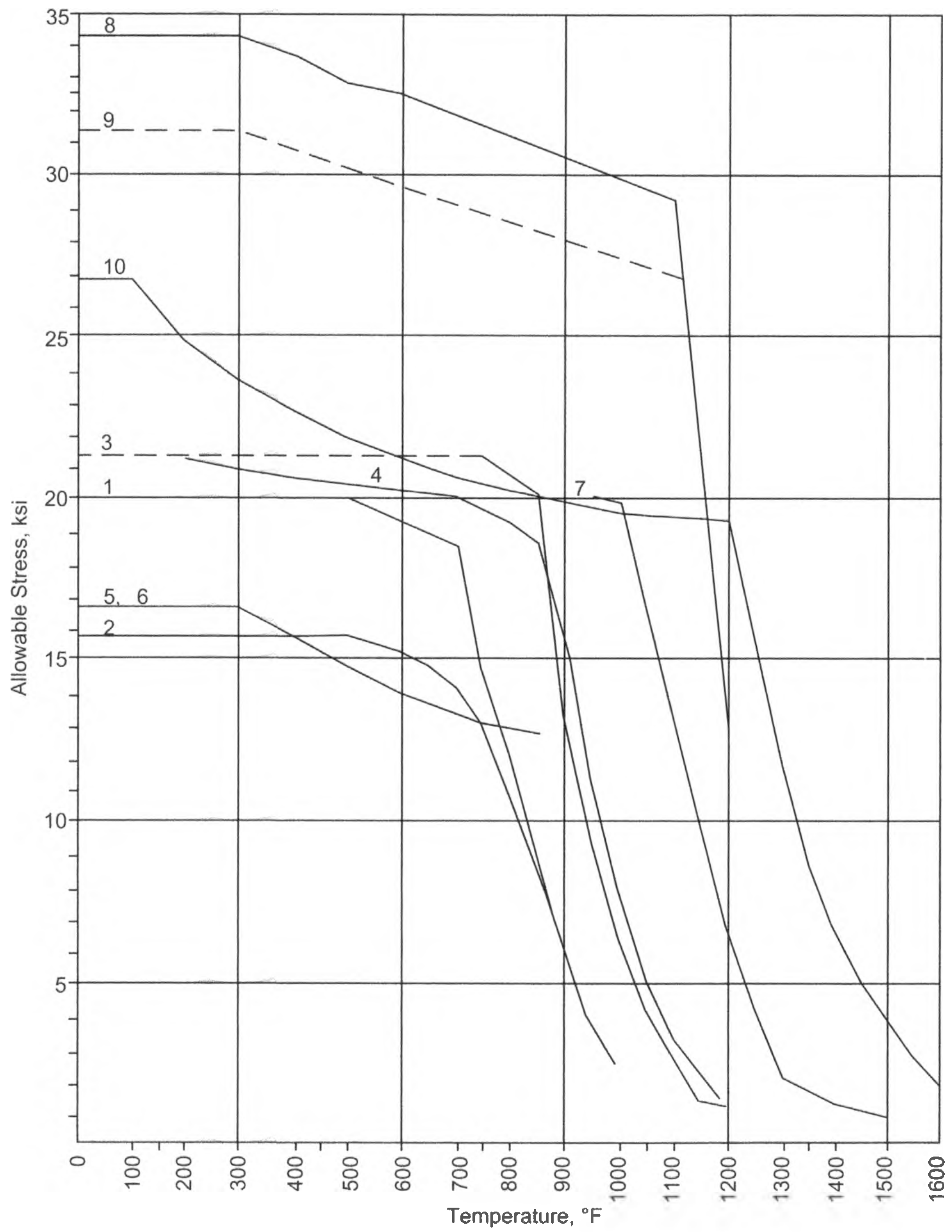


Figure 11-1. Allowable stresses per ASME Section II, Part D

Materials

1. SA-516-70, SA-515-70
2. SA-285-C
3. SA-387-11-2
4. SA-387-22-2
5. SA-240-316L, High Stress
6. SA-240-304L, High Stress
7. SB-409-800
8. SB-443-625-1, High Stress
9. SB-443-625-1, Low Stress
10. SB-443-625-2, High Stress

Table 11-5
Material properties

Material		Temperature, °F														
		70	200	300	400	500	600	700	800	900	1000	1100	1200	1300	1400	1500
	E	29.4	28.8	28.3	27.9	27.3	26.5	25.5	24.2	22.5	20.4	18.0				
Carbon steel C ≤ 0.3%	α	6.4	6.7	6.9	7.1	7.3	7.4	7.6	7.8	7.9	8.1	8.2	8.3	8.4		
	F_y	38.0	34.8	33.6	32.5	31.0	29.1	27.2	25.5	24.0	22.6					
	E	29.6	29.0	28.5	28.0	27.4	26.9	26.2	25.6	24.8	23.9	23.0	21.8	20.5	18.9	
Chrome moly 1/2 - 2Cr steels	α	6.4	6.7	6.9	7.1	7.3	7.4	7.6	7.8	7.9	8.1	8.2	8.3	8.4		
	F_y	45.0	41.5	39.5	37.9	36.5	35.3	34.0	32.5	30.6	28.2					
	E	30.6	29.9	29.4	28.8	28.3	27.7	27.0	26.3	25.6	24.7	23.7	22.5	21.1	19.4	
Chrome moly 2 1/4 - 3Cr steels	α	6.4	6.7	6.9	7.1	7.3	7.4	7.6	7.8	7.9	8.1	8.2	8.3	8.4		
	F_y	45.0	41.2	39.4	38.1	37.3	36.5	35.6	34.3	32.4	29.7					
	E	31.0	30.3	29.7	29.2	28.6	28.1	27.5	26.9	26.2	25.4	24.4	23.3	22.0	20.5	
Chrome moly 5 - 9Cr steels	α	6.4	6.7	6.9	7.0	7.1	7.2	7.2	7.3	7.4	7.5	7.6	7.6	7.7	7.8	
	F_y	45.0	40.7	39.2	38.7	38.4	37.8	36.7	34.6	31.6	27.7					
	E	29.2	28.4	27.9	27.3	26.8	26.2	25.5	24.5	23.2	21.5	19.2	16.5			
High chrome moly 12 - 17 steels	α	5.9	6.2	6.3	6.4	6.5	6.5	6.6	6.7	6.7	6.8	6.8	6.9	6.9	7.0	7.0
	F_y	25.0	23.0	22.2	21.8	21.5	21.0	20.2	18.9	16.9	14.4					
	E	28.3	27.5	27.0	26.4	25.9	25.3	24.8	24.1	23.5	22.8	22.0	21.2	20.3	19.2	18.1
Austenitic stainless steel	α	8.5	8.9	9.2	9.5	9.7	9.9	10.0	10.1	10.2	10.3	10.4	10.6	10.7	10.8	10.8
	F_y	30.0	25.0	22.4	20.7	19.4	18.4	17.6	16.9	16.2	15.5					
	E	31.0	30.3	29.9	29.4	29.0	28.6	28.1	27.6	27.1	26.5	25.9	25.3	24.6	23.9	23.1
Inconel 600	α	6.8	7.1	7.3	7.5	7.6	7.8	7.9	8.0	8.2	8.3	8.4	8.6	8.7	8.9	9.0
	F_y	35.0	32.0	31.2	30.7	30.3	29.9	29.4	28.7	27.3						
	E	28.5	27.9	27.5	27.1	26.7	26.2	25.8	25.4	24.9	24.4	23.8	23.2	22.6	21.9	21.2
Incoloy 800	α	7.9	8.4	8.6	8.8	8.9	9.0	9.1	9.2	9.3	9.4	9.5	9.6	9.7	9.8	10.0
	F_y	30.0	27.7	26.6	25.8	25.1	24.5	23.8	23.2	22.7	22.1					

Notes:

1. Nomenclature and units are as follows:
   - E = modulus of elasticity, 10^6 psi
   - α = mean coefficient of thermal expansion from 70°F, in/in/°F
   - F_y = minimum specified yield strength, ksi
2. α and F_y are for the following grades:
   - Carbon steel C ≤ 0.3% = SA-516-70
   - Chrome moly 1/2 - 2Cr steels = SA-387-11-2
   - Chrome moly 2 1/4 - 3Cr steels = SA-387-22-2
   - Chrome moly 5 - 9Cr steels = SA-387-5-2
   - High chrome moly 12 - 17 steels = SA-240-405
   - Austenitic stainless steel = SA-240-304
   - Inconel 600 = SB-168
   - Incoloy 800 = SB-409

Source: ASME Section II, Part D

Table 11-6
Values of yield strength, ksi

Material	Temp									
	100°	200°	300°	400°	500°	600°	700°	800°	900°	1000°
SA-285c, SA-516-55	30	27.4	26.6	25.7	24.3	22.2	21.6	20.0	19.1	16.7
SA-516-60	32	29.2	28.4	27.5	26	23.7	23.1	21.3	20.3	17.8
SA-516-65	35	31.9	31	30	28.3	25.9	25.2	23.3	22.2	19.5
SA-105	36	32.9	31.9	30.9	29.2	26.6	26	24.0	22.9	20.1
SA-516-70	38	34.8	33.6	33.5	31.0	29.1	27.2	25.5	24.0	22.6
SA-204-B (C – ½Mo)	40	37.6	36.1	34.8	33.8	32.7	31.5	30.0	27.9	25.2
SA-302-B (Mn – Mo)	50	47.2	45.3	44.5	43.2	42.0	40.6	38.8	34.9	28.4
SA-387-2-2 (½Cr – Mo)	–	–	–	–	–	–	–	–	–	–
SA-387-12-2 (1Cr – ½Mo)	40	36.9	35.1	33.7	32.5	31.4	30.2	28.8	27.2	25.0
SA-387-11-2 (1¼Cr – ½Mo)	45	41.5	39.5	37.9	36.5	35.3	34.0	32.4	30.6	28.2
SA-387-22-2 (2¼Cr – 1Mo)	45	41.2	39.4	38.1	37.3	36.5	35.6	34.3	32.4	29.7
T-405 (13Cr)	25	23.0	22.2	21.8	21.5	21.1	20.2	18.9	16.9	14.4
T-410/T-430 (13/17Cr)	30	27.6	26.6	26.1	25.8	25.3	24.2	22.7	20.3	17.2
T-304 SST	30	25.0	22.4	20.7	19.4	18.4	17.6	16.9	16.2	15.5
T-304L SST	25	21.4	19.2	17.5	16.4	15.5	15.0	14.5	14.0	13.3
T-316 SST	30	25.9	23.4	21.4	20.0	18.9	18.2	17.6	17.3	17.0
T-321 SST	30	27.0	24.8	23.0	21.5	20.3	19.4	18.8	18.4	18.8
T-347 SST	30	27.6	25.7	24.0	22.6	21.5	20.7	20.3	20.2	20.1
SA-203-B (2½ Ni)	40	–	–	–	–	–	–	–	–	–
SA-203-D (3½ Ni)	37	–	–	–	–	–	–	–	–	–
Nickel 200	15	15	15	15	15	15	–	–	–	–
Monel 400	28	24.7	22.4	22.2	22.2	22.2	22.2	21.4	–	–
Inconel 600	35	32.7	31.0	29.9	28.8	27.9	27	26.1	–	–
Incoloy 800	30	27.6	26.0	25.0	24.1	23.9	23.5	23.0	–	–

Source: ASME Section II, Part D.

Table 11-7
Material selection guide

	Design Temperature, °F	Material	Plate	Pipe	Forgings	Fittings	Bolting
Cryogenic	−425 to −321	Stainless steel	SA-240-304, 304L, 347, 316, 316L	SA-312-304, 304L, 347, 316, 316L	SA-182-304, 304L, 347, 316, 316L	SA-403-304, 304L, 347, 316, 316L	SA-320-B8 with SA-194-8
	−320 to −151	9 nickel	SA-353	SA-333-8	SA-522-1	SA-420-WPL8	
Low temperature	−150 to −76	3½ nickel	SA-203-D	SA-333-3	SA-350-LF3	SA-420-WPL3	SA-320-L7 with SA-194-4
	−75 to −51	2½ nickel	SA-203-A				
	−50 to −21	Carbon steel	SA-516-55, 60 to SA-20	SA-333-6	SA-350-LF2	SA-420-WPL6	
	−20 to 4		SA-516-All	SA-333-1 or 6			SA-193-B7 with SA-194-2H
	5 to 32		SA-285-C	SA-53-B SA-106-B	SA-105 SA-181-60,70	SA-234-WPB	
Intermediate	33 to 60 61 to 775		SA-516-All SA-515-All SA-455-II				
Elevated temperature	776 to 875	C-½Mo	SA-204-B	SA-335-P1	SA-182-F1	SA-234-WP1	
	876 to 1000	1Cr-½Mo	SA-387-12-1	SA-335-P12	SA-182-F12	SA-234-WP12	
		1-¼Cr-½Mo	SA-387-11-2	SA-335-P11	SA-182-F11	SA-234-WP11	
	1001 to 1100	2¼Cr-1Mo	SA-387-22-1	SA-335-P22	SA-182-F22	SA-234-WP22	with SA-193-B5 SA-194-3
	1101 to 1500	Stainless steel	SA-240-347H	SA-312-347H	SA-182-347H	SA-403-347H	SA-193-BB with SA-194-B
		Incoloy	SB-424	SB-423	SB-425	SB-366	
	Above 1500	Inconel	SB-443	SB-444	SB-446	SB-366	

From Bednar, H.H., *Pressure Vessel Design Handbook*, Van Nostrand Reinhold Co., 1981.

Note:

1. Material specifications shown are for non-corrosive service only. Actual material selection must take corrosion rates into account.
2. This table should be used as a guideline for material selection based on temperature only. No consideration for various services has been made in the assembly of this table.

11.3. Bolting

Specifications

SA-193: Specification for Alloy steel and Stainless Steel Bolting Material for High-temperature Service
SA-320: Specification for Alloy steel Bolting Materials for Low Temperature Service
SA-540: Specification for Alloy Steel Bolting Materials for Special Applications
SB-637: Specification for Precipitation hardening Nickel Alloy bars, Forging and Forging stock for High Temperature Service

Some other Specifications utilized by the process industry:

SA-307: Carbon steel bolting, low strength
SA-325: Used mainly in structural applications
SA-490: Used mainly in structural applications

Some exotic applications;

1. SA-193-B408 to UNS NO8810	Inco 718
2. SA-193-B8S	Nitronic 60
3. SA-193-XM-19	Nitronic 50
4. SA-540-B22-Class 1:	
5. SB-637-NO7718	Inco 718

Heat treat condition (Class) of SA-193

Class 1:	N&T or Q&T and solution treated
Class 1A:	Solution treated after finishing
Class 1B:	Solution treated for Nitrogen bearing SST
Class 1C:	Solution treated for Nitrogen bearing SST
Class 2:	Annealed and strain hardened

In general all SST bolting should have the threads formed after heat treatment. However certain grades of Classes 1A, 1B, and 1C are to be solution treated in the final condition.

Bolting

Notes

1. Bolt and thread dimensions shall be in accordance with ANSI B1.1.
2. Nut dimensions shall be a accordance with ANSI B18.2.2.
3. Washer dimensions shall be per ANSI B18.22.1.
4. Mechancial testing of bolting materials shall be conducted in accordance with ASTM A-370.
5. Where practical all threads shall be cut or formed after heat treatment. Heat treatment can be performed after threading if agreed by purchaser. Certain grades of SA-193 are required to be heat treated after threading. Grade B7M is required to be Q&T after threading.
6. Class of Fit;
   a. Class 1: Loose
   b. Class 2: Standard
   c. Class 3: Exceptionally high quality
   d. Class 4: Selective Fit
7. Thread Series:
   a. NC: National Course
   b. NF: National Fine
   c. UNEF: Extra Fine
   d. 8 thread series (typically used in flange bolting above 1 inch diameter)
   e. 12 thread series
   f. 16 thread series

Table 11-8
Bolting materials

Type of Material	Material Specification		
	Symbol	Bolts	Nuts
Aluminum alloy 2014-T6	AL	B211, TP-2014-T6	B211, TP-2014-T6
AISI T-501(5 Cr)	B5	SA-193-B5	SA-194-3
AISI T-410(12 Cr)	B6	SA-193-B6	SA-194-6
AISI T-4140, 4142, 4145	B7	SA-193-B7	SA-194-2H
304 SS	B8	SA-193-B8	SA-194-8
Cr-Mo-V	B16	SA-193-B16	SA-194-2H
Carbon steel	CS1	SA-307-B	SA-307-B
Carbon steel	CS2	SA-325	SA-325
Copper alloy, CDA 630	CU	CDA 630 to SB-150	CDA 630 to SB-150
Hastelloy C	HC	SB-336 annealed	SB-336 annealed
Hastelloy X	HX	SA-193 to B-435	SA-193 to B-435
AISI T-4140, 4142, 4145	L7	SA-320-L7	SA-194-4
Monel 400	M4	SA-193 to B-164	SA-193 to B-164
Inconel 600	N6	SA-193 to B-166	SA-193 to B-166
Incoloy 800	L8	SA-193 to B-408	SA-193 to B-408
19 Cr – 9 Ni	SS	SA-453 GR 651, CL A	SA-453 GR 651, CL A
321 SS	8T	SA-193-B8T	SA-194-8T
316 SS	8M	SA-193-B8M	SA-194-8M
Nitronic 60	8S	SA-193-B8S	SA-194-8S

Table 11-9
Bolting application

		Temperature Range, °F											
Service		–121 to –420	–51 to –120	–21 to –50	59 to –20	60 to 399	400 to 649	650 to 849	850 to 999	1000 to 1099	1100 to 1199	1200 to 1499	>1500
Low Temperature	SST	B8	L7	L7									
Low Temperature	ALUM	B8	AL	AL	AL	AL							
Low Temperature	9 Ni	B8	L7	L7	B7	B7							
Low Temperature	3-½ Ni		L7	L7	B7	B7							
Low Temperature	CS			L7	B7	B7							
Low Temperature	Copper			CU	CU	CU	CU						
Intermediate Temperature	C.I.				CS	CS							
Intermediate Temperature	CS				B7	B7	B7						
Intermediate Temperature	Low alloy					B7	B7	B7	B7				
Elevated Temperature	Low alloy					B7	B7	B7	B16	B16	B5		
Elevated Temperature	321 SS					8T	8T	8T	8T	8T			
Elevated Temperature	316 SS					8M	8M	8M	8M	8M	8M	8M	
Elevated Temperature	Corro-sion					M4	M4	M4	M4	N6	N6	L8	L8
Elevated Temperature	Corro-sion								HC				HX

Table 11-10
Allowable stress for bolts

Material	Spec	Class	Min. Spec. Tensile	Min. Spec. Yield	Size, in.	100	200	300	400	500	600	700	800	900	1000	1100	1200
Carbon steel	Sa-307–B		60			7.00	7.00	7.00	7.00								
Carbon steel	SA-325		105	81		20.20	20.20	20.20	20.20	20.20	20.20						
5Cr-½ Mo	SA-193-B5		100	80	<4	20.00	20.00	20.00	20.00	20.00	20.00	20.00	18.50	10.40	5.60	3.10	1.30
13Cr	SA-193-B6		110	85	<4	21.20	21.20	21.20	21.20	21.20	21.20	21.20	19.50	12.00			
1Cr-⅕Mo	SA-193-B7		125	105	<2.5	25.00	25.00	25.00	25.00	25.00	25.00	25.00	21.00	12.50	4.50		
			115	95	2.5–4	23.00	23.00	23.00	23.00	23.00	23.00	23.00	20.00	12.50	4.50		
			100	75	4–7	18.70	18.70	18.70	18.70	18.70	18.70	18.70	18.00				
18Cr-8Ni	SA-193-B8	2	125	100	<.75	25.00	25.00	25.00	25.00	25.00	25.00	25.00	25.00	25.00	24.10		
			115	80	.75–1	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00		
			105	65	1–1.25	16.30	16.30	16.30	16.30	16.30	16.30	16.30	16.30	16.30	16.30		
			100	50	1.25–1.5	12.50	12.50	12.50	12.50	12.50	12.50	12.50	12.50	12.50	12.50		
1Cr-½Mo-V	SA-193-B16		125	105	<2.5	25.00	25.00	25.00	25.00	25.00	25.00	25.00	25.00	20.50	11.00	2.80	
			110	95	2.5–4	23.00	23.00	23.00	23.00	23.00	23.00	23.00	22.00	18.50	11.00	2.80	
			100	85	4–7	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	16.70	11.00	2.80	
1Cr-½Mn-¼Mo	SA-540-B22	1	165	150	<1.5	33.00	33.00	33.00	33.00	33.00	33.00	33.00					
		2	155	140	<3	31.00	31.00	31.00	31.00	31.00	31.00	31.00					
		3	145	130	<4	29.00	29.00	29.00	29.00	29.00	29.00	29.00					
		4	135	120	<4	27.00	27.00	27.00	27.00	27.00	27.00	27.00					
		5	120	105	<2	24.00	24.00	24.00	24.00	24.00	24.00	24.00					
		5	115	100	2–4	23.00	23.00	23.00	23.00	23.00	23.00	23.00					
1Cr-⅕Mo	SA-320-L7		125	105	<2.5	25.00	25.00	25.00	25.00	25.00	25.00	25.00					
1C-¼ Mo	SA-320-L7A		125	105	<2.5	25.00	25.00	25.00	25.00	25.00	25.00						
1C-1/5 Mo	SA-320-L7M		100	80	<2.5	20.00	20.00	20.00	20.00	20.00	20.00	20.00	18.50	12.50	4.50		
1 ¾Ni-¾ Cr-¼Mo	SA-320-L43		125	105	<4	25.00	25.00	25.00	25.00	25.00	25.00	25.00					

Notes:

1. All values are in ksi.
2. Values per ASME, Section II, Part D.

Table 11-11
Material designation and strength

Material	Bolts SA-193-	Size (dia, in.)	UTS (ksi)	Min Spec Yield (ksi)	Nuts SA-194-
5Cr-½Mo	B5	<4	100	80	3
12Cr(T-410 SS)	B6	<4	110	85	6
1Cr-1/5 Mo	B7	<2.5	125	105	2H
1Cr-1/5 Mo	B7	2.5 to 4	115	95	2H
1Cr-1/5 Mo	B7	4 to 7	100	75	2H
1Cr-1/5 Mo	B7M	<2.5	100	80	2H
1Cr-½Mo-V	B16	<2.5	125	105	2H
1Cr-½Mo-V	B16	2.5 to 4	110	95	2H
1Cr-½Mo-V	B16	4 to 7	100	85	2H
304 SS	B8-2	<0.75	125	100	8
304 SS	B8-2	75 to 1	115	80	8
304 SS	B8-2	1 to 1.25	105	65	8
304 SS	B8-2	1.25 to 1.5	100	50	8
316 SS	B8M-2	<0.75	110	95	8M
316 SS	B8M-2	0.75 to 1	100	80	8M
316 SS	B8M-2	1 to 1.25	95	65	8M
316 SS	B8M-2	1.25 to 1.5	90	50	8M
321 SS	B8T-2	<0.75	125	100	8T
321 SS	B8T-2	0.75 to 1	115	80	8T
321 SS	B8T-2	1 to 1.25	105	65	8T
321 SS	B8T-2	1.25 to 1.5	100	50	8T
347 SS	B8C-2	<0.75	125	100	8C
347 SS	B8C-2	75 to 1	115	80	8C
347 SS	B8C-2	1 to 1.25	105	65	8C
347 SS	B8C-2	1.25 to 1.5	100	50	8C
Nitronic 60	B8S	—	95	50	8S
		SA-320 (Low Temp)			
304 SS	B8A	—	75	30	8
316 SS	B8MA	—	75	30	8M
321 SS	B8TA	—	75	30	8T
347 SS	B8CA	—	75	30	8C

Table 11.12
Summary of requirements for 100% X-ray and PWHT*

P. No.	GRP. No.	Material Description	PWHT	Temperature °F	100% R.T.
1	1	Carbon steel: SA-36, SA-285-C, SA-515/-516 Grades 55, 60, 65	>1.5 in.	1100°	>1.25 in.
	2	Carbon steel: SA-515/-516 Grade 70, SA-455-I or II	>1.5 in.	1100°	>1.25 in.
3	1	Low alloy: C-½ Mo (SA-204-B)	>.625 in.	1100°	>.75 in.
	2	Low alloy: 1/2 Cr-½ Mo (SA-387-2-2)	>.625 in.	1100°	>.75 in.
	3	Low alloy: Mn-Mo (SA-302-B)	All	1100°	>.75 in.
4	1	Low alloy: 1Cr-½ Mo (SA-387-12-2) 1Cr-½ Mo (SA-387-11-2)	(1)	1100°	>.625 in.
5	1	Low alloy: 2Cr-1Mo (SA-387-22-2) 3Cr-1Mo (SA-387-21-2)	All	1250°	All
	2	Low alloy: 5,7,9Cr-½ Mo	All	1250°	All
6	1	13Cr (410) Martensitic SST	(2)	1250°	(2)
7	1	13Cr (405, 410S) Martensitic SST	(2)	1350°	(2)
	2	17Cr (430) Ferritic SST	All	1350°	(2)
8	1	(304,316,321,347) Austenitic SST	–	1950°	>1.5 in.
	2	(309,310) Austenitic SST	–	1950°	>1.5 in.
9A	1	Low alloy: 2½ Ni (SA-203-A,B)	>.625 in.	1100°	>.625
9B	1	Low alloy: 3½ Ni (SA-203-D,E)	>.625 in.	1100°	>.625
41	–	Nickel 200	–	–	>1.5 in.
42	–	Monel 400	–	–	>1.5 in.
43	–	Inconel 600, 625	–	–	>.375 in.
45	–	Incoloy 800, 825	–	–	>.375 in.

Notes:

1. See ASME Code, Section VIII, Div. 1 Table UCS-56, for concessions/restrictions.
2. PWHT or radiography depends upon carbon content, grade of material, type of welding, thickness, preheat and interpass temperatures, and types of electrodes. See ASME Code, Section VIII, Div. 1 Table UHA-32, and paragraphs UHA 32 and 33 for concessions/restrictions.
3. Radiography shall be performed after PWHT when required. 100% R.T. is required for all vessels in lethal service (ASME Code UW-2(a)). Materials requiring impact testing for low temperature service shall be PWHT (ASME Code, UCS-67(c)).
4. Radiography applies to category A and B, type 1 or 2 joints only. Thicknesses refer to thinner of two materials being joined.

**Per ASME Code, Section VIII, Div. 1 for commonly used materials.*

11.4. Testing & Examination

The terms examination and test are often used interchangeably. This is not correct in a purely technical sense. The two terms have different meanings and should not be confused.

Examination

An examination is a passive evaluation technique or procedure that evaluates the material or work piece without subjecting the work piece to potential stress or strain. Examination cannot cause the work piece to be deformed or to fail.

Nondestructive Examination (NDE) is defined as the development and application of technical methods to examine materials and/or components in ways that do not impair future usefulness and serviceability in order to detect, locate, measure, interpret and evaluate flaws.

Examples of NDE:

- UT (Ultrasonic)
- PT (Penetrant or sometimes Liquid Penetrant)
- MT (Magnetic Particle Testing)
- PMI (Positive Material Identification)
- RT (Radiographic Testing)
- Eddy Current

Test

A test is an invasive procedure that engages the equipment, work piece or material as part of the testing process. The material, equipment or coupon participates in the test. Testing may cause the work piece to fail or be deformed. Tests are divided into destructive tests and non-destructive tests.

Examples of Tests

Destructive Tests:

- Tensile Test
- Bend Test
- Charpy Impact Test
- HIC Testing
- Autoclave testing for disbonding

Non-Destructive Tests:

- Hydrotest
- Pneumatic Test
- Soap Bubble Test
- Helium Leak Test
- Performance Test
- Acoustic Emission Test
- Hardness Test
- Ferrite Check
- Copper Sulfate Test
- PMI

Defects and Failures

No material or fabrication is perfect. Every man-made material has defects, no matter how slight. Our quest as engineers is not to find or create the perfect material or part, but rather to establish the maximum size of defect that is acceptable and will allow the part to function.

Different codes and standards have different acceptance levels for the same defect. Thus a defect, or indication, may be rejectable under one code but acceptable under another.

Defect: One or more flaws whose aggregate size, shape, orientation, location or properties do not meet specified acceptance criteria and are rejectable. A flaw becomes a defect when it is rejectable under a specific code or standard. A defect can further be defined as a lack or absence of something essential for completeness or perfection. Defects can range in size from atom sized dislocations to major discontinuities.

Examples of defects are as follows;

1. Discontinuity
2. Indication
3. Flaw
4. Flaw characterization
5. Imperfection
6. Nonrelevant indication
7. Relevant indication

Failure/Rejection: Failure of a material or part is defined as the omission to perform or non-performance, often involving deterioration or decay. A part may not be suitable for its intended purpose for a variety of reasons such as tolerance, surface finish, etc, and this would be a condition for rejection.

Many apparent defects may not reduce the service life of the vessel or part. On the other hand, a small, unseen sub-surface defect, may actually lead to failure.

NDE or NDT can help to find defects, but it is the code, standard or specification that determines if the defect is acceptable or not.

Hydrostatic, Pneumatic, and Proof Testing of Pressure Vessels

Shop Hydrostatic Testing (UG-99)

1. ASME Section VIII, Division 1 requires that the minimum metal temperature during hydrostatic test shall be at least 30°F above the MDMT of the vessel that is stamped on the nameplate but not greater than 120°F.
2. Gauges used for hydrotests shall have been calibrated within one year of the test for not less than 1.5 times, nor more than 4 times the pressure of the test.
3. Minimum holding time for test shall be 1 hour minimum.
4. The vessel may be tested with painting and or lining on both the exterior and interior. Although not an ASME Code requirement it is recommended that the weld seams should be left unpainted approximately 1 inch on either side of the seam.
5. Testing may be performed after refractory lining. That is, the test may be performed through the lining. The ASME Code Inspector (AI) must give permission prior to testing.
6. There is no "maximum" hydrostatic test pressure specified by the Code. Good engineering practice limits the general primary membrane stress to .9 F_y for carbon steel components and F_y for stainless steel components.
7. Vessels may be tested with liquids other than water.

Field Hydrostatic Testing. Field hydrostatic testing is not an ASME Code requirement. Field testing is optional to test the tightness of piping joints attached to the vessel after installation. Often it is a contractor's policy to design vessels and vessel foundations, with rare exceptions, for a future field hydrotest in the corroded condition. This gives clients the option to test the vessel on its foundation in the future should alterations or repairs warrant such a test.

1. Vessels may be filled with water and tested as part of the piping field test. It is easier and preferable in most cases to "test through" the vessels as opposed to blanking off the connections to test the field piping. In addition this tests the tightness of joints attached to the vessel.
2. Horizontal vessels may be tested at the same pressure as the shop test.
3. Vertical vessels may be tested to a maximum of the shop test pressure minus the hydrostatic head of liquid.
4. Vessels may be hydrotested, pneumatic tested or a combination of both.
5. All test pressures should be gauged at the top of the vessel as a minimum. For very large field fabricated vessels, gauges may also be employed on the side or bottom of the vessel.
6. Ensure that the vessel has been designed for a field hydrostatic test.
7. Either remove SST internals or use water with less than 50 PPM chlorides. Water greater than 200 PPM chlorides should not be used.
8. Examples of vessels that are typically exempted from field testing are large refractory lined vessels such as FCC reactors and regenerators.

Pneumatic Testing (UG-100)

1. Pneumatic testing may be used in lieu of hydrostatic testing provided;
   a. Cannot be safely filled or supported with water
   b. Cannot be dried sufficiently after the test
   c. A hydrostatic test could result in damage to internals
2. A pneumatic test shall be 1.1 times the MAWP times the stress material ratio (SMR)
3. Pressure shall be applied gradually up to ½ the test pressure. After that the pressure shall be increased in increments of 1/10 the ultimate pressure. Then the test pressure shall be reduced to 4/5 of the test pressure and held for a suitable period of time to allow inspection.
4. Secondary containment closures of nuclear power plants are pneumatically tested to approximately 65 PSIG and are over 200 feet in diameter.
5. Vessels to be pneumatically tested may be painted or coated internally and externally prior to the test.
6. All nozzle and attachment welds shall be 100% PT or MT examined, dependent on material, prior to testing.

Proof Testing (UG-101). A proof test is used to establish the MAWP by testing rather than calculation. A proof test is required to determine the MAWP of a vessel only when no other suitable means can do so with sufficient accuracy. That is, the configuration or construction cannot be adequately analyzed to mathematically develop a MAWP. This is an elaborate and cumbersome procedure that is rarely used. Designs that cannot be demonstrated by normal analytical techniques are rare exceptions.

The author has only been involved with two proof tests. One had a very large round flanged opening in a 2:1 SE head, offset from the vessel centerline, that resulted in significant loss of structural integrity of the head. Normal Code reinforcement methods were inadequate to replace the loss of rigidity of the head.

The second case involved the use of a 24 inch by 24 inch tee as part of the vessel shell. The proof test was done at the insistence of the ASME Code inspector. Proof tests may be required by the AI regardless of the mathematical proofs and FEA performed, if in their opinion, the design is sufficiently complex as to defy mathematical modeling.

Proof tests may result in permanent vessel deformation.

There are two types of proof tests provided for by the ASME Code. They are as follows;

A. Tests based on the yielding of the part
B. Tests based on the bursting of the part.

In the second test, at least two vessels are built by identical means. One vessel is pressured to either failure, leakage or bursting. This "failure pressure" is then used to develop an MAWP for the other vessel. The surviving vessel is then given a standard hydrostatic or pneumatic test based on the MAWP established.

Hardness Testing

Hardness testing is a critical NDE tool utilized to ensure that the welding, heat treatment and fabrication methods have not altered the original material of construction in a deleterious way. Hardness testing is a quick method to determine that forming and fabrication techniques have not made the material too soft or too hard. Only ductile materials are allowed for pressure vessel construction, however, forming, welding and heat treatment can alter the original material properties. The altered properties can be a result of work hardening (strain hardening) or metallurgical change. Almost all metals work harden.

Although hardness testing is normally performed to detect if a material is too hard, it can also identify materials that are too soft. This would indicate a loss of tensile strength which may have weakened the material beyond its ability to satisfy the ASME Code design. In the past we have seen vessels that were subject to a prolonged sub-critical anneal in order to reduce excessive hardness readings. The prolonged heat treatment weakened the material and the vessel had to be derated for the reduced tensile strength.

Hardness Requirements

Hardness requirements vary by type of material and service. We have had contracts where the Brinell hardness for carbon steel in wet H2S service was 185, however this number would typically be 200 HB or below. API 934 requires, for vessels of 2-1/4 or 3 Cr material, in high temperature, high pressure hydrogen service, a hardness of 225 HB for conventional materials and 235 HB for advanced steels. Carbon steels in hydrogen service should be 200 HB maximum. For general service, the following can apply but refer to specific client specifications for details;

P-1 (Corrosive service)	200HB
P-1	225HB
P-3 & 4	225HB
P-5,6 & 7	241HB
P-10	225HB

Locations of Test

Weld procedures require hardness testing on a section of the weld. The tests are performed on the weld metal, the HAZ and the base metal. Production tests are on the weld metal only for each welding process, filler metal and technique used. The location for the testing of the production welds shall be at the discretion of the inspector.

When?

After PWHT when required.

Quantity of Tests?

One set of hardness tests shall be taken in the weld metal and one in the HAZ. Each set shall consist of three samples.

Methods

The property of "hardness" is based on the material's ability to resist scratching, wear, penetration, machinability, or the ability to cut. There are over 30 methods used for measuring hardness. A representative listing is as follows;

1. Knoop
2. Rockwell
3. Vickers
4. Moh's: Comparitive scale between talc and diamond
5. Shore Durometer: For rubber and plastics
6. Scleroscope: utilizes a steel ball bounced off the specimen
7. Brinell

Of these, only three are really important to the steel/refining industry. They are;

1. Rockwell
2. Vickers
3. Brinell

In our industry, the most common application is the Brinell test method but the following will summarize the three processes.

Brinell Testing (BHN)

Brinell was a Swedish engineer who developed this testing process to determine both hardness and tensile strength. It consists of indenting the surface of the metal by a hardened steel ball under a load and then measuring the indentation. The diameter of the ball is 10 mm and the load is 3000 Kg, 1000 Kg for copper and 500 Kg for aluminum. Other ball sizes can be used and the results are just ratioed off of the ball size.

The time of the loading is 15 seconds. The indentation is measured with either a special microscope fitted with a scale or a portable version.

The indentation falls into two categories:

1. Piling up: Indicates a low rate of hardening by deformation
2. Sinking: Indicates the ability to work harden.

The approximate tensile strength in PSI can be ascertained by multiplying the Brinell hardness number × 500. For metric applications the tensile strength in N/mm^2 can be obtained by multiplying the Brinell number by 3.54 for annealed steels, and 3.24 for quench and tempered steels.

The numerical Brinell hardness number is equal to the load divided by the spherical surface area of the indentation expressed in Kg/mm^2

BHN = Brinell Hardness Number

= Load/Surface area of indentation

The Brinell test has several limitations;

1. Cannot be used on soft materials
2. The test may not be valid for thin specimens. The minimum thickness is about 0.313 in.
3. The test is not valid for case hardened materials
4. The test should not be conducted too close to the edge of material
5. The indentation may be objectionable on the finished part
6. The edge of the indentation may be difficult to see on some materials

Errors arise when the Brinell test is performed on very hard materials, resulting in low values owing to: (a) the spherical shape of the indentor (b) flattening of the ball. The Brinell number is not reliable above 600.

Vickers Pyramid Hardness Testing (DPH)

The Vickers Hardness Test is similar to the Brinell method, with a square based pyramid used as the indentor. As in the Brinell test, the Vickers number is the ratio of the load to the surface area of the indentation in kilograms per square millimeter. An advantage of the Vickers test is the increased accuracy in determining the diagonal of a square as opposed to the diameter of a circle.

Although Vickers test method is different than Brinell, the scales are identical up to about a hardness of 300. The Vickers test is less prone to the errors produced by the Brinell system because a diamond square based pyramid is used, which does not deform as easily as a ball.

Since the impressions are small, the machine is very suitable for polished or hardened materials.

Rockwell Hardness Testing

The Rockwell hardness test has eight different scales labeled A thru H. Each scale supports a different material, brass, bronze and soft metals. For our industry we are only concerned with the B and C scales designated as R_B and R_C. The Rockwell C scale is used for determining the hardness of hard steels. A conical diamond indentor is employed, called a brale, under a 150 Kg load. The Rockwell B test applies a 100 Kg load under a $^1/_{16}$ inch steel ball. For comparison purposes, the hardest steel is R_C 65. For reference, a steel is considered unmachinable when the hardness exceeds R_C 35.

Charpy Impact Testing (CIT)

Charpy impact testing, also known as Charpy V notch testing, is performed on materials to determine toughness properties, usually at low temperature. CIT enables one to determine the transition temperature between brittle and ductile failure for any material or material specimen. CIT is also a good indication of a materials ability to absorb shock loads at low temperatures. CIT is used predominantly for carbon and low alloy steels. It is not used for stainless steels because stainless steels do not fail in a brittle manner until extremely low temperatures.

CIT is a destructive test that utilizes test specimens machined from actual production test plates or sample materials. The test specimens can be machined for impact testing of all base metal, all weld metal or the heat affected zone (HAZ). Weld samples can be taken from the root area or any other specific area of the weld metal.

For forgings and fittings, the Code allows specimens to be machined from a sample piece of material that has experienced the same forming, forging or gross reduction of area as the work piece it represents. As an alternative, two forgings, flanges or fittings may be produced and one set destructively tested.

Test specimens are 10 mm × 10 mm × 55 mm long with a 2 mm deep 45 degree groove or notch cut into the specimen. Provisions are made in the ASME Code for thinner materials where sub-size specimens are used. The specimens are cooled in liquid nitrogen and allowed to warm to the exact temperature required for testing. At this point the specimen is placed in the swinging hammer device for testing. The hammer is pre-loaded to a certain starting position and locked. Once the hammer is released the amount of absorbed energy is recorded by the furthest travel of the swing arm. The absorbed energy, in foot pounds or joules, is the difference between the starting position of the hammer and the finishing position.

The main factors determined by the test are;

1. Absorbed energy
2. Lateral expansion
3. Percent shear

Lateral expansion is the amount of growth experienced by the specimen at the notch. The percent shear, or percent of fibrous fracture, is determined by comparing the samples to fracture appearance charts in ASTM A 370.

The ASME Code, Section VIII, Paragraph UG-84 defines the testing process and gives minimum absorbed energy for the test based on the material, thickness and tensile strength. Materials should be tested in their final heat treated condition. Each test consists of three samples each. The average of all three specimens shall meet the criteria specified, however one specimen is allowed to be 2/3 of the average energy required for the three specimens. In the event of a failure a retest can be performed. The retest shall consist of three new specimens and must meet the original criteria.

Types of Magnetic Particle Inspection

Techniques;

1. Continuous Technique
2. Residual Technique

Methods;

1. Dry powder application – Best for deep subsurface defects and is most convenient for field inspection with portable equipment. Best for rough surfaces.
   a. sprinkling from a shaker
   b. spraying from a puff bottle
   c. spraying from blowers
2. Wet application – Best for detecting fine cracks on relatively smooth material.
   a. Spray can – particles suspended in a liquid vehicle
3. Fluorescent – Must be observed under ultraviolet light
   a. Wet – the finest detection method of MT methods. Used for detecting microfissures in base material and welds. Usually required for all interior surfaces for vessels in hydrogen or wet H2S service.
   b. Dry

Types of Ultrasonic Examination

Major Types

1. Angle Beam – Used predominantly for forgings
2. Straight Beam – Used for plates
3. Time of Flight Diffraction (TOFD) – Used to provide a permanent record.
4. Shear Wave – May be either straight or angle beam. Refers to the direction in which the pulse echo enters the material.
5. Phased Array (PAUT)- Multiple probe technique for finding very small, minute cracks.

ASME Specifications for UT Examination

SA-388: Specification for the UT examination of heavy steel forgings

SA-435: Specification for straight beam UT examination of steel plates (½ in and over)

SA-577: Specification for the UT angle beam examination of steel plates

SA-578: Specification for straight beam UT examination of plain and clad steel plates for special applications (used to examine clad plates made to SA-263, -264, and -265, ⅜ in and over)

SA-745: Practice for UT examination of stainless steel forgings (straight and angle beam examination)

SA-20:

Supplement 8: UT examination in accordance with SA-435

Supplement 11: UT examination in accordance with SA-577

Supplement 12: UT examination in accordance with SA-578

Optional extent of examination for plate: 4 in linear or 9 in grid

Forgings are 100% examined

Acceptance criteria shall be per ASME Section VIII, Division 1

Requirements and methods shall be per ASME Section V, Article 5

All plate greater than 4 inches thick shall be UT examined per SA-435

All forgings greater than 4 inches thick shall be 100% UT examined per SA-388

Code Case 2235: Allows for UT of welds in lieu of radiography where required.

Types of Radiographic Examination (RT)

1. X-Ray
2. Gamma Ray
3. Source (Isotopes)
   a. Iridium 192
   b. Cobalt 60
   c. Selenium 75 (Thin Wall)
4. Linear Accelerator
5. Digital RT
6. Computed RT

11.5. Heat Treatment

1. **Types of Heat Treatment**
   a. Spheroidizing
   b. Tempering
   c. Homogenization (soaking of cast metals)
   d. Stress Relieving (sub-critical anneal / PWHT)
      - Global
      - Local
      - Progressive
   e. Normalizing
   f. Case Hardening
      - Nitriding
      - Carburizing
      - Cyaniding (.010 to .020 deep)
   g. Annealing
      - Process
      - Full
   h. Quenching
      - Direct
      - Interrupted
   i. Solution Annealing
   j. Combination
      - Quench and Temper
2. **Purpose for Heat Treatment**
   a. To harden, strengthen or toughen metal
   b. To soften metal, improve ductility
   c. To improve machinability
   d. To alter electrical or magnetic properties
   e. To refine or coarsen grain structure
   f. To surface treat metal
   g. To produce a constitutional change
   h. Removal of contained gas from materials
   i. Improving creep ductility
   j. Improving resistance to SCC
   k. Improving fatigue strength
3. **Types of Hardening of Metals**
   a. Alloy Hardening
   b. Cold Working
      - Forming
      - Drawing
      - Shot peening
   l. Precipitation Hardening
      - 17-7 PH Stainless Steel
      - Maraging steel
      - Aluminum alloys
   m. Transformation Hardening
      - Martensite (heat treating)
      - Quench & tempering
      - Austempering
      - Martempering
   n. Surface Hardening (case hardening)
      - Nitriding
      - Carbuerizing
      - Cyaniding
      - Coatings (spray on type)

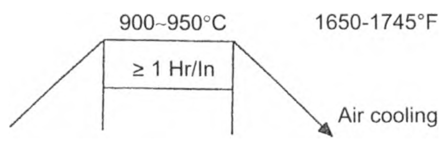
Heat Treatment Terms & Definitions

Air Hardening: A process used in steels that contain sufficient quantity of carbon or other alloys that will harden during air cooling.

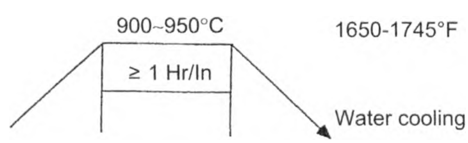
Annealing: The term annealing for carbon and alloy steels, implies slow cooling to soften or change the microstructure or crystalline structure. It is used to remove stresses, induce softness, alter ductility, toughness, improve machinability, dimensional stability, magnetic or other physical or mechanical properties. There are many specific types of annealing to include; black annealing,

TYPES OF HEAT TREATMENT

NORMALIZING



QUENCHING



TEMPERING

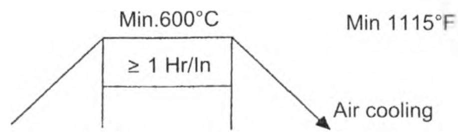
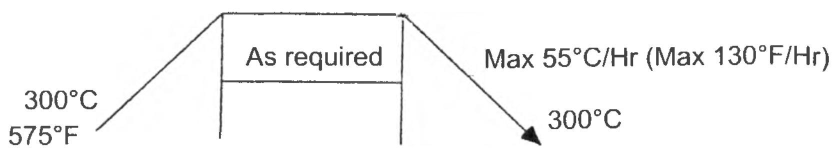


TABLE: PWHT TEMPERTURES

MATERIAL	TEMPERATURE	
	°C	°F
Carbon Steel	595-650	1100-1200
Low Nickel	595-635	1100-1175
.3-.5 Mo Stl	595-660	1100-1220
1 Cr - 1/2 mo	680-720	1250-1325
1-1/4 Cr - 1/2 Mo	680-720	1250-1325
2-1/4 Cr - 1Mo	680-720	1250-1325
5 Cr- 1/2 Mo	720-760	1325-1400
9 Cr - 1 Mo	720-760	1325-1400
3.5 Ni	595-635	1100-1175
13 Cr	700-720	1250-1325
17 Cr	730-790	1350-1450

PWHT (See Table for Temperature Ranges)

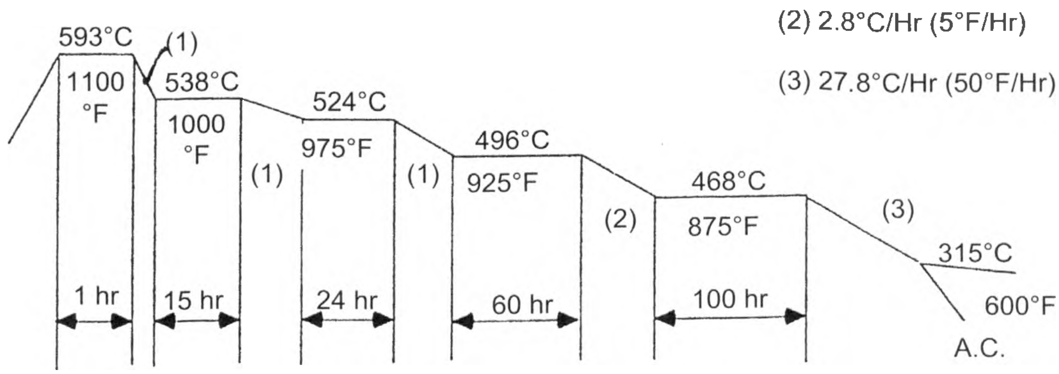


STEP COOLING FOR TEST BLOCK (Cr-Mo Only)

(1) 5.6°C/Hr (10°F/Hr)

(2) 2.8°C/Hr (5°F/Hr)

(3) 27.8°C/Hr (50°F/Hr)



blue annealing, box annealing, Bright annealing, cycle annealing, flame annealing, process annealing, full annealing, sub-critical annealing, quench annealing and isothermal annealing. When applied solely to the relief of stress, the process is more accurately called stress relieving.

Full Anneal: Austenitizing and then cooling at a rate such that the hardness of the part is minimum.

Heat Treatment: A combination of heating or cooling of a metal to obtain desired conditions or properties. Heating, solely for the purpose of hot working is excluded from this definition.

Homogenization (Soaking): A high temperature heat treatment intended to eliminate or decrease chemical segregation by diffusion.

Interrupted Quench: A quenching procedure where the initial quench is interrupted, followed by final quenching at a different rate or in a different medium to alter the quench depth or properties.

Normalizing: Heat treatment of an iron based alloy is heated to a temperature at least 100 degrees above the transformation range and then cooled in still air. This process produces a recrystallization and refinement of the grain in the material that results in uniform hardness and structure.

Process Anneal: A generic term to define a heat treatment that improve workability.

Quenching: Also known as quench hardening. Heating uniformly to a pre-determined temperature and cooling rapidly in air or liquid to produce a desired crystalline structure. Quenching can be done in water, brine, oil, polymer or even forced or still air. There are two types of quenching. The first to obtain mechanical properties. The second to retain uniformity of material.

Recrystallization (or anneal): Used for non-ferrous or work hardened metals, to soften and remove strain hardening.

Solution Annealing: A process in which certain alloys are heated to a suitable temperature to allow the constituents to enter into solid solution. The ingredients are held in this state until rapid cooling occurs. In stainless steel, the material is heated to 1950°F and quenched rapidly in liquid. The purpose is to freeze the constituents in the austenitic phase.

Spheroidization: Heating and cooling in a cycle designed to produce spheroidal or globular forms of carbide within the microstructure. It is used primarily in cast iron.

Stabilizing Treatment: A heat treatment to stabilize the dimensions of the part or work piece. In stainless steels it refers to heating the metal to below the solution heat treatment temperature to allow the precipitation of carbides to combine with certain alloy ingredients, specifically titanium or columbium (niobium).

Stress Relief: A heat treatment process to reduce internal residual stress by heating to a desired temperature and holding for a suitable period of time, also known as a sub-critical anneal. Residual stresses can be induced by forging, casting, forming, welding or cold working of metal.

Sub-Critical Anneal: A high temperature tempering process for steel that produces many of the benefits of annealing but does not require cooling at a controlled rate.

Tempering: Heating a quench hardened or normalized ferrous alloy to a temperature below the transformation range to produce desired changes in properties, predominantly to soften or toughen. It is used to remove brittleness from quench hardened steel. In chrome moly Q&T steel, the tempering processs is accomplished by the final PWHT.

Transformation Range: The temperatures at which austenite forms during heating or cooling.

Transformation Temperature: The temperature at which a change in phase occurs.

Autoclave Testing: This is a test for cladding/overlay disbondment for all reactors in hydrogen service. The autoclave testing proves that the WPS is good for the intended service. Typically results of previous tests for a particular WPS will be acceptable if the other parameters are in the range. The test consists of welding a sample and putting it in a hydrogen rich atmosphere in an autoclave for a specified time at the design conditions. Then sample is removed for disbanding tests. Minimum shear is 20,000 PSI.

DHT (Dehydrogenation Heat Treatment): This is a heat treatment procedure used during the fabrication cycle only when welding or preheat is interrupted or stopped. Done at 600 – 650°F (min 570°F). Very common and used in lieu of ISR. It is a bakeout to ensure that trapped hydrogen in the welds has the opportunity to escape to the atmosphere. Used for less restrained welds like main reactor seams.

ISR (Intermediate Stress Relieve): This is a heat treatment procedure used during the fabrication cycle prior to allowing the material temperature to cool below the preheat temperature. Done at 1150°F. Must be done in a furnace to achieve these temperatures. Fabricators usually elect to do DHT in lieu of ISR due to ease and convenience.

Step Cooling: This is a testing procedure only to evaluate the long term effects of temper embrittlement. The test was developed by GE originally for turbine blades and since adopted by the refining industry for hydroprocessing reactors. This test of temper embrittlement is used for 2-1/4 Cr materials only. The heat treatment takes about 12 days before testing of the coupon can occur.

J Factor: Since temper embrittlement is a function of alloy and tramp elements present in the steel. The J factor is based on a mathematical equation that combines the overall effects of the various ingredients that are to be controlled. For 2-1/4 Cr and 3 Cr the limit is typically 100. For 1-1/4 Cr it is about 180 maximum. It applies to all product forms except tubing. The equation is;

$$\text{J Factor} = (\text{Si} + \text{Mn}) \times (\text{P} + \text{Si}) \times 10^4 (\text{Si, Mn, P \& Si are wt \%})$$

In addition the Cu content should be limited to .2% Maximum and Ni to .3% Maximum.

X Factor: Similar to J factor but only applies to weld consumables.

$$\text{X Factor} = (10\text{P} + 5\text{Sb} + 4\text{Sn} + \text{As})/100 < \text{or} = \text{to } 15(\text{P, Sb, Sn, As are in PPM})$$

Minimum PWHT: Consists of one heat treatment cycle.

Maximum PWHT: Consists of all heat treatment cycles specified (usually three) in order to allow for future PWHT cycles that may be required. The material and WPS are prequalified with multiple PWHT cycles to ensure properties.

Post Weld Heat Treatment (PWHT) Alternatives

Post weld heat treatment of a vessel that cannot be contained in a single furnace load:

Although it is preferable to post weld heat treat the completed vessel in an enclosed furnace, this is not always possible. If it is not possible to place the entire vessel inside a furnace for PWHT the alternatives are as follows:

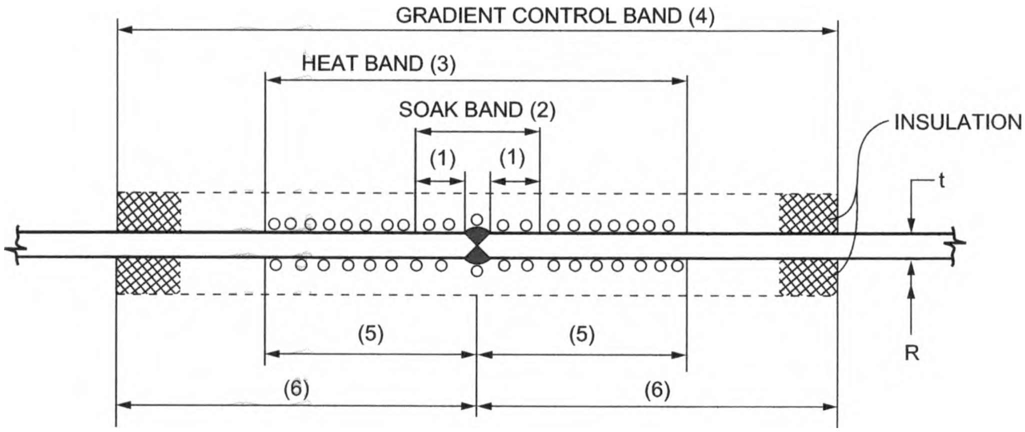
1. Heating the vessel portions in more than one heat: If the vessel is too long for the furnace then one portion of the completed vessel is post weld heat treated and then the vessel is turned around to do the remaining portion. This method requires a thermal gradient control band for that portion of the vessel extending outside the furnace. The minimum overlap of each portion is 5 feet.
2. Heating the vessel in two or more sections in a furnace, then perform a local PWHT on the final closure seams.
3. Heating vessel internally: Typically done with burners placed through nozzles or manways. The vessel shall be fully insulated on the outside and fully instrumented for temperature control.

Local Post Weld Heat Treatment:

This procedure is typically done following a repair or as the closure seam for a vessel that is post weld heat treated in multiple sections.

1. Heating shall be done with a full circumferential band, typically with electric heating coils.
2. There are three types of bands required for a local PWHT and are as follows:
   a. Soak band: The soak band is the area including the weld seam as well as an area on either side of the weld. The minimum band width shall be the greater of 2t or 2 inches on either side of the weld measured from the toe of the weld. The time and temperature of the soak band shall meet the PWHT criteria.
   b. Heating band: The heating band shall extend to each side of the soak band for a minimum distance of $2(Rt)^{1/2}$. The temperature shall be lower than the soak temperature and determined to prevent severe thermal gradients.
   c. Gradient control band (also known as the insulation band): The GCB shall extend either side of the heating band. The distance shall be determined to reduce thermal gradients. Heating coils may, or may not be required in this region.
3. An insulating bulkhead may be required to isolate the heat within a certain area of the vessel. The bulkhead is positioned to prevent heat loss to adjacent areas.

REQUIREMENTS FOR LOCAL PWHT



NOTES:

(1) Distance = Larger of 2t or 2"
(2) Soak Band: PWHT time & temperature
(3) Heat Band: ½ PWHT temperature
(4) Gradient control Band: No heat mandatory. Insulation only.
(5) Distance = 2 $(Rt)^{1/2}$
(6) Distance = 4 $(Rt)^{1/2}$
(7) All bands shall be full circumferential bands.
(8) Heating coils should be used inside and out, if possible