LOW-TEMPERATURE PROPERTIES OF NICKEL ALLOY STEELS

A PRACTICAL GUIDE TO THE USE OF NICKEL-CONTAINING ALLOYS

Nº 1238

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Location of Data

[a] The AISI-SAE system for numbering steels is used if applicable.

Low Temperature Properties of Nickel Alloy Steels

INTRODUCTION

This bulletin provides information on the properties of nickel alloy steels at temperatures below 75 F. The effects of heat treatment, section size, production practice and fabricating procedure are discussed and illustrated. Detailed information is presented on specifications and properties of the steels commonly used for the construction of equipment to operate at subzero temperatures.

Numerous aspects of the effects of low tempearture on the properties of metals and equipment are covered in references selected from the many available on this subject: (a) material,* design and construction specifications,[1-8] (b) material testing specifications, [9-10] and (c) general and specific information on the ferritic steels, especially the straight nickel steels.[11-86] Data for the AISI-SAE steels are mostly from references 87 to 93 and data for the cast steels are from references 94 to 96.

GENERAL EFFECTS OF LOW TEMPERATURES ON CARBON AND ALLOY STEELS

In carbon and most low-alloy steels, as the temperature drops below 75 F, strength and hardness increase, tensile ductility generally decreases, and notch-impact values decrease drastically, as illustrated in Figure 1 for a nickel-chromium-molybdenum steel. Nickel, especially in the straight nickel steels, can minimize this loss in notch-impact toughness, as illustrated in Figure 2 and as shown in this bulletin.

STANDARD SPECIFICATIONS FOR NICKEL STEELS FOR USE AT LOW TEMPERATURES

Specifications for the 2¼, 3½, 5, 8 and 9 nickel steels follow:

American Society for Testing and Materials

Part 1, Steel Piping, Tubing, and Fittings, and Part 4, Steel-Pressure Vessel, Forgings, Railway, Reinforcing, Structural

A 203 Nickel Alloy Steel Plates for Pressure Vessels.

A 300 Notch Toughness Requirements for Normalized Steel Plates for Pressure Vessels (discontinued).

A 320 Alloy Steel Bolting Materials for Low-Temperature Service.

A 333 Seamless and Welded Steel Pipe for Low-Temperature Service.

A 334 Seamless and Welded Carbon and Alloy Steel Tubes for Low-Temperature Service.

A 350 Forged or Rolled Carbon and Alloy Steel Flanges, Forged Fittings, and Valves and Parts for Low-Temperature Service.

A 352 Ferritic Steel Castings for Pressure-Containing Parts Suitable for Low-Temperature Service.

A 353 Nine Per Cent Nickel Alloy Steel Plates, Double Normalized and Tempered, for Pressure Vessels.

A 420 Piping, Fittings of Wrought Carbon Steel and Alloy Steel for Low-Temperature Service.

A 522 Forged or Rolled Nine Per Cent Nickel Alloy Steel Flanges, Fittings, Valves, and Parts for Low-Temperature Service.

A 553 Eight and Nine Per Cent Nickel Alloy Steel Plate, Quenched and Tempered, for Pressure Vessels.

A 593 Charpy V-Notch Testing Requirements for Steel Plates for Pressure Vessels (discontinued).

A 645 Five Per Cent Nickel Alloy Steel Plate, Specially Heat Treated, for Pressure Vessels.

A 671 Electric-Fusion-Welded Steel Pipe for Atmospheric and Lower Temperatures.

American Society of Mechanical Engineers

Boiler and Pressure Vessel Code, Section II, Material Specifications (Part A, Ferrous)

These comprise SA-203, SA-320, SA-333, SA-334, SA-350, SA-352, SA-353, SA-420, SA-522, SA-553 and SA-645, all identical with the above corresponding ASTM numbers.

2¼ PER CENT NICKEL STEEL

The 2¼ per cent nickel steel is specified for equipment operating at temperatures as low as −90 F. It is covered by Grades A and B, ASTM A 203 and ASME SA-203.

Requirements for Low-Temperature Use

Specifications for composition, heat treatment, ten-

* These are in addition to ASTM material specifications which are listed further along in this bulletin.

sile and impact properties, and allowable design stresses for the two grades, A and B, of this steel are summarized in Table I. ASTM A 203 specifies the composition and tensile requirements of the two grades at two tensile strength ranges. A normalizing heat treatment or heating uniformly for hot forming is specified for both grades by ASTM A 203 and ASTM A 300 for all thicknesses. A suitable temperature for normalizing is 1650 F, and tempering or stress relieving, if employed, should not exceed 1200 F. The time at temperature for normalizing or stress relieving should be at least one hour per inch of thickness. Impact requirements are listed in Table I; they are discussed separately below.

A Charpy keyhole-notch level of 15 foot-pounds at −75 F is specified for the two grades by ASTM A 300,

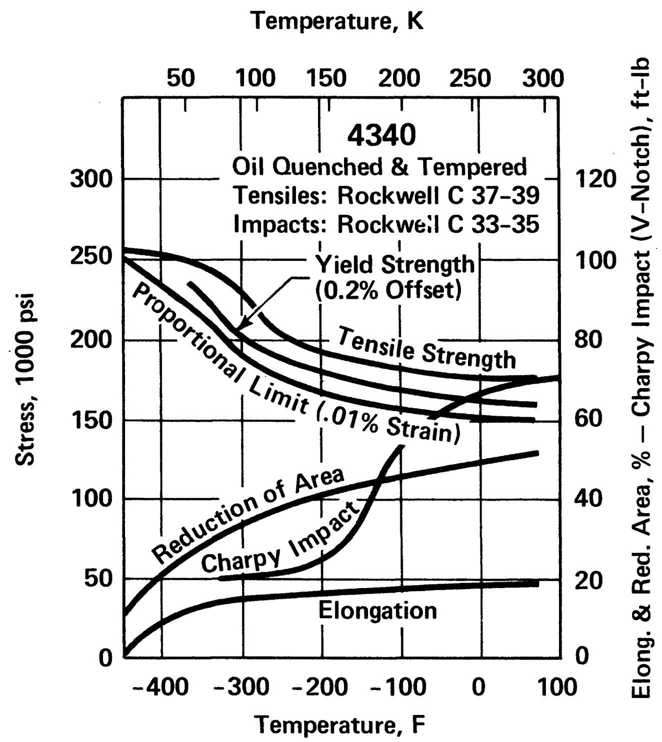


Fig. 1. Effect of test temperature on tensile and impact properties of quenched and tempered AISI 4340 steel. Tensile data: Reference 43. Impact data: Reference 38.

Fig. 2. Effect of nickel on impact toughness of normalized and tempered ½ inch plates of low-carbon steel.[31]

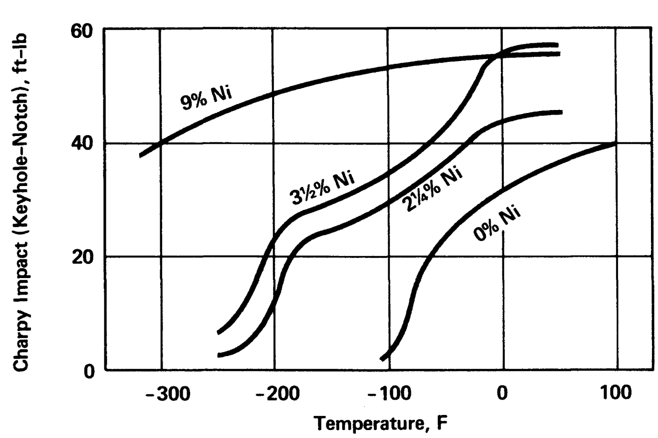


TABLE I

Composition, Heat Treatment and Mechanical Properties Specified for 2¼% Nickel Steel Plate for Low-Temperature Service

Composition (ASTM A 203)	Grade A[a]	Grade B[a]
Carbon, max, %		
To 2 in.	0.17	0.21
Over 2 to 4 in.	0.20	0.24
Over 4 in.	0.23	0.25
Manganese, max, %		
To 2 in.	0.70	0.70
Over 2 in.	0.80	0.80
Phosphorus, max, %	.035	.035
Sulfur, max, %	.04	.04
Silicon, %	0.15-0.30	0.15-0.30
Nickel, %	2.10-2.50	2.10-2.50
Tensile Requirements (ASTM A 203)[b]		
Tensile Strength, psi	65,000-77,000	70,000-85,000
Yield Point, min, psi	37,000	40,000
Elongation (8 in.), min, %	19	17
Elongation (2 in.), min, %	23	21
Heat Treatment	Normalize[c]	Normalize[c]
Impact Requirements		
ASTM A 300		
Charpy (Keyhole-Notch), min, ft-lb	15 at −75 F	15 at −75 F
ASTM A 593		
Charpy (V-Notch), min, ft-lb		
For 2-in. and thinner plate	13 at −90 F	15 at −90 F
For 2- to 3-in. plate	13 at −75 F	15 at −75 F
Bending Requirements, Ratio: Bend Dia to Specimen Thickness		
1 in. and under	1	1½
Over 1 to 4 in.	1½	2
Over 4 in.	2	2½
Allowable Design Stress		
ASME,[2] Sec. VIII, Div. 1, Table UCS-23 Up to 650 F, max, psi	16,200	17,500
ASME,[3] Sec. VIII, Div. 2, Table ACS-1 Up to 100 F, max, psi	21,700	23,300

[a] The maximum plate thickness is normally limited to six inches.

[b] Flat specimens: ASTM A 20. Plates over two inches thick shall be heat treated to produce grain refinement by normalizing or by heating uniformly for hot forming.

[c] Although not specified, a satisfactory normalizing temperature is 1650 F.

as shown in Table I. Alternatively, ASTM A 593, also shown in Table I, specifies 13 foot-pounds Charpy V-notch for Grade A and 15 foot-pounds for Grade B at −90 F for plates 2 inches or less in thickness, and similar impact values at −75 F for plates 2 to 3 inches in thickness. Present practice favors the use of Charpy V-notch impact requirements specified by ASTM A 593.

Typical Mechanical Properties

Room temperature (75 F) tensile properties of commercial plates surpass the tensile requirements listed in Table I, as shown in another bulletin.*

The effect of heat treatment on the low temperature tensile properties is demonstrated in Figures 3 (normalized) and 4 (quenched and tempered) for A 203 Grade A plate.[11] Definite added strength at low temperature is obtained by the quench and temper heat treatment.

The effect of heat treatment on the low temperature impact properties is shown in Figures 5 (normalized) and 6 (quenched and tempered) for A 203 Grade A plate.[11] In the transverse direction, the material in the normalized condition had a 15 ft-lb transition temperature of −110 F whereas the quenched and tempered material had a transition temperature of −140 F. Other Charpy V-notch impact tests showed superior notch toughness of quenched and tempered material over normalized material.

Further tests using quarter section normalized and quenched and tempered plate gave results shown in Table II. The quenched and tempered material had a nil-ductility transition (NDT) temperature of −110 F whereas the normalized material's NDT was −75 F. The effects of heat treatment and plate thickness are shown in Table III and Figure 7 for Charpy V-notched specimens. Figure 7 also illustrates how this steel meets

* Bulletin 2-C: "Nickel Alloy Steel Plates."

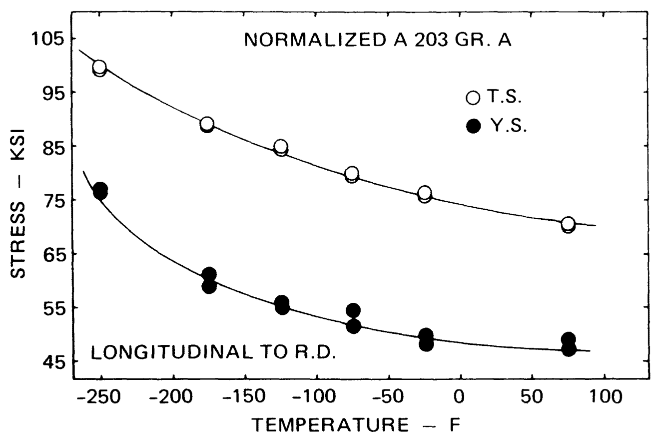


Fig. 3. Effect of temperature on tensile data of normalized A 203 Grade A material.

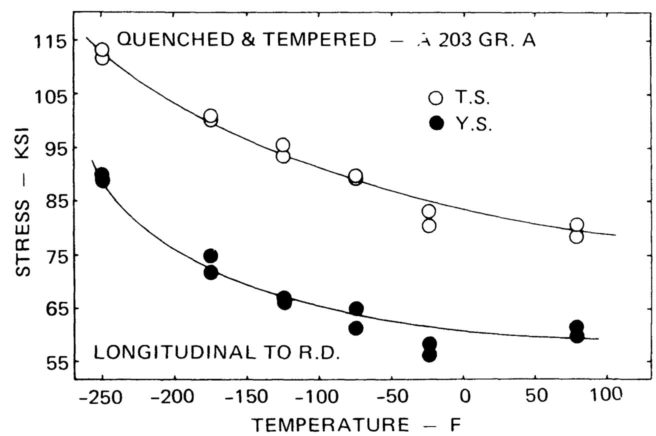


Fig. 4. Effect of temperature on tensile data of quenched and tempered A 203 Grade A material.

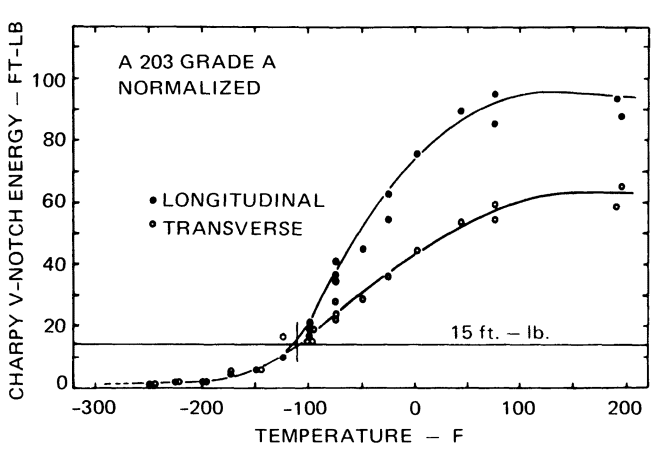


Fig. 5. Charpy V-notch impact test transition temperature curves for normalized A 203 Grade A specimens.

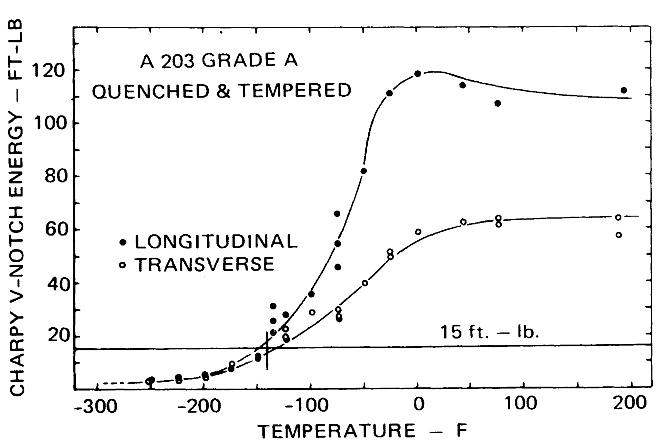


Fig. 6. Charpy V-notch impact test transition temperature curves for quenched and tempered A 203 Grade A specimens.

TABLE II

Charpy V-Notch Impact and Drop Weight Data for ASTM A 203 Grade A

Transition Temperature, F.									
Longitudinal					Transverse				NDT
15 ft-lb	25 ft-lb	15 mil	50% S		15 ft-lb	25 ft-lb	15 mil	50% S	F
				Normalized					−75
−113	−90	−145	−50	Quarter Section	−105	−67	−145	−50	
				Quenched and Tempered					−110
−155	−128	−163	−75	Quarter Section	−140	−100	−155	−50	

TABLE III

Effects of Plate Thickness, Heat Treatment and Welding on Fracture Toughness of Low-Carbon 2¼% Nickel Steel

		Transition Temperature, F		
		Charpy Impact (V-Notch)		
Plate Condition[a]	Notch Location[b]	15 ft-lb	15 mil Lateral Expansion	Nil Ductility Transition NDT
	½-Inch Plate			
Normalized	Base Plate	−130	−110	−110
Normalized and Tempered	Base Plate	−100	−100	−130
As Welded	FZ	−135	—	—
As Welded	Middle HAZ	−140	—	—
As Welded	Edge HAZ	−130	—	—
	1-Inch Plate			
Normalized	Base Plate	−100	—	−90
Normalized and Tempered	Base Plate	−105	—	−100
As Welded	FZ	−130	—	—
As Welded	Middle HAZ	−120	—	—
As Welded	Edge HAZ	−100	—	—

[a] Normalized 1600 F, tempered 1100 F. Welded with E8018-Cl electrode.
[b] FZ = Fusion Zone. HAZ = Heat-affected Zone.

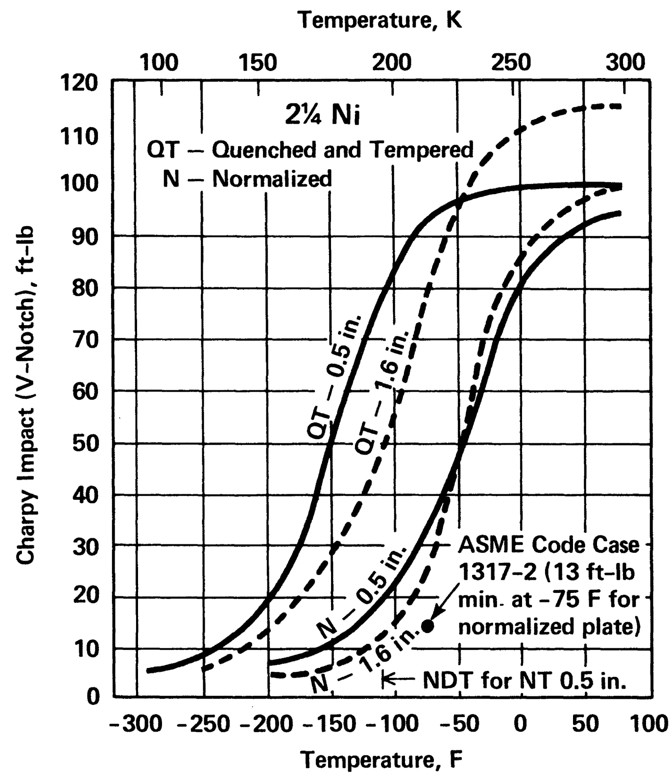


Fig. 7. Effect of heat treatment and plate thickness on Charpy V-notch impact of low-carbon 2¼ per cent nickel steel plate (ASTM A 203, Grade A). Longitudinal specimens.[51]

some of its impact requirements.

The low and cryogenic temperature static fracture toughness data for A 203 Grade A plate are given in Table IV.

Fatigue data obtained on normalized commercial ½-inch plate made to ASTM Specification A 203, Grade B, indicate a room-temperature rotating-beam endurance limit of 45,000 psi and an endurance/tensile ratio of 0.64 for smooth bars.

Physical Properties

A few data on thermal expansion, thermal conductivity and specific heat are given in Table V.

Welding

For pressure vessel construction, this material falls into Group P-9A, Table Q-11.1, Section IX of the ASME Code governing welding procedure qualifications.[4] Pre-heating to 300 F may be advisable under conditions of heavy restraint. Stress relieving at 1100 F minimum is required for structures falling under Paragraph UCS-67 of the ASME Boiler and Pressure Vessel Code[2] but this temperature should not exceed 1200 F. For metal-arc welding, coated electrodes of the

TABLE IV

Static Fracture Toughness Data for ASTM A 203 Grade A

Specimen No.	Testing Temperature, F	K_{max} [a] ksi $\sqrt{in.}$	K_{1c} [b] ksi $\sqrt{in.}$
NA5	−75	108.9	—
NA6	−75	105.1	—
NA9	−110	114.3	—
NA10	−110	111.0	—
NA1	−150	98.2	—
NA2	−150	86.9	—
NA7	−200	50.0	50.0
NA8	−200	52.2	52.2
NA3	−250	38.9	38.9
NA4	−250	40.2	40.2
QTA6	−75	140.8	—
QTA7	−75	140.8	—
QTA1	−150	95.2	—
QTA3	−150	118.8	—
QTA9	−175	90.4	—
QTA2	−200	101.5	—
QTA8	−200	80.9	—
QTA4	−250	53.1	53.1
QTA5	−250	61.0	61.0
QTA10	−300	40.7	40.7

[a] Fracture toughness computed using maximum load.
[b] Valid plane strain fracture toughness value.
N = Normalized condition and QT = quenched and tempered condition.

TABLE V

Thermal Properties of Low-Carbon 2¼% Nickel Steel

Temperature F	Mean Coefficient of Thermal Expansion per °F	Thermal Conductivity Btu/hr/sq ft/°F/in.	Mean Specific Heat Btu/lb/°F
−100 to 0	5.8×10^{-6}	—	—
0 to 200	6.2×10^{-6}	—	—
−50	—	248	—
68	—	267	—
200	—	280	—
−150 to 80	—	—	.080
80 to 1000	—	—	0.144

E8016-C1 and E8018-C1 classifications conforming to AWS Specification A5.5 are used. These electrodes deposit weld metal of the same composition as the base material. Steel wire containing 3½ per cent nickel is now commercially available for inert-gas consumable electrode welding and has been used for joining 2¼ per cent nickel steel for low-temperature applications. Submerged-arc welding of 2¼ per cent nickel steel has been accomplished by using nickel-containing fluxes and low-carbon steel welding wires.

The properties of welded ½ and 1-inch plate, notched as indicated, are given in Table III. The base plate was normalized at 1600 F or normalized and tempered at 1100 F and the welds were made with E8018-C1 electrodes. No difficulty was experienced in meeting the Charpy V-notch impact requirements.

3½ PER CENT NICKEL STEEL

The 3½ per cent nickel steel is specified for equipment operating at temperatures as low as −150 F. It is covered by Grades D and E, ASTM A 203 and ASME SA-203.

Requirements for Low-Temperature Use

Table VI comprises a summary of specifications for composition, heat treatment, tensile and impact properties, and allowable design stresses for the two grades of this steel. Composition and tensile properties of both Grades D and E at two tensile strength ranges are specified in ASTM A 203. A normalizing heat treatment or heating uniformly for hot forming is specified for both grades by ASTM A 203 and ASTM A 300 for all thicknesses. A suitable temperature for normalizing is 1600 F, and tempering or stress relieving, if employed, should not exceed 1175 F. The time at temperature for normalizing or stress relieving should be at least one hour per inch of thickness. Impact requirements are listed in Table VI and are discussed below.

ASTM A 300 and the ASME Boiler and Pressure Vessel Code, Section VIII, Division 1, Paragraph UG-84[2] specify a Charpy keyhole-notch level of 15 foot-pounds at −150 F for the two grades. Alternatively ASTM A 593, also shown in Table VI, specifies 13 foot-pounds Charpy V-notch for Grade D and 15 foot-pounds for Grade E at −150 F for plates 2 inches or less in thickness, and similar impact values at −125 F for plates 2 to 3 inches in thickness. Present practice favors the use of Charpy V-notch impact requirements specified by ASTM A 593.

Typical Mechanical Properties

The tensile properties of commercial 3.5 per cent nickel steel at 75 F surpass the tensile requirements given in Table VI, as shown in another bulletin.*

The effect of heat treatment in the low temperature tensile properties is shown in Figures 8 (as-rolled), 9 (normalized) and 10 (quenched and tempered) for A 203 Grade D plate.[11] Definite added strength at low temperatures is obtained by the quench and temper heat treatment.

The effect of heat treatment on the low temperature impact properties is shown in Figures 11 (as-rolled), 12 (normalized) and 13 (quenched and tempered) for A 203 Grade D plate.[11] In the transverse direction, the material in the normalized condition had a 15 ft-lb

* Bulletin 2-C: "Nickel Alloy Steel Plates."

TABLE VI

Composition, Heat Treatment and Mechanical Properties Specified for 3½% Nickel Steel Plate for Low-Temperature Service

Composition (ASTM A 203)	**Grade D**[a]	**Grade E**[a]
Carbon, max, %		
To 2 in. thick, incl.	0.17	0.20
Over 2 to 4 in. thick, incl.	0.20	0.23
Manganese, max, %		
To 2 in. thick, incl.	0.70	0.70
Over 2 to 4 in. thick, incl.	0.80	0.80
Phosphorus, max, %	.035	.035
Sulfur, max, %	.04	.04
Silicon, %	0.15-0.30	0.15-0.30
Nickel, %	3.25-3.75	3.25-3.75
Tensile Requirements (ASTM A 203)[b]		
Tensile Strength, psi	65,000-77,000	70,000-85,000
Yield Point, min, psi	37,000	40,000
Elongation (8 in.), min, %	19	17
Elongation (2 in.), min, %	23	21
Heat Treatment	Normalize[c]	Normalize[c]
Impact Requirements		
ASTM A 300		
Charpy (Keyhole-Notch), min, ft-lb	15 at −150 F	15 at −150 F
ASTM A 593 and ASME,[3] Sec. VIII, Div. 2		
Charpy (V-Notch), min, ft-lb		
For 2-in. and thinner plate	13 at −150 F	15 at −150 F
For 2- to 3-in. plate	13 at −125 F	15 at −125 F
Bending Requirements, Ratio: Bend Dia to Specimen Thickness		
1 in. and under	1	1½
Over 1 in.	1½	2
Allowable Design Stress		
ASME,[2] Sec. VIII, Div. 1, Table UCS-23		
Up to 650 F, max, psi	16,200	17,500
ASME,[3] Sec. VIII, Div. 2, Table ACS-1		
Up to 100 F, max, psi	21,700	23,300

[a] The maximum plate thickness is normally limited to four inches.

[b] Flat specimens: ASTM A 20. Plates over two inches thick shall be heat treated to produce grain refinement by normalizing or by heating uniformly for hot forming.

[c] Although not specified, a satisfactory normalizing temperature is 1600 F.

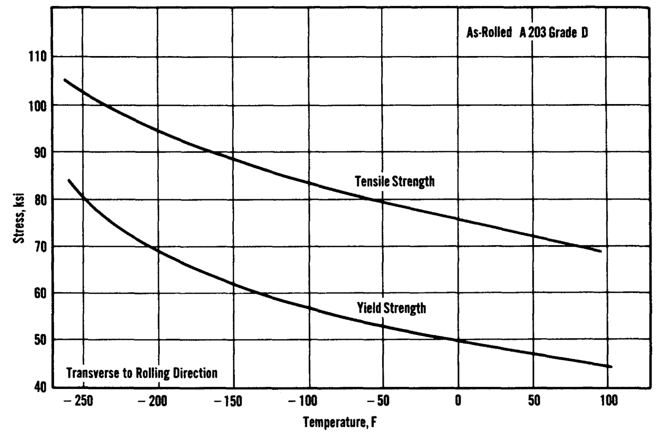


Fig. 8. Effect of temperature on tensile data of as-rolled A 203 Grade D material.

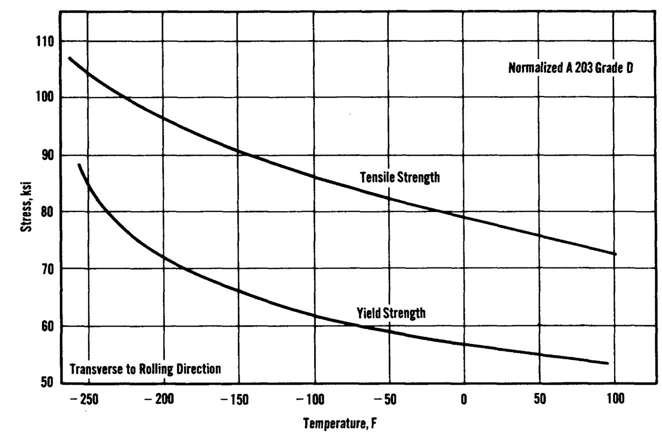


Fig. 9. Effect of temperature on tensile data of normalized A 203 Grade D material.

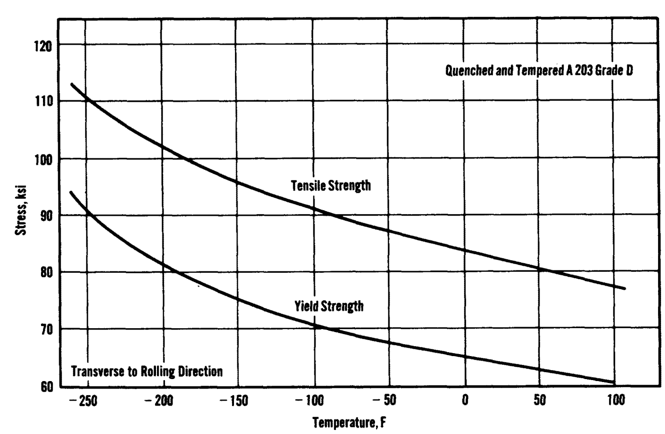


Fig. 10. Effect of temperature on tensile data of quenched and tempered A 203 Grade D material.

transition temperature of —170 F while the quenched and tempered material had a transition temperature of —225 F. Other Charpy V-notch impact tests showed superior notch toughness of quenced and tempered material over normalized material.

The effect of cooling rate on the transition temperature of Charpy V-notch specimens is shown in Table VII. The effects of plate thickness and heat treatment on impact properties are illustrated in Figures 14 and 15. The reason for heat treatment becomes apparent from results of the as-rolled specimens.

Figure 16 shows both Charpy V-notch and keyhole-notch transition curves and also the nil-ductility transition (NDT) temperature determined by drop weight tests.[39]

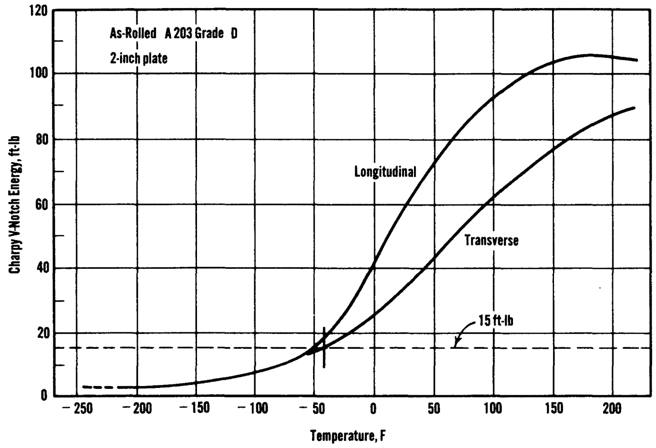


Fig. 11. Charpy V-notch impact test transition temperature curves for as-rolled A 203 Grade D material.

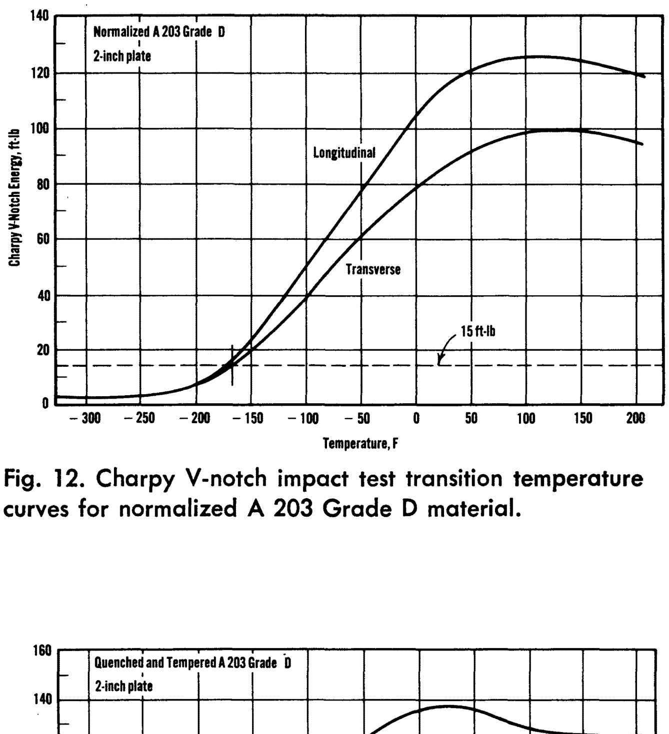


Fig. 12. Charpy V-notch impact test transition temperature curves for normalized A 203 Grade D material.

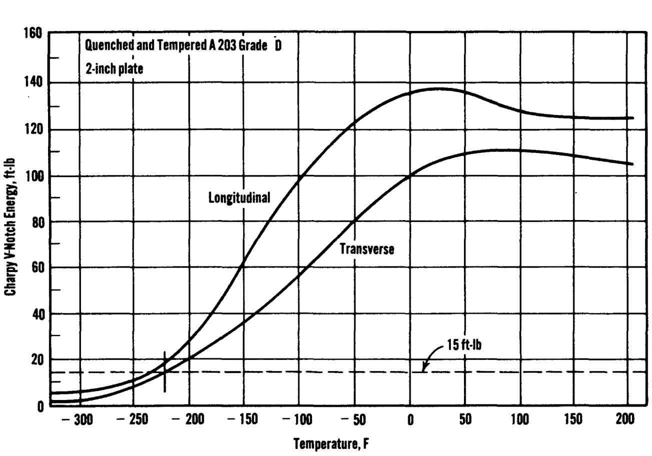


Fig. 13. Charpy V-notch impact test transition temperature curves for quenched and tempered A 203 Grade D material.

Table VII

Effect of Cooling Rate on Transition Temperature of Low-Carbon 3½% Nickel Steel[a]

Condition	Approximate Cooling Rate °F/sec at 1300 F	Transition Temperature, F, Charpy Impact (V-Notch): 15 ft-lb	15 mil Expansion
	As Cooled from Austenitizing Temperature		
Water Quenched	200	−195	—
Oil Quenched	36	−105	−66
Plate Cooled	5.7	−126	−115
Air Cooled	1.0	−135	−135
Foil Cooled	0.26	−128	−124
	Cooled as Above and Tempered at 1150 F		
Water Quenched	200	−248	−216
Oil Quenched	36	−205	−180
Plate Cooled	5.7	−170	−160
Air Cooled	1.0	−162	−162
Foil Cooled	0.26	−130	−130

[a] Reference 45.

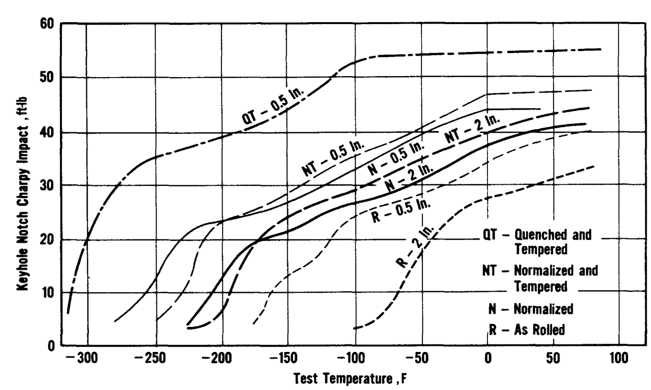


Fig. 14. Effect of heat treatment and plate thickness on Charpy keyhole-notch impact of low-carbon, 3½ per cent nickel steel plate (ASTM A 203, Grade D). Longitudinal specimens.[31]

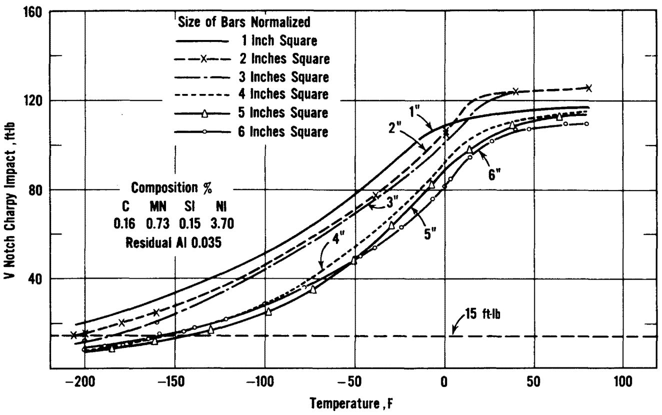


Fig. 15. Effect of section size on impact properties of normalized 3½ per cent nickel steel.

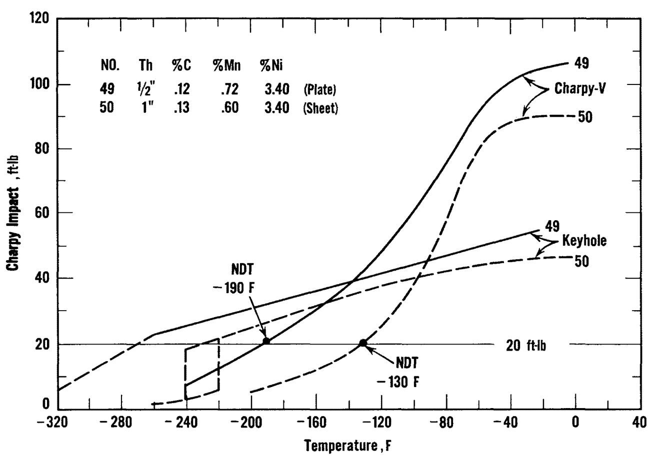


Fig. 16. Charpy impact and drop-weight test (NDT) results for 3½ per cent nickel steel plates.[39]

Further tests using quarter section as-rolled, normalized and quenched and tempered plate gave results shown in Table VIII. The quenched and tempered material had a NDT temperature of −130 F whereas the normalized material's NDT was −110 F with both being far superior to the as-rolled condition.

The low and cryogenic temperature static toughness data for A 203 Grade D plate are given in Table IX. Dynamic fracture toughness data are given in Table X.

Normalized commercial ½-inch plate made to ASTM specification A 203 Grade D, shows a room-temperature rotating-beam endurance limit of 49,000 psi and a smooth-bar endurance/tensile ratio of 0.61.

Physical Properties

Data follow on modulus of elasticity, density and electrical resistivity.

Modulus of Elasticity (68 F), psi	30×10^6
(−148 F), psi	31×10^6
Density, lb/cu in.	0.284
g/cu cm	7.85
Electrical Resistivity (32 F), microhm-cm	25.9

Extensive data on thermal expansion, thermal conductivity, specific heat and magnetic properties are given in another bulletin.*

Welding

For pressure vessel construction, this material falls into Group P-9B, Table Q-11.1, Section IX of the ASME Code governing welding procedure qualifications.[4] Preheating to 300 F may be advisable under conditions of high restraint. Stress relieving at 1100 F minimum is required for structures falling under Paragraph UCS-67 of the ASME Code[2] but this temperature should not exceed 1175 F. For metal-arc welding,

* Bulletin 7-A: "Physical Properties of Nickel Alloy Steels."

TABLE VIII

Charpy Impact and Drop Weight Data for ASTM A 203 Grade D

Transition Temperature, F									
Longitudinal					Transverse				NDT
15 ft-lb	25 ft-lb	15 mil	50% S		15 ft-lb	25 ft-lb	15 mil	50% S	F
				As-Rolled					−50
−50	−20	−75	50	Quarter Section	−53	−5	−65	50	−50
				Normalized					−110
−170	−145	−175	−75	Quarter Section	−162	−132	−175	−50	
				Quenched and Tempered					−130
−220	−205	−230	−125	Quarter Section	−215	−175	−223	−75	

TABLE IX

Static Fracture Toughness Data for ASTM A 203 Grade D

Specimen No.	Testing Temperature, F	K_{max} [a] ksi $\sqrt{in.}$	K_{1c} [b] ksi $\sqrt{in.}$
1HR7	–50	88.5	—
1HR8	–50	80.1	—
1HR10	–75	79.1	—
1HR5	–100	61.4	—
1HR6	–100	57.2	—
1HR9	–125	42.6	42.6
1HR3	–150	52.4	36.3
1HR4	–150	39.3	39.3
1HR1	–200	39.4	39.4
1HR2	–200	36.4	36.4
2HR7	–50	99.2	—
2HR8	–50	75.7	—
2HR5	–100	50.7	—
2HR6	–100	62.5	—
2HR10	–125	47.6	47.6
2HR3	–150	63.5	—
2HR4	–150	43.6	43.6
2HR9	–150	57.5	—
2HR1	–200	42.4	42.4
2HR2	–200	36.0	36.0
N5	–125	116.3	—
N8	–125	131.5	—
N1	–150	126.2	—
N2	–150	118.7	—
N9	–175	105.8	—
N10	–175	105.7	—
N3	–200	68.9	68.9
N4	–200	68.1	68.1
N6	–250	48.1	48.1
N7	–250	47.3	47.3
QT7	–150	150.7	—
QT8	–150	155.2	—
QT1	–200	148.2	—
QT2	–200	125.1	—
QT6	–225	97.5	—
QT3	–250	65.5	—
QT4	–250	86.9	—
QT5	–275	75.7	75.7
QT9	–300	38.5	38.5
QT10	–300	39.5	39.5

[a] Fracture toughness computed using maximum load.
[b] Valid plane strain fracture toughness value.
HR = As-rolled condition, N = normalized condition, and QT = quenched and tempered condition.

coated electrodes of the E8016-C2 and E8018-C2 classifications conforming to AWS Specification A5.5 are used. These electrodes deposit weld metal of the same composition as the base material. (Austenitic stainless steel electrodes corresponding to classification E310 under AWS Specification A5.4 have been used for joining 3½ per cent nickel steel; here the difference in the coefficient of expansion must be kept in mind.) Austenitic nickel-chromium-iron electrodes corresponding to the ENiCrFe-2 classification of AWS Specification A5.11 also are used for welding 3½ per cent nickel steel. Wire for inert-gas metal-arc welding and submerged-arc welding of 3½ per cent nickel steel is available commercially.

The properties of welded ½-inch plate, notched as indicated, are given in Table XI. The base plate was normalized at 1600 F and the welds were made with

TABLE X

Dynamic Fracture Toughness Data for ASTM A 203 Grade D

Specimen No.	Testing Temperature, F	K_{max} [a] ksi $\sqrt{in.}$	K_{1c} [b] ksi $\sqrt{in.}$
N7	–100	63.2	—
N8	–100	62.4	—
N5	–150	46.9	46.9
N6	–150	43.5	43.5
QT7	–100	103.9	—
QT8	–130	66.4	66.4
QT2	–150	77.3	—
QT3	–150	60.3	60.3
QT4	–200	40.8	40.8
QT5	–250	38.3	38.3

[a] Fracture toughness computed using maximum load.
[b] Valid plane strain fracture toughness value.
N = Normalized condition and QT = quenched and tempered condition.

TABLE XI

Charpy Impact Data on Welded ½-Inch Plate of 3½% Nickel Steel

Condition	Notch Location	Charpy Impact (Keyhole-Notch) at –150 F ft-lb
As Welded	Base plate	20
	Edge heat-affected zone	14
	Middle heat-affected zone	16
	Fusion line	17
	Weld metal	23
Stress Relieved at 1150 F	Base plate	28
	Edge heat-affected zone	22
	Middle heat-affected zone	36
	Fusion line	36
	Weld metal	21

E8016-C2 electrodes. Further impact data on welded plate using matching 3½ per cent nickel steel electrodes (E8015-C2) are given in Figures 17 and 18.

5 PER CENT NICKEL STEEL

The 5 per cent nickel steel has been used in the United Kingdom and Europe for pressure vessels operating at subzero temperatures. This steel is covered by British Standard Specifications En 37 and by German Iron and Steel Association Specification 680. Plates of the latter grade are preferably used in the quenched and tempered condition. Its use in Europe has been more extensive than in the United States, however, there is a general trend to replace it either by 3½ per cent nickel steel down to −165 F or by 9 per cent nickel steel for lower temperatures.

The European version of the 5 per cent nickel steel

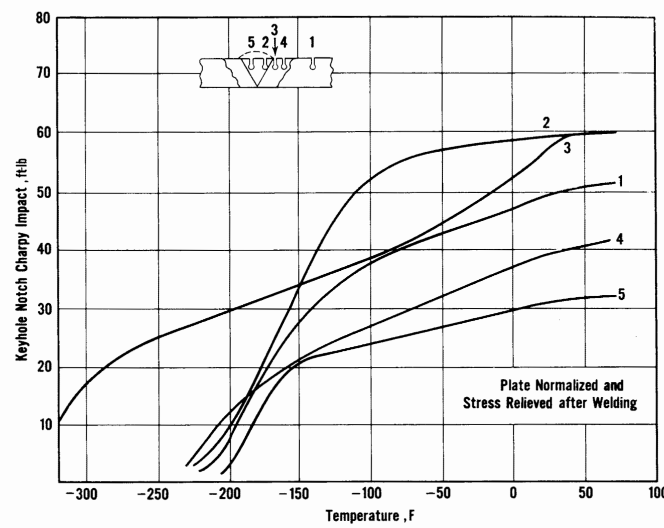


Fig. 17. Group of impact curves for one condition of welding and heat treatment of 3½ per cent nickel steel plate.

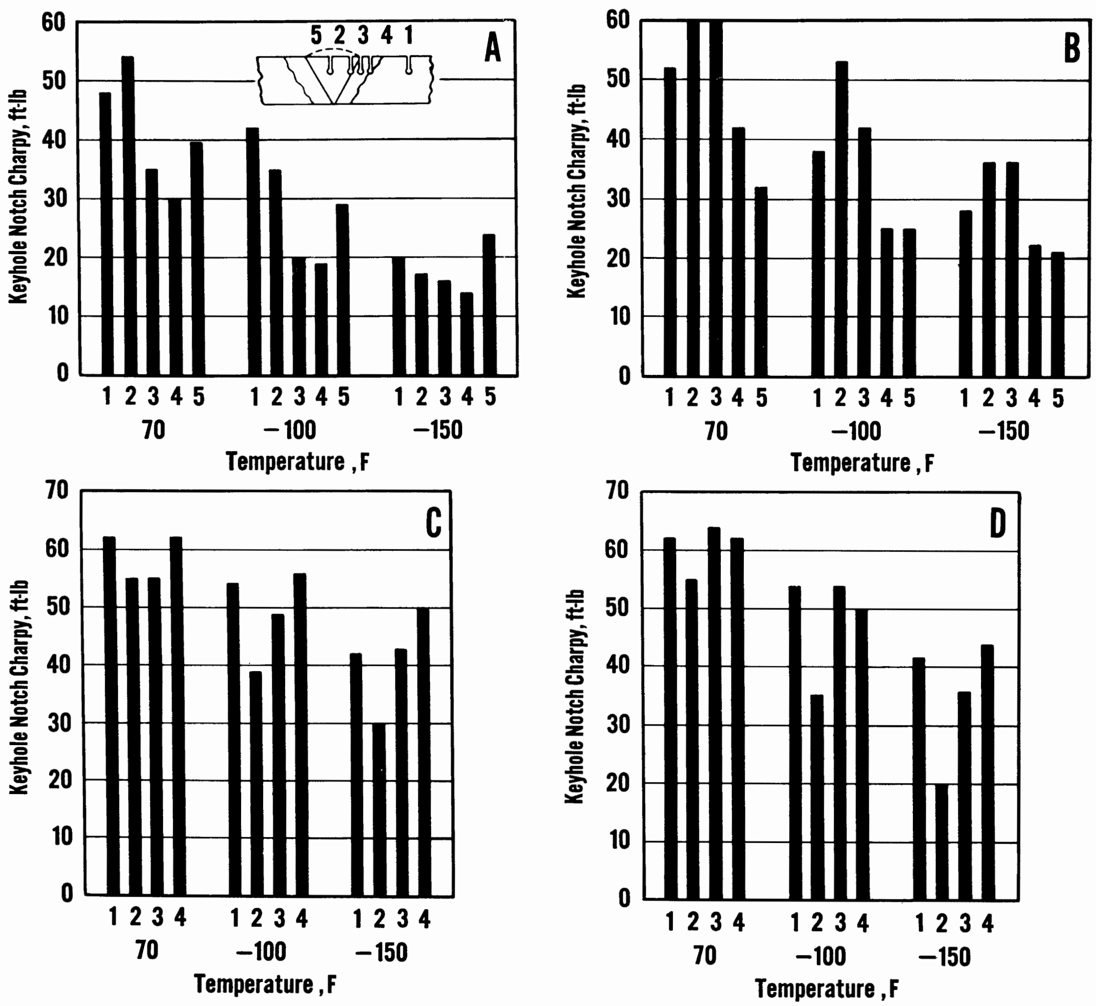


Fig. 18. Effect of welding on impact properties of low carbon, 3½ per cent nickel steel. References 29 and 44. A. Plate normalized. Tested as welded. B. Plate normalized. Stress-relieved at 1150 F after welding. C. Plate quenched and tempered. Tested as welded. D. Plate quenched and tempered. Stress relieved at 1150 F after welding.

usually is welded with austenitic stainless steel electrodes of the 18 chromium-9 nickel or 25 chromium-20 nickel type. In addition, a filler wire of the 18 chromium-8 nickel-6 manganese type is used in Europe; the weld deposit is fully austenitic and is resistant to hot cracking.

In North America, a 5 per cent nickel steel version with 0.25 per cent molybdenum has been developed for plate applications primarily for use down to −275 F. It is covered by ASTM A 645 and ASME SA-645. The balance of this section is devoted to the 5 Ni-0.25 Mo steel referred to simply as 5 per cent nickel steel.

Requirements for Low-Temperature Use

Table XII gives the required composition, tensile and impact properties of this steel. Composition and tensile properties are specified in ASTM A 645. A special three-stage heat treatment comprising austenitizing, double reheating, and quenching is specified by ASTM A 645. The maximum thickness covered is limited only by the ability of the material to meet the specified mechanical property requirements.

The following procedures are required for heat treating the 5 per cent nickel steel:

1. *Hardening—ASTM A 645*

   Heat the plate to a temperature of 1575 to 1675 F, hold at this temperature for 1 hour/inch of thickness, but in no case less than 15 minutes, and water quench to below 300 F.

2. *Reheating—ASTM A 645*

   Reheat the plate to a temperature of 1325 to 1400 F, hold at this temperature for 1 hour/inch of thickness, but in no case less than 15 minutes, and water quench to below 300 F.

3. *Reheating—ASTM A 645*

   Reheat the plate to a temperature of 1150 to 1225 F, hold at this temperature for 1 hour/inch of thickness, but in no case less than 15 minutes, and water quench to below 300 F.

Typical Mechanical Properties

The tensile properties of the 5 per cent nickel steel at room temperature surpass the requirements in Table XII as shown in Table XIII.

Average Charpy V-notch impact data listed in Table XIV show energy absorbed and lateral expansion for tests at −275 F and −320 F. The energy absorbed exceeds the supplementary requirements of ASTM A 645 while meeting the lateral expansion requirements.

Fracture Toughness Tests

Drop-weight tests made on ⅝ to 1½-inch thick plate show that the NDT (Nil-Ductility-Transition) temperature is below −320 F.

Crack-started explosion-bulge tests on 5 per cent nickel steel show that the Fracture-Transition-Elastic (FTE) temperature for both base plate and weldments is at or below −260 F.

Fracture toughness tests made on ¼ to 1¼-inch thick plate at −275 F gave stress intensity (K_c) values and critical crack lengths ($2a_c$) as shown in Table XV.

Additional fracture toughness tests on 1-inch thick plate at −260 and −320 F gave the conditional plane strain fracture toughness values, K_Q, as shown in Table XVI for compact tension specimens and Table XVII

TABLE XII

Composition, Tensile, Impact and Bending Requirements for 5% Nickel Steel Plate Specially Heat Treated [a]

Composition (ASTM A 645)		
Carbon, max, %	0.13	
Manganese, %	0.30-0.60	
Phosphorus, max, %	.025	
Sulfur, max, %	.025	
Silicon, %	0.20-0.35	
Nickel, %	4.75-5.25	
Molybdenum, %	0.20-0.35	
Aluminum, total, %	.05-0.12	
Nitrogen, max, %	.020	
Tensile Requirements		
Tensile Strength, psi	95,000-115,000	
Yield Strength (0.2% Offset), min, psi	65,000	
Elongation (2 in.), min, %	20.0	
Charpy Impact (V-Notch) Requirements at −275 F*		
Lateral Expansion, min, mil	15	
Supplementary Requirements of Charpy Impact (V-Notch) Test		
	Longitudinal	Transverse
Full size (10 x 10 mm), min, ft-lb	25	20
¾ Width (10 x 7.5 mm), min, ft-lb	19	15
⅔ Width (10 x 6.67 mm), min, ft-lb	17	13
½ Width (10 x 5 mm), min, ft-lb	13	10
⅓ Width (10 x 3.33 mm), min, ft-lb	8	7
¼ Width (10 x 2.5 mm), min, ft-lb	6	5
Bending Requirements, Ratio: Bend Dia to Specimen Thickness		
¾ in. and under	2	
Over ¾ to 1¼ in., inclusive	2½	
Over 1¼ in.	3	
Allowable Design Stresses†		
ASME, Section VIII, Division I Table UTH-23, max, psi	23,700	
ASME, Section VIII, Division II Table AQT-1, max, psi	31,700	
API Standard 620, Appendix Q Table Q.3.3, max, psi	31,700	

[a] Heat Treatment: austenitized, double reheating and quenching.
* Values of energy absorption and fracture appearance to be reported for information.
† ASME values are for temperatures not exceeding 150 F.

TABLE XIII

Room Temperature Tensile Properties of 5% Nickel Steel Plate[a]

Plate Thickness in.	Specimen Orientation	Tensile Strength psi	Yield Strength (0.2% Offset) psi	Elong. (2 in.) %	Reduction of Area %
3/16	Longitudinal	104,200	88,600	32	—
	Transverse	104,300	88,000	34	—
3/8	Longitudinal	100,700	84,600	36	—
	Transverse	101,400	82,400	37	—
5/8	Longitudinal	103,100	87,600	30	77
	Transverse	101,800	84,400	30	72
1¼	Longitudinal	98,100	74,600	33	74
	Transverse	98,400	73,600	33	77

[a] Data supplied by Armco Steel Corporation.
Composition of heat tested: .08C, 0.60Mn, .010P, .009S, 0.25Si, 5.03Ni, 0.30Mo, .08Al, .010N.

for bend bar specimens. Valid plane strain fracture toughness values, K_{1c}, would require specimens 4½ to 5 inches thick.[71]

Physical Properties

Data follow on modulus of elasticity, density, thermal expansion and thermal conductivity.

Modulus of Elasticity (70 F), psi	28.7×10^6
Modulus of Elasticity (−320 F), psi	30.7×10^6
Density, lb/cu in.	0.282
g/cu cm	7.82
Thermal Expansion (70 to −300 F), per°F	5.0×10^6
Thermal Conductivity (−320 F), Btu/hr/sq ft/°F/in.	90

Welding

For pressure-vessel construction, 5 per cent nickel steel falls into Group P-11A, Table Q-11.1, Section IX of the ASME Code governing welding procedure qualification.[4]

This material has been successfully welded using three welding processes: (1) shielded metal-arc welding, (2) submerged-arc welding and (3) gas metal-arc welding. Filler metals employed were of the austenitic nickel-chromium-iron types commonly applied to welding 9 per cent nickel steel such as INCO-WELD* A Electrode and INCONEL* Filler Metal 92. Tensile testing of weldments indicate that specimens mostly broke in the weld metal because of the use of nickel-base alloy filler metal; however, no particular difficulty was experienced in meeting the minimum tensile requirement of 95,000 psi of the base plate. Charpy V-notch impact testing of weldments at −275 F indicates adequate impact toughness in the heat-affected zone and that the energy absorption and lateral expansion requirements were met.

* Registered trademarks of The International Nickel Company, Inc.

TABLE XIV

Charpy V-Notch Impact Data on 5% Nickel Steel Plate at Low Temperatures[a]

Plate Thickness in.	Avg. Absorbed Energy, ft-lb		Avg. Lateral Expansion, mil	
	Longitudinal	Transverse	Longitudinal	Transverse
	Properties at −275 F			
3/16 [b]	18	19	42	43
3/8 [c]	93	54	74	50
5/8	98	89	56	51
1¼	56	58	34	35
	Properties at −320 F			
3/16 [b]	24	15	61	44
3/8 [c]	77	46	74	50
5/8	90	58	63	47
1¼	50	40	41	33

[a] Data supplied by Armco Steel Corporation. Same composition as Table XIII.
[b] ¼ size impact specimen.
[c] ¾ size impact specimen.

TABLE XV

Fracture Toughness Test Results of 5% Nickel Steels at −275 F

Plate Thickness in.	Stress Intensity Factor, K_c ksi $\sqrt{in.}$	Critical Crack Length,* $2a_c$ in.
¼	355	142.8
¼	405	185.9
5/8	330	123.4
5/8	320	116.1
5/8	300	102.0
5/8	307	106.8
1¼	205	47.6
1¼	205	47.6

* Calculated using maximum allowable design stress of 23,700 psi.

TABLE XVI

Compact Tension Fracture Toughness Evaluation of 5% Nickel Steel at −260 and −320 F

Temperature F	Notch Location	K_Q ksi $\sqrt{in.}$	$K_{1st\ pop}$ ksi $\sqrt{in.}$	K_m ksi $\sqrt{in.}$
−320	Base plate	78.0	78.0	120
−320	Base plate	63.8	78.0	120
−260	Base plate	79.5	None	177[a]
−260	Base plate	92.1	118.0	—
−260	HAZ	80.2	80.2	92.4
−260	HAZ	105.5[b]	None	105.5[b]

[a] At −210 F.
[b] At −220 F.
HAZ = Heat-affected Zone.

TABLE XVII

Bend Bar Fracture Toughness Evaluation of 5% Nickel Steel at −260 F

Notch Location	K_Q ksi $\sqrt{in.}$	$K_{1st\ pop}$ ksi $\sqrt{in.}$	K_m ksi $\sqrt{in.}$
Base Plate	54.2	—	100[a]
Base Plate	65.4	83.7	83.7
HAZ	57.9	71.2	71.2
HAZ	65.1	65.1	—

[a] At −200 F.
HAZ = Heat-affected Zone.

8 PER CENT NICKEL STEEL

The 8 per cent nickel steel was developed for use down to −275 F. It is covered by ASTM A 553, Type II. In general, its microstructural and property characteristics are similar to the 9 per cent nickel steel except that the latter is suitable for applications at lower temperatures.

Requirements for Low-Temperature Use

A summary of composition, heat treatment, tensile, impact and bending requirements for 8 per cent nickel steel plate is presented in Table XVIII. ASTM A 553, Type II covers this steel in the quenched and tempered (QT) condition. The maximum plate thickness covered is normally limited to 2 inches; however, greater thicknesses may be obtained provided the composition meets the specified mechanical property requirements. This steel has been approved for the construction of pressure vessels in accordance with the requirements of Section VIII of the ASME Boiler and Pressure Vessel Code. Allowable design stresses are given in Table XVIII.

TABLE XVIII

Composition, Tensile, Impact and Bending Requirements for 8% Nickel Steel Plate Quenched and Tempered

Composition (ASTM A 553, Type II)		
Carbon, max, %	0.13	
Manganese, max, %	0.90	
Phosphorus, max, %	0.035	
Sulfur, max, %	0.040	
Silicon, %	0.15-0.30	
Nickel, %	7.50-8.50	
Tensile Requirements		
Tensile Strength, psi	100,000-120,000	
Yield Strength (0.2% Offset), min, psi	85,000	
Elongation (2 in.), min, %	20.0	
Charpy Impact (V-Notch) Requirements at −275 F*		
Lateral Expansion, min, mil	15	
Supplementary Requirements of Charpy Impact (V-Notch) Test		
	Longitudinal	Transverse
Full size (10 x 10 mm), min, ft-lb	25	20
¾ Width (10 x 7.5 mm), min, ft-lb	19	15
⅔ Width (10 x 6.67 mm), min, ft-lb	17	13
½ Width (10 x 5 mm), min, ft-lb	13	10
⅓ Width (10 x 3.33 mm), min, ft-lb	8	7
¼ Width (10 x 2.5 mm), min, ft-lb	6	5
Bending Requirements, Ratio: Bend Dia to Specimen Thickness		
¾ in. and under	2	
Over ¾ to 1¼ in., inclusive	2½	
Over 1¼ in.	3	
Allowable Design Stresses†		
ASME, Section VIII, Division 1, Table UHT-23, max, psi	25,000 (BM) 23,700 (W)	
ASME Code Case 1499, Table UHT-23, max, psi	25,000 (W)‡	

* Values of energy absorption and fracture appearance to be reported for information.
† ASME values are for temperatures not exceeding 150 F.
‡ Welded product must meet minimum tensile strength of 100,000 psi.
Abbreviations:
BM = Base Metal. W = Welded.

The following procedures are required for heat treating the 8 per cent nickel steel:

1. *Quench and Temper (QT)—ASTM A 553*

   Heat until the plate or part attains a uniform temperature of 1475 F, hold at this temperature in the ratio of 1 hour/inch of thickness, but in no case less than 15 minutes, and water quench. Reheat to a uniform temperature within the range of 1050 to 1125 F, hold at this temperature in the ratio of 1 hour/inch of thickness, but in no case less than 15 minutes, and cool in air or water quench; the cooling rate to be not less than 300°F/hour.

2. *Stress Relieve (SR)—ASTM A 553*

Heat the steel gradually and uniformly to a temperature between 1025 and 1085 F, hold for a minimum of 2 hours for thicknesses up to 1 inch, plus an additional period in proportion to 1 hour for each additional inch of thickness, and cool at a minimum rate of 300°F/hour in air or water to a temperature not exceeding 600 F.

Typical Mechanical Properties

The tensile properties of the 8 per cent nickel steel at 75 F surpass the requirements in Table XVIII, as shown in Figure 19 for quenched and tempered material.

Typical Charpy V-notch impact data in Figure 20 show energy absorbed and lateral expansion for tests at −275 F. The data show that this steel greatly exceeds the 15-mil lateral expansion requirement for transverse specimens. The energy absorbed exceeds the supplementary requirements of ASTM A 553 for quenched and tempered material.

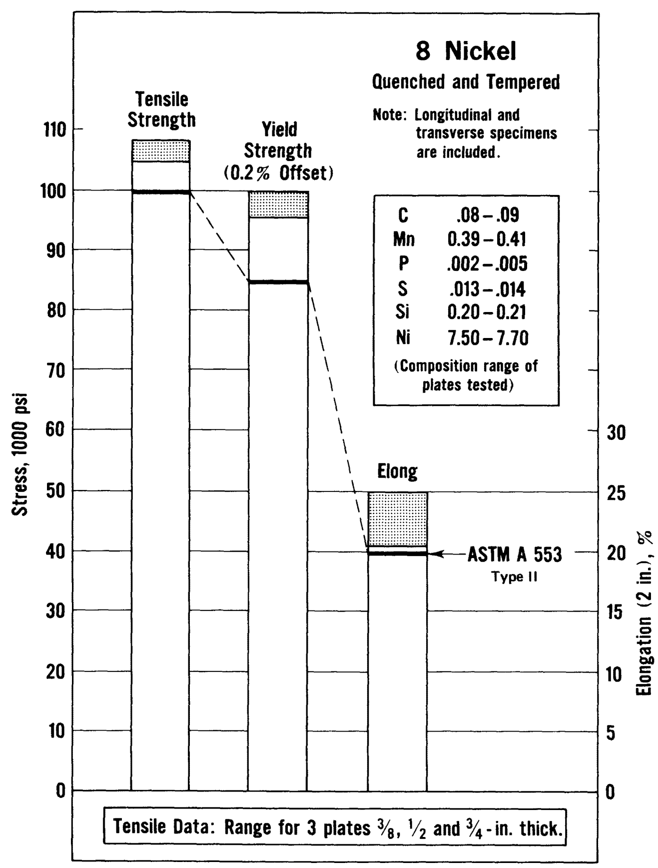


Fig. 19. Representative tensile properties for quenched and tempered 8 per cent nickel steel plates and how they compare with the minima specified in ASTM A 553.[66]

Thermal Expansion

The average coefficients of thermal expansion per degree F for the quenched and tempered 8 per cent nickel steel are:

5.3×10^{-6} for the range −260 to 80 F
7.0×10^{-6} for the range 80 to 800 F

Effects of Stress Relief and Cold Work

Figure 21 summarizes the data on the effects of stress relief and cold work. Stress relieving treatments have no significant effect on tensile properties; this is shown only for yield strength in Figure 21. The toughness of quenched and tempered material is not affected by stress relief for 2 hours at 1050 F, if followed by water quenching, but slower cooling rates (250 or 50°F per hour) give lower impact values. Ten per cent cold work increases yield strength and substantially lowers the impact value. Stress relief at 1050 F after the 10 per cent cold work restores the yield strength to the original quenched and tempered level. It also raises impact values but not to the pre-cold worked levels for the three cooling rates from 1050 F.

Welding

For pressure vessel construction, this material falls into Group P-11A, Table Q-11.1, Section IX of the ASME Code governing welding procedure qualification.[4] Quenched and tempered plates ⅝-inch thick, welded by the manual shielded metal-arc process with

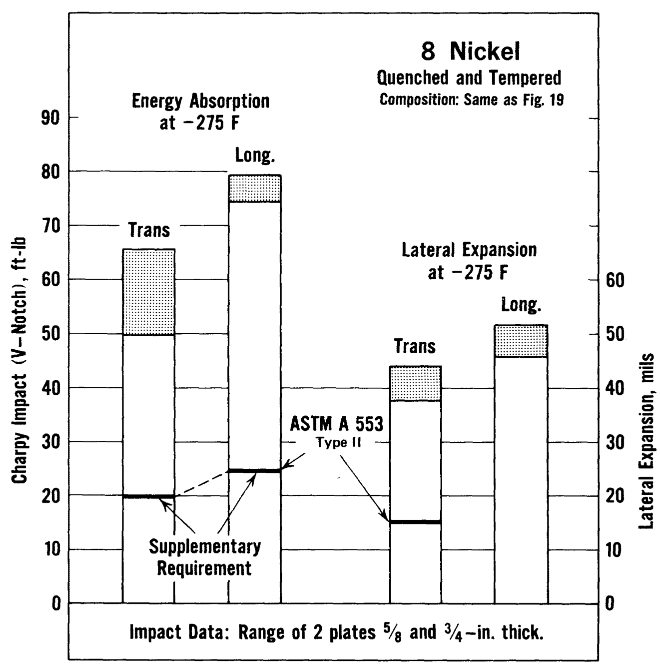


Fig. 20. Representative Charpy V-notch impact data on 8 per cent nickel steel plate and how they compare with the minima specified in ASTM A 553.[66]

INCO-WELD A Electrodes, develop –275 F Charpy V-notch impact properties of the weld metal and the weld heat-affected zone that match or exceed those of the base metal. The steel meets radiographic quality, joint efficiency, and bend ductility requirements satisfactorily. Table XIX presents the mechanical properties of these welds in plates of 8 per cent nickel steel.

Crack-starter explosion-bulge performance is excellent for base plate and butt-welded plate, both with and without postweld stress relief, with fracture-transition-elastic (FTE) temperatures below –275 F.[58]

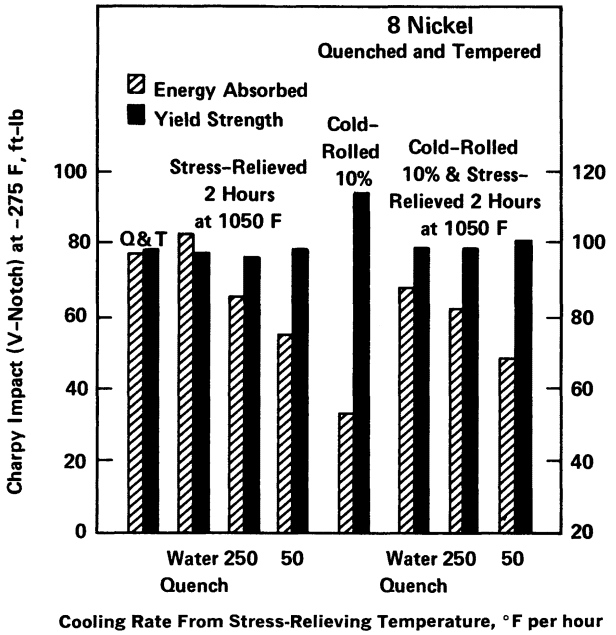


Fig. 21. Effect of stress-relief heat treatment, 10 per cent cold work and cooling rate from stress-relieving temperature on the properties of quenched and tempered 8 per cent nickel steel plates.[66]

9 PER CENT NICKEL STEEL

The 9 per cent nickel steel is specified for equipment operating at temperatures as low as –320 F. It is covered by ASTM A 353 and ASTM A 553, Type I.

Requirements for Low-Temperature Use

Low-carbon 9 per cent nickel steel is supplied in either the quenched and tempered or double normalized and tempered condition to meet the requirements of the latest revision of the ASME Boiler and Pressure Vessel Code. Table XX gives the required composition, heat treatment and mechanical properties, including allowable design stresses. No stress relief is required after welding for applications at temperatures down to –320 F in sections up to 2 inches thick. As shown in Table XX, ASTM Designation A 353 covers double normalized and tempered plate and A 553, Type I covers quenched and tempered plate, both normally limited to a thickness of 2 inches; however, greater thicknesses may be obtained provided the composition meets the specified mechanical property requirements. Other forms, including forgings, are covered by ASTM A 522.

The following procedures for heat treatment are recommended in the standards mentioned above:

1. *Double Normalize and Temper (NNT)—ASTM A 353*

   Heat to a uniform temperature of 1650 F; hold at this temperature in the ratio of 1 hour per inch of thickness; but in no case less than 15 minutes; cool in air. Reheat until the plate attains a uniform temperature of 1450 F; hold at this temperature in the ratio of 1 hour per inch of thickness, but in no case less than 15 minutes; cool in air. Reheat to a uniform temperature within the range of 1050 to 1125 F; hold at this temperature in the ratio of 1 hour per inch of thickness, but in no case less than 15 minutes; cool in air or water quench, at a rate not less than 300°F per hour. If hot forming is performed within the range 1650-1750 F, the first normalize may be omitted.

2. *Quench and Temper (QT)—ASTM A 553*

   Heat to a uniform temperature of 1475 F; hold at this temperature in the ratio of 1 hour per inch of thickness, but in no case less than 15 minutes; quench in water. Reheat until the plate attains a uniform temperature within the range of 1050 to 1125 F; hold at this temperature in the ratio of 1 hour per inch of thickness, but in no case less than 15 minutes; cool in air or water quench, at a rate not less than 300°F per hour.

3. *Stress Relieve (SR)—ASTM A 353 and A 553*

   Stress relieving of parts, when required, may be accomplished by heating at 1025-1085 F for a minimum of 2 hours for thicknesses up to 1 inch, plus an additional period in proportion to 1 hour for each additional inch of thickness, and cool at a minimum rate of 300°F/hour in air or water to a temperature not exceeding 600 F.

Typical Mechanical Properties

Tensile and Impact Properties or Plate

Typical tensile properties as a function of temperature in 3/8-inch thick plates, double normalized and tempered, are shown in Figure 22. Figure 23 shows similar typical properties for 3/8 and 3/4-inch thick plates in the quenched and tempered condition. Although this steel is not utilized normally for elevated

TABLE XIX

Mechanical Properties of Quenched and Tempered ⅝-Inch Plates of 8% Nickel Steel Butt-Welded with INCO-WELD A Electrodes[a]

Description of Property or Material	As Welded[b]	Postweld Heat-Treated[c]
Tensile Properties		
Tensile Strength, psi	107,000	108,000
Joint Efficiency, %	100[d]	100[d]
Failure Location	Weld and bond	Weld and bond
ASME Guided-Bend-Test Results, degrees		
Longitudinal Face Bend	180	180
Charpy V-Notch Energy Absorption at −275 F, ft-lb		
Base Metal	77	66
Weld Metal	69	72
Heat-Affected Zone	91	109
Charpy V-Notch Lateral Expansion at −275 F, mils		
Base Metal	51	47
Weld Metal	51	61
Heat-Affected Zone	50	59

[a] Reference 66.
[b] Welded by shielded metal-arc welding process with joints perpendicular to final rolling direction of plate.
[c] Two hours at 1050 F, cooled at rate of 250°F per hour.
[d] This may be a little high because INCO-WELD A welds in 9% nickel steel generally exhibit a joint efficiency slightly less than 100%.

temperature service, specific requirements allow pressure vessels to be cycled from moderately elevated temperatures to subzero temperatures. Consequently, a few short-time elevated-temperature tensile data for both heat-treated conditions are given in Table XXI.

The probable range and normal expectancy curves for Charpy V-notch impact values of commercial plate, as currently produced for double normalized and tempered and quenched and tempered material, are presented in Figures 24 and 25 respectively. Typical Charpy-V-notch values are shown by the curves of Figure 26, which also shows that these values substantially exceed the supplementary requirements of ASTM A 353 and A 553 for double normalized and tempered and quenched and tempered material, respectively. Additional impact data are shown in Table XXII for plates up to 2 inches thick at −320 F.

Charpy V-notch impact requirements have largely replaced Charpy keyhole-notch requirements for steel plates for pressure vessels as covered by the general specification ASTM A 20. Charpy keyhole-notch requirements are specified in ASTM A 300; however, impact data on this type of specimen show that this requirement is met quite readily.

Tensile and Charpy-impact data on the 9 per cent nickel steel in plate form, in relation to existing ASTM specifications, are summarized in Figures 27, 28 and 29. The double normalized and tempered condition is covered in Figure 27 and quenched and tempered in Figure 28. Some lateral expansion data, along with data on energy absorbed and fracture appearance, are in-

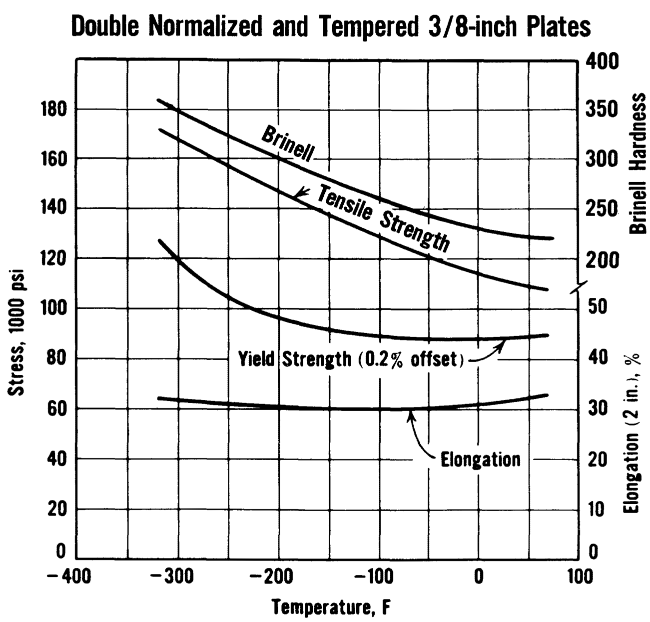


Fig. 22. Effect of temperature on hardness and tensile properties of 9 per cent nickel steel in double normalized and tempered condition.[52]

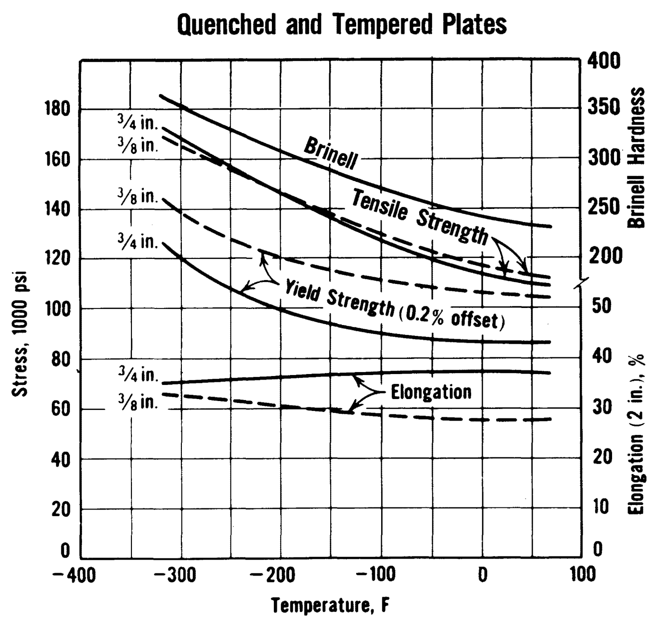


Fig. 23. Effect of temperature on hardness and tensile properties of 9 per cent nickel steel in quenched and tempered condition.[52]

TABLE XX

Composition, Heat Treatment and Mechanical Properties Specified for 9% Nickel Steel Plate for Low-Temperature Service

Composition (ASTM A 553, Type I)		
Carbon, max, %	0.13	
Manganese, max, %	0.90	
Phosphorus, max, %	0.035	
Sulfur, max, %	0.040	
Silicon, %	0.15-0.30	
Nickel, %	8.50-9.50	
Heat Treatment	NNT (ASTM A 353)	QT (ASTM A 553, Type I)
Tensile Requirements		
Tensile Strength, psi	100,000-120,000	100,000-120,000
Yield Strength (0.2% Offset), min, psi	75,000	85,000
Elongation (2 in.), min, %	20.0	20.0
Charpy Impact (V-Notch) Requirements at –320 F*		
Lateral Expansion, min, mil	15	
Supplementary Requirements of Charpy (V-Notch) Test	Longitudinal	Transverse
Full size (10 x 10 mm), min, ft-lb	25	20
¾ Width (10 x 7.5 mm), min, ft-lb	19	15
⅔ Width (10 x 6.67 mm), min, ft-lb	17	13
½ Width (10 x 5 mm), min, ft-lb	13	10
⅓ Width (10 x 3.33 mm), min, ft-lb	8	7
¼ Width (10 x 2.5 mm), min, ft-lb	6	5
Bending Requirements, Ratio: Bend Dia to Specimen Thickness		
¾ in. and under	2	
Over ¾ to 1¼ in.	2½	
Over 1¼ in.	3	
Allowable Design Stresses**	NNT (ASTM A 353)	QT (ASTM A 553, Type I)
ASME, Section VIII, Division 1, Table UHT-23, max, psi	25,000 (BM) 23,700 (W)	25,000 (BM) 23,700 (W)
ASME Code Case 1499, Table UHT-23, max, psi	25,000 (W)†	25,000 (W)†
ASME, Section VIII, Division 2, Table AQT-1, max, psi	33,300 (BM) 31,700 (W)†	33,300 (BM) 31,700 (W)†
API Standard 620 for large low-pressure welded storage tanks for liquefied natural gas, Table Q.3.3, max, psi	31,700 (W)‡	31,700 (W)‡

* Values of energy absorption and fracture appearance reported for information.
** ASME values are for temperatures not exceeding 150 F.
† Welded product must meet minimum tensile strength of 100,000 psi.
‡ Minimum tensile strength 95,000 psi in welded construction.
Abbreviations:
N = Normalized. Q = Quenched. T = Tempered.
BM = Base Metal. W = Welded.

TABLE XXI

Short-Time Elevated-Temperature Tensile Properties for 9% Nickel Steel[a]

Test Temperature F	Plate Thickness in.	Heat Treatment[b]	Tensile Strength psi	Yield Strength (0.2% offset) psi	Elongation (1 in.) %	Reduction of Area %
Room	½	QT	110,000	93,000	25	74
250	½	QT	101,000	91,000	23	73
450	½	QT	101,000	90,000	23	73
650	½	QT	95,000	82,000	31	78
850	½	QT	76,000	68,000	26	79
Room	½	NNT	110,000	88,000	26	71
250	½	NNT	100,000	77,000	24	71
450	½	NNT	102,000	76,000	26	69
650	½	NNT	91,000	70,000	30	77
850	½	NNT	70,000	60,000	30	81
Room	2	QT	109,000	100,000	25	72
250	2	QT	102,000	91,000	23	73
450	2	QT	101,000	88,000	22	69
650	2	QT	96,000	83,000	29	77
850	2	QT	76,000	70,000	26	82
Room	2	NNT	103,000	80,000	26	69
250	2	NNT	91,000	73,000	25	72
450	2	NNT	90,000	71,000	25	70
650	2	NNT	88,000	68,000	32	76
850	2	NNT	66,000	57,000	34	85

[a] Reference 51.
[b] Q = Water quench NN = Double normalize T = Temper

TABLE XXII

Effect of Plate Thickness on Charpy Impact Values at –320 F of Commercial 9% Nickel Steel in Quenched and Tempered Condition

Plate Thickness in.	Charpy Impact (V-Notch), ft-lb: Longitudinal Range	Longitudinal Avg.	Transverse Range	Transverse Avg.	Reference
0.4	31-38[a]	45[a]	—	—	55
0.5	28-46[a]	38[a]	27-36[a]	32[a]	52, 54
0.9	45-50	48	34-39	36	54
1.6	41-50	45	30-31	30	51
1.9	30-47[a]	35[a]	26-31	28	51
2	32-48[a]	40[a]	20-25	22	51

[a] Two or more heats and/or plates.

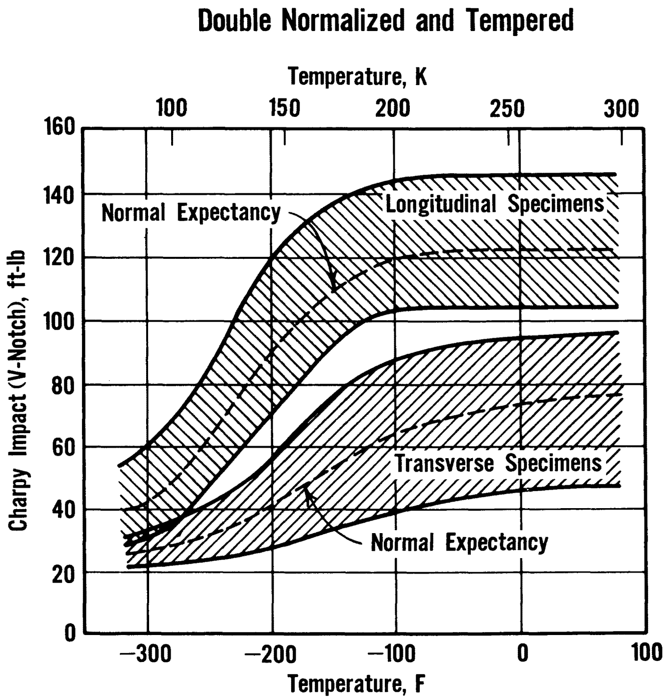


Fig. 24. Probable range of Charpy V-notch impact values for double normalized and tempered (at 1050-1075 F) low-carbon 9 per cent nickel steel plate. Data from many sources.

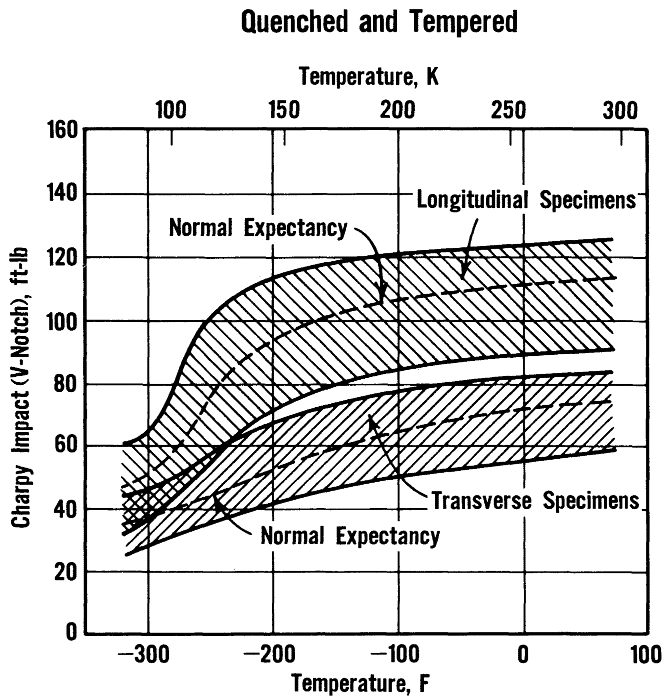


Fig. 25. Probable range of Charpy V-notch impact values for quenched and tempered (at 1050-1075 F) low-carbon 9 per cent nickel steel plate. Data from many sources.

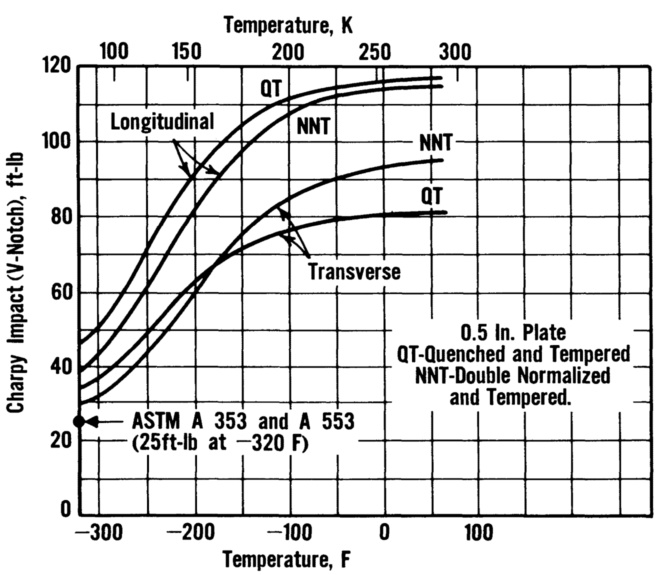


Fig. 26. Effect of heat treatment and rolling direction on Charpy V-notch impact of low-carbon 9 per cent nickel steel plate. Operation Cryogenics.[52]

cluded in Figure 29 for the quenched and tempered condition. The 15-mil lateral expansion requirement for transverse specimens is exceeded substantially.

Stability of Impact Properties on Cycling to Low Temperatures

Table XXIII shows the effect on impact properties of low-temperature cycling with and without applied stress.

Fracture Toughness Tests

Naval Research Laboratory drop-weight tests on quenched and tempered plates and weldments in thicknesses up to 1 inch show that the nil-ductility transition (NDT) temperature is below –320 F.[63] Similar tests conducted by Nippon Steel Corporation[64] on quenched and tempered plates up to 1.6 inches thick show that the NDT is below –320 F.

Crack-starter explosion-bulge tests on quenched and tempered plates in thicknesses up to ¾ inch show that the fracture-transition-elastic (FTE) temperature is at or below –320 F.[67]

Wells wide-plate (WWP) tests on welded and notched double normalized and tempered plates ½ inch thick show fracture occurs under stresses of 129,900 psi and 136,600 psi after gross plastic strains of 0.6 and 0.87 per cent respectively.[68]

Brittle-fracture initiation tests of welded and deep-notched quenched and tempered plate ½ inch thick show that a half-crack length of 3.1 inches is required to initiate brittle fracture at –320 F in the heat-affected

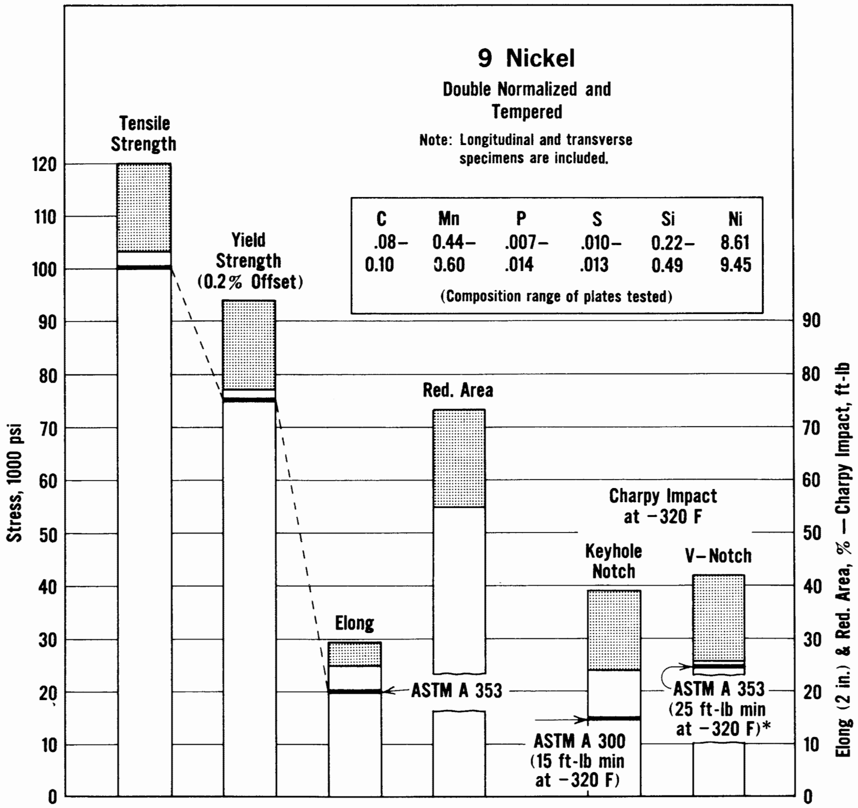


Fig. 27. Representative tensile and impact properties for a number of double normalized and tempered plates of 9 per cent nickel steel and how these properties compare with the specified minima.[31, 51,-52, 54, 63]

Double Normalized and Tempered: 1650 F, air cooled, 1450 F, air cooled, 1050–1100 F, water quenched.

Tensile Data: Range of 8 plates 0.4 to 2-in. thick.

Keyhole-Notch Data: Range of 3 plates 0.5 to 2-in. thick.

V-Notch Data: Range of 6 plates 0.5 to 1-in. thick.

* Supplementary requirement. Lateral expansion of 0.015-in. minimum at −320 F is specified for transverse specimens.

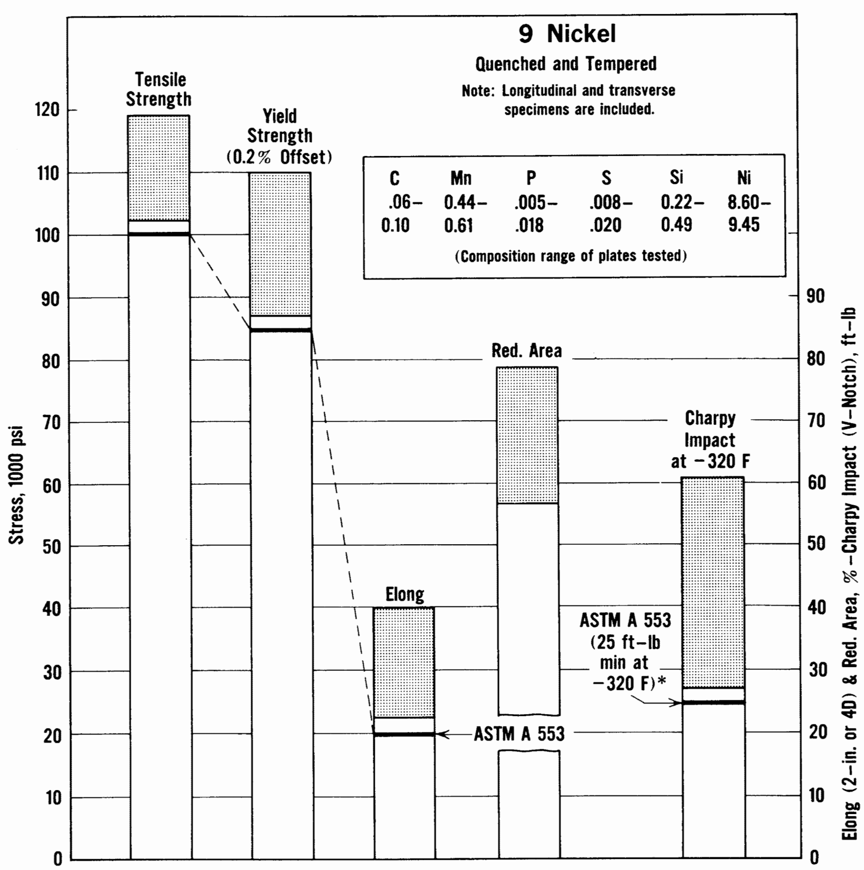


Fig. 28. Representative tensile and impact properties for a number of quenched and tempered plates of 9 per cent nickel steel and how these properties compare with the specified minima.[31, 52, 54, 55, 63]

Quenched and Tempered: 1450–1475 F, water quenched, 1060–1100 F, water quenched.

Tensile Data: Range of 17 plates 0.4 to 2-in. thick.

Charpy Impact Data: Range of 15 plates 0.4 to 1-in. thick.

* Supplementary requirement, longitudinal.

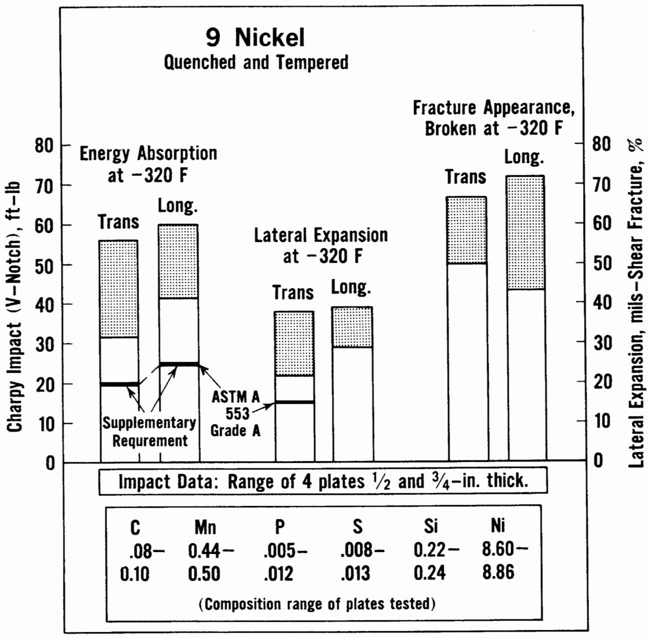


Fig. 29. Charpy impact properties of quenched and tempered 9 per cent nickel steel plate at —320 F and how they compare with those specified in ASTM A 553.[67]

TABLE XXIII

Effect of Low-Temperature Cycling and Tensile Stress on Impact Properties of 9% Nickel Steel[a]

Applied Tensile Stress psi	No. of Cooling Cycles 68 to −320 F	Charpy Impact (V-Notch) At 68 F Energy Absorbed ft-lb	At 68 F Fibrous Fracture %	At −320 F Energy Absorbed ft-lb	At −320 F Fibrous Fracture %
0	0	111	100	44, 48	63, 67
0	20	110	100	48, 52	67, 68
22,250[b]	20	109	100	46, 52	67, 68

[a] Double normalized and tempered.[51]
[b] 89% of allowable design stress.

TABLE XXIV

Compact Tension Fracture Toughness Evaluation of Quenched and Tempered 9% Nickel Steel at —260 and —320 F

Temperature F	K_Q[a] ksi $\sqrt{in.}$	$K_{1st\ pop}$ ksi $\sqrt{in.}$	K_m ksi $\sqrt{in.}$
−320	129.0	136.0	—
−320	133.0	—	197
−260	98.8	—	194
−260	139.0	—	185

[a] Conditional plane strain fracture toughness.

zone under a tensile stress of 0.4 times the yield strength.[69]

Fracture toughness tests conducted by Del Research Corporation[70] on quenched and tempered plate 1 inch thick at —260 and —320 F gave the conditional plane strain fracture toughness, K_Q, values shown in Table XXIV. Valid K_{1c} values would require specimen thicknesses of 4½ to 5 inches.

Fracture toughness tests conducted by TRW Inc.[71] on quenched and tempered plate 3 inches thick at 75, 100 and —321 F indicate K_Q values in all cases as shown in Table XXV. Valid K_{1c} values were not obtained because of insufficient specimen size; however, the toughness of the material appeared to be high based on the crack size factor, $(K_Q/\sigma_{ys})^2$.

Crack opening displacement (C.O.D.) fracture toughness tests on plate up to 3 inches thick at temperatures down to —321 F gave $C.O.D._{max}$ values at the first onset of maximum load of .010-.016 inch and K_{max} values of 150,000-210,000 psi$\sqrt{in.}$ Only minor differences in fracture toughness properties of quenched and tempered and double normalized and tempered plate up to 1.2 inches thick were found.[72]

Compact tension fracture toughness tests conducted by the University of California, Berkeley[73] on double normalized and tempered plates ¾ inch thick gave valid K_{1c} values at 73 ksi$\sqrt{in.}$ at —450 F. Compact tension (WOL) specimens 0.70 inch thick were used for these tests. Additional specimens of the same thickness were too thin for valid K_{1c} values at —320 F; however, a conditional fracture toughness value, K_Q, in the range 130 to 150 ksi$\sqrt{in.}$ was obtained.

Compressive Strength

Nine per cent nickel steel, like other ductile materials, has no compressive strength corresponding to ulti-

TABLE XXV

Fracture Toughness Test Results of Quenched and Tempered 9% Nickel Steel in 3 in. Plate Thicknesses at 75, —100 and —321 F

Temperature F	0.2% Yield Strength ksi	K_Q[a] ksi $\sqrt{in.}$
75	92.3	95.0
		101.5
		100.5
		101.4
−100	96.6	99.8
		98.5
		96.3
−321	124.5	114.1
		100.8
		106.5

[a] Conditional plane strain fracture toughness.

mate tensile strength. Its compressive yield strength (0.2 per cent offset), for quenched and tempered ¾-inch plate, is 90,000 psi at 75 F and 136,000 psi at −320 F.

Hardness and Hardenability

There is no appreciable difference in hardness between material in the double normalized and tempered and quenched and tempered condition of heat treatment. Figure 23 gives the hardness of quenched and tempered material at test temperatures between 75 and −320 F. A typical end-quench hardenability curve for 9 per cent nickel steel and its isothermal transformation diagram are given in other bulletins.*

Fatigue Properties

Figures 30, 31 and 32 summarize the fatigue properties of 9 per cent nickel steel. Figure 32 shows results of a plastic fatigue test, which was developed by Lehigh University, in which the degree of plastic strain is plotted against cycles to failure.[62]

Effect of Cold Straining on Impact Properties

Figure 33 shows the effect of cold working on the Charpy V-notch impact values of 9 per cent nickel steel. It will be noted that the material is restored to its original properties by stress relieving. ASME (Section VIII, Div. 1, page 199 and Div. 2, page 167) recommends that the material should be stress relieved if the amount of strain exceeds 3 per cent, as determined by the following formula:

$$\text{Per Cent Strain} = \frac{65t}{R_f}\left(1 - \frac{R_f}{R_o}\right)$$

where t = Plate Thickness
R_f = Final Radius
R_o = Original Radius (equals infinity for flat plate)

Physical Properties

Data follow on modulus of elasticity, density and electrical resistivity. These apply to the 9 per cent nickel base material in both conditions of heat treatment.

Modulus of Elasticity (70 F), psi	27×10^6
Modulus of Elasticity (−320 F), psi	30×10^6
Density, lb/cu in.	0.284
g/cu cm	7.86
Electrical Resistivity (70 F), microhm-cm	33.0

Additional data on thermal expansion, thermal conductivity, specific heat and magnetic properties are given in another bulletin.†

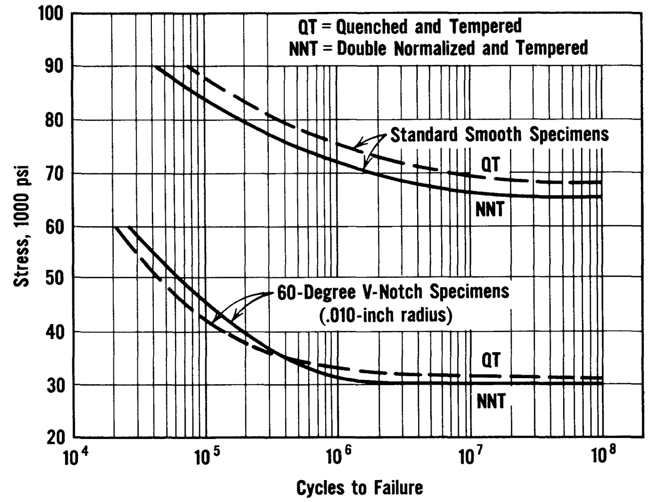


Fig. 30. Rotating-beam fatigue data for smooth and notched bars of 9 per cent nickel steel.[51]

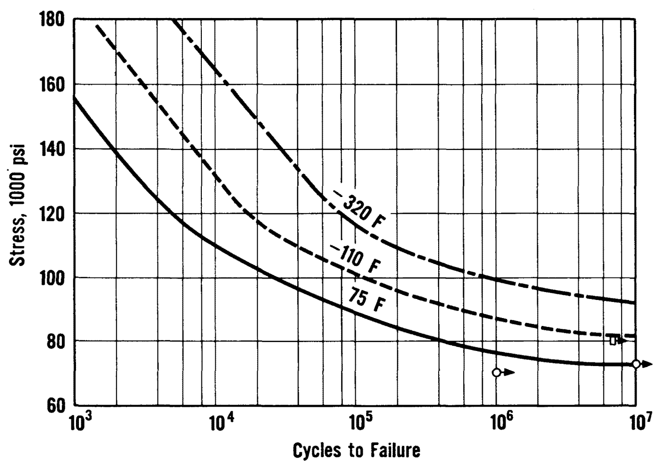


Fig. 31. Reciprocating-beam fatigue data for normalized 9 per cent nickel steel at three temperatures.[28]

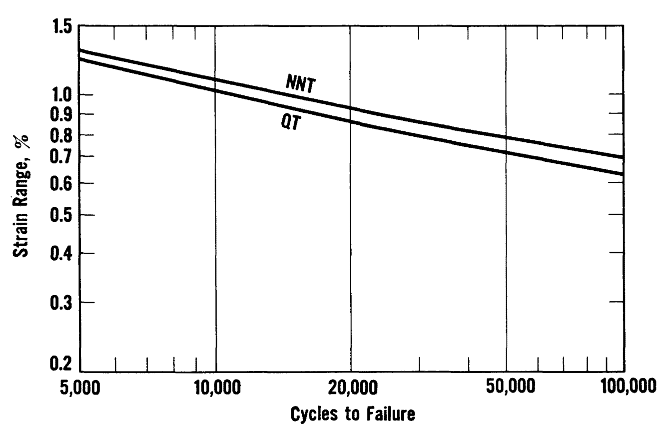


Fig. 32. Plastic-fatigue behavior of 9 per cent nickel steel in double normalized and tempered and quenched and tempered conditions.[34]

* Bulletin 6-A: "Hardenability of Nickel Alloy Steels."
Bulletin 6-B: "Isothermal Transformation Diagrams of Nickel Alloy Steels."

† Bulletin 7-A: "Physical Properties of Nickel Alloy Steels."

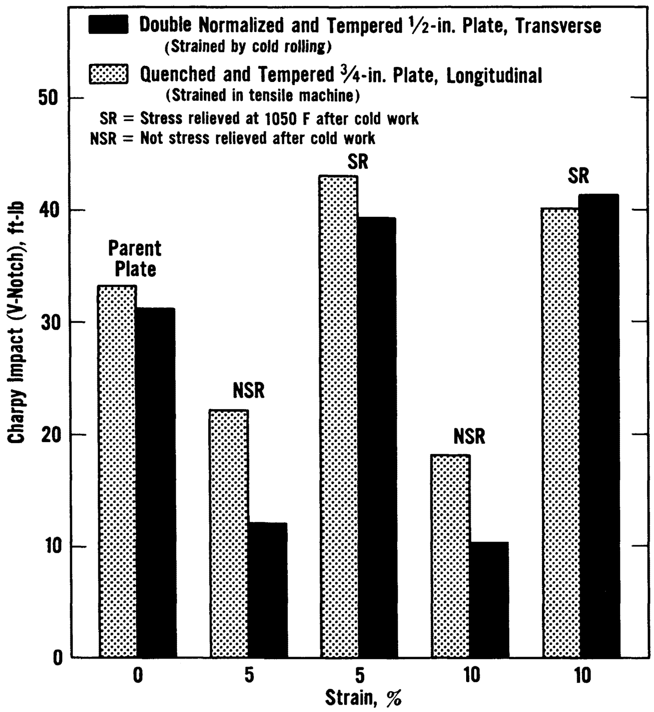


Fig. 33. Effect of cold-work strain and subsequent stress relief on Charpy impact level of 9 per cent nickel steel at −320 F.

Welding

For pressure vessel construction, 9 per cent nickel steel falls into Group P-11A, Table Q-11.1, Section IX of the ASME Code governing welding procedure qualification.[4] The ASME toughness requirements for weld metal and heat-affected zone for low-temperature service are the same as for the base metal. Many pressure vessels for low-temperature applications have been welded successfully with austenitic nickel-chromium-iron alloy filler materials to achieve welds with high strength, good ductility and notch toughness, and thermal expansion matching the base plate. Welded design values are based on the use of austenitic nickel-chromium-iron alloys that have 95 per cent of the base-metal strength. However, design stresses matching those of the base material are allowed provided that the welded products meet the minimum tensile strength of the base material.

Nine per cent nickel steel can be welded manually with coated electrodes and by gas metal processes (MIG and TIG) using INCO-WELD A Electrode or INCONEL Filler Metal 92 filler materials. These electrodes correspond, respectively, to the ENiCrFe-2 classification of AWS Specification A5.11 and the ERNiCrFe-6 classification of AWS Specification A5.14. Typical weld-joint tensile properties as a function of temperature and welding processes are shown in Figure 34.[52] Table XXVI shows impact properties of welded 9 per cent nickel plate up to 1 inch in thickness. Additional typical mechanical property data for welds in 9 per cent nickel steel are given in Table XXVII.[78, 79] Welds of matching strength to the base plate have been achieved using appropriate filler metals such as INCONEL Filler Metal 625, INCONEL Welding Electrode 112 or INCO-WELD B Electrode.[77]

Some vessels have been welded using short-circuiting arc or pulsating-arc processes. Both of these processes are variations of the standard gas metal-arc processes (MIG). Normally a smaller diameter wire (.030-.045 in.) is used and all position welding is possible.[77]

Submerged-arc welding has been used successfully for the fabrication of vessels and tanks for low temperature service. This process was employed in welding tanks using INCONEL Filler Metal 625 and INCOFLUX* 4 Submerged Arc Flux. Matching strengths across the welds were obtained.[77]

AISI-SAE NICKEL ALLOY STEELS

The tensile and fatigue properties of a number of wrought straight nickel and nickel-containing alloy steels in the range from room temperature to low temperatures are presented in Table XXVIII. These data are from numerous sources as indicated by the column on references.

Figures 35, 36, 37 and 38 show that the AISI medium-carbon alloy constructional steels have good fracture toughness at low temperatures. Figure 35 shows the advantage of liquid quenching over normalizing and Table XXIX demonstrates the important benefit conferred by adequate quenching in contrast to slack quenching. Figures 36, 37 and 38 relate fracture toughness (Charpy V-notch) to tempering temperature and hardness, and also show the effect of mixed martensitic-bainitic structures produced by austempering heat treatments.

Table XXX presents extensive Charpy V-notch impact data on a number of quenched and tempered constructural steels, showing the effects of carbon content, tempering temperature and hardness. The greater toughness of low-carbon martensites in contrast to high-carbon martensites of equal hardness is illustrated.

NICKEL ALLOY STEEL CASTINGS

The low-temperature impact behavior of cast nickel alloy steels parallels that of their wrought counterparts, as shown in Tables XXXI and XXXII. The expected advantage for the tempered martensite structure is evident, as indicated in Figure 39. Table XXXI shows that nickel progressively improves the low-temperature performance of normalized low-carbon cast steels, just

* Registered trademark of The International Nickel Company, Inc.

as it does wrought steels. The requirements for the four cast nickel and nickel alloy steels covered by ASTM Specification A 352 are shown in Table XXXII, but the specification should be consulted for details.

Data for some cast medium-carbon nickel alloy steels of the AISI type are given in Table XXXIII for both the normalized and tempered and the quenched and tempered conditions.

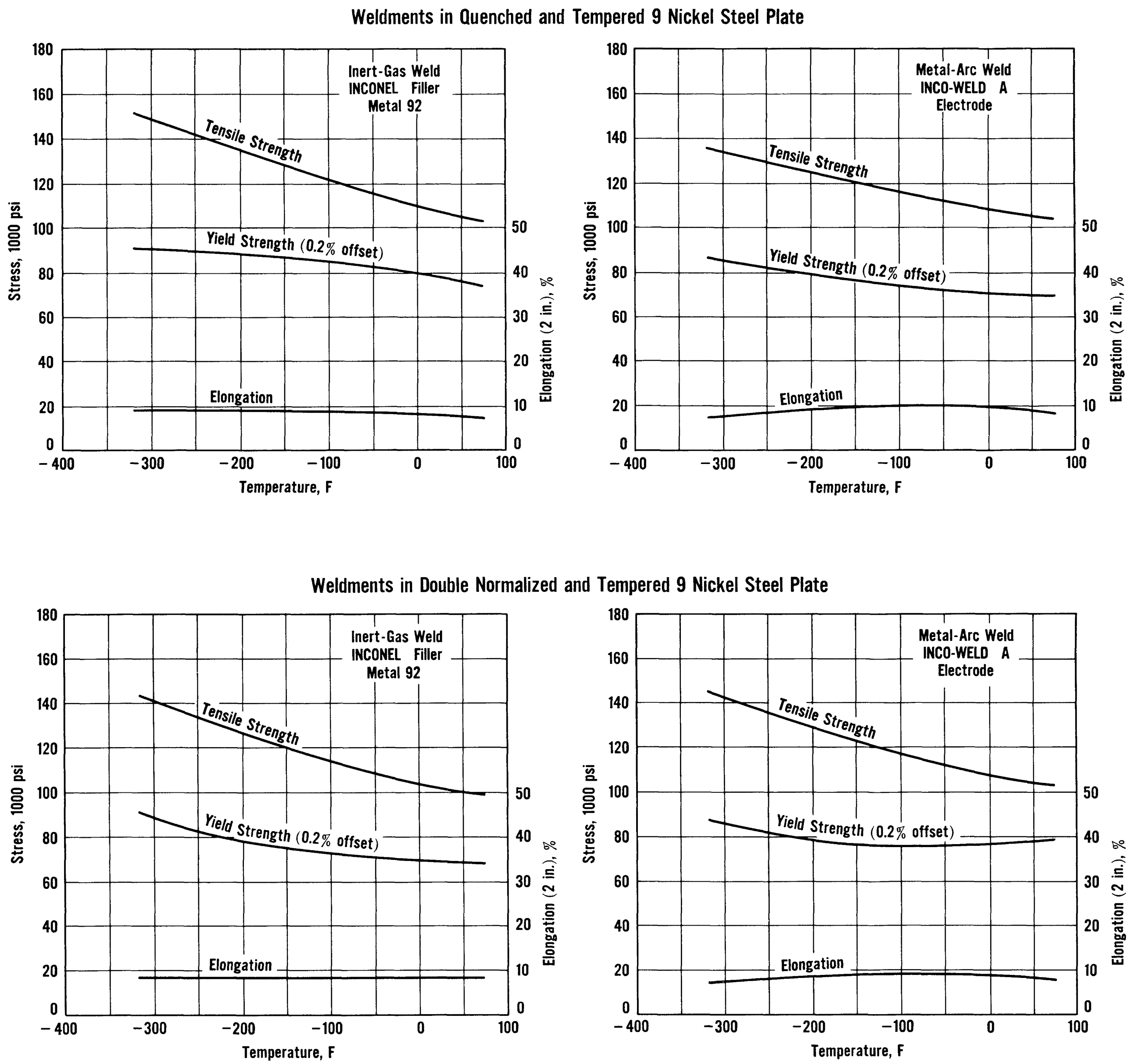


Fig. 34. Tensile properties from −320 to 75 F for transversely butt-welded plates comprising INCONEL and INCO-WELD A deposits in as-welded ⅜-inch 9 per cent nickel steel plate. (Note: The elongation values appear to be lower than plate values because most of the elongation occurs in the more ductile, narrow weld-metal band which is only a small portion of the 2-inch gage length. See Figures 22 and 23 for elongation values of plate.) [51]

TABLE XXVI

Charpy Impact Data at —320 F for Welded 9% Nickel Steel Plate[a]

Electrode[b]	Treatment After Welding	Notch Location[c]	Charpy Impact, ft-lb: Double Normalized and Tempered: V-Notch	Double Normalized and Tempered: Keyhole Notch	Quenched and Tempered: V-Notch	Quenched and Tempered: Keyhole Notch
		3/8-Inch Plate[d] — 3/4-Width Specimens[51,52]				
Base Metal	—	BM	25- 39	27-32	28-35	—
Electrode A	As Welded	HAZ	28- 33	25-27	19-24	22-27
Electrode A	As Welded	WM	35- 36	24-26	41-45	21-23
Electrode A	Stress Relieved[e]	HAZ	19- 21	21-38	27-30	23-24
Electrode A	Stress Relieved[e]	WM	42- 46	23	35-37	22-26
MIG-92	As Welded	HAZ	28- 72	—	41-53	—
MIG-92	Stress Relieved[f]	HAZ	37- 54	—	23-36	—
		1/2-Inch (NNT) and 3/4-Inch (QT) Plates — Full-Size Specimens[47,51,52]				
Base Metal	—	BM	32	35	46	43
Electrode A	As Welded	HAZ	68- 82	29-37	52-65	—
Electrode A	As Welded	WM	60- 71	28-34	—	—
Electrode A	Stress Relieved[f]	FZ	73- 74	34-40	33-47	—
Electrode A	Stress Relieved[f]	WM	56- 64	29-33	—	—
MIG-92	As Welded	HAZ	43- 60	22-34	71-91	—
MIG-92	As Welded[f]	WM	96-101	44-52	—	—
MIG-92	Stress Relieved[f]	FZ	84-111	44-57	31-86	—
MIG-92	Stress Relieved[f]	WM	76- 98	45-51	—	—
		1-Inch Plate — Full-Size Specimens[47]				
Electrode A	Stress Relieved[f]	FZ	60- 85	39-41	—	—
Electrode A	Stress Relieved[f]	WM	65-105	40-60	—	—
MIG-92	Stress Relieved[f]	FZ	57- 83	29-35	—	—
MIG-92	Stress Relieved[f]	WM	97-112	51-65	—	—

[a] All welding was horizontal.
[b] Electrode A is covered, metal-arc type (INCO-WELD A Electrode). MIG-92 is consumable wire, inert gas type (INCONEL Filler Metal 92).
[c] BM = Base Metal. HAZ = Heat-Affected Zone. FZ = Fusion Zone. WM = Weld Metal.
[d] Tempered at 1100 F. [e] Stress relieved 1050 F, cooled at 300°F/hour. [f] Stress relieved 1050 F, 2 hours, air cooled.

TABLE XXVII

Typical Mechanical Properties for Welds in 9% Nickel Steel[a]

Welding Product	Type Test	Tensile Strength psi	0.2% Offset Yield Strength psi	% Elong. in 2 in.	Failure Location	Charpy V-Notch Impact: Weld 80 F	Weld –320 F	HAZ 80 F	HAZ –320 F
INCONEL Welding Electrode 112	AWM	115,000	74,000	36	—				
	Trans	114,500	—	—	Weld & Plate	56.0	47.0	72.0	35.5
INCO-WELD A	AWM	97,000	59,000	39	—	74.7	65.7	91.0	57.0
	Trans	101,000	—	—	Weld				
INCONEL Filler Metal 625 Pulsing Arc	AWM	119,000	79,100	29	—	67.5	53.7	99.3	62.0
	Trans	112,000	—	—	Plate & Fusion Line				
INCONEL Filler Metal 92 Pulsing Arc	AWM	105,000	65,000	39	—	134	126	81.0	66.0
	Trans	102,600	—	—	Weld				
INCONEL Filler Metal 625 INCOFLUX 4	AWM	111,000	66,600	32	—	N.A.	N.A.	N.A.	N.A.
	Trans	108,700	—	—	Weld & Plate				
INCONEL Filler Metal 82 INCOFLUX 4	AWM	97,500	55,100	39	—	84.6	80.5	64.2	41.5
	Trans	101,000	—	—	Weld				
INCO-WELD B	AWM	107,800	65,700	31.7	—	—	44	—	53

[a] These properties are quoted as typical values only, and are not intended for use as minimum or design values. Mechanical properties can vary with technique, heat input, and, in some cases, joint design.
AWM = All Weld Metal. Trans = Transverse. N.A. = Not Available.

TABLE XXVIII

Tensile and Fatigue Properties of Some Wrought Nickel-Containing Steels at Low Temperatures

Steel Type	Chemical Composition, % C	Mn	Ni	Cr	Mo	Heat Treatment F	Test Temperature F	Tensile Strength psi	Yield Strength (0.2% Offset) psi	Elongation (4D) %	Reduction of Area %	Hardness DPH	Modulus of Elasticity psi	Endurance Limit psi Unnotched	Notched	Reference
2330	0.28/	0.60/	3.25/	—	—	Normalized	77	109,000	89,000	12	50	246	26.9 x 10^6	59,000	—	28
	0.33	0.80	3.75				−108	121,000	105,000	12	46	284	28.0	63,000	—	
							−314	163,000	141,000	13	33	315	30.8	112,000	—	
2330	0.28/	0.60/	3.25/	—	—	1500, OQ; Temp 925	77	145,000	139,000	18	59	322	29.2 x 10^6	75,000	17,500	28
	0.33	0.80	3.75				−108	159,000	140,000	20	50	358	30.0	95,000	—	
							−314	180,000	186,000	20	40	384	31.6	125,000	40,000	
4340	0.46	0.70	1.78	0.95	0.23	1550, OQ; Temp 1200	77	146,000	136,000	20	60	—	30.9 x 10^6	74,000	20,000	87
							−314	208,000	200,000	20	44	—	31.8	116,000	20,000	
4340	0.46	0.70	1.78	0.95	0.23	1550, OQ; Temp 800	77	231,000	214,000	12	46	—	30.7 x 10^6	89,000	49,000	87
							−314	288,000	267,000	4	11	—	30.9	122,000	36,000	
4340	0.40	0.75	1.86	0.84	0.23	1575, OQ; Temp 450, 4 hr; Temp 450, 4 hr	79	269,000	225,000	12	40	531	28.4 x 10^6	—	—	88
							−108	281,000	239,000	12	40	548	30.6	—	—	
							−321	319,000	278,000	10	24	639	30.6	—	—	
							−423	332,000	—	0.6	0.2	818	30.4	—	—	
8630	0.27/	0.70/	0.48/	0.49/	0.18	Normalized	77	90,000	80,000	16	58	217	27.1 x 10^6	46,000	—	28
	0.33	0.90	0.67	0.56			−108	104,000	92,000	18	57	252	28.9	58,000	—	
							−314	150,000	134,000	12	28	289	31.7	93,000	—	
8630	0.27/	0.70/	0.48/	0.49/	0.18	1500, OQ; Temp 850	77	142,000	122,000	16	60	302	29.8 x 10^6	70,000	30,000	28
	0.33	0.90	0.67	0.56			−108	154,000	127,000	17	57	332	31.1	80,000	—	
							−314	192,000	166,000	12	50	376	32.3	125,000	35,000	
5% Ni	0.16	0.50	5.16	—	—	1560, OQ; Temp 1040	68	86,000	66,000[a]	28[b]	69	175[c]	—	—	—	93
							−297	136,000	120,000	28[b]	57	255[c]	—	—	—	
Ni-Mo-Si[f]	0.26	1.26	1.91	—	0.43	Normalized	77	232,000	196,000	12	44	—	29.8 x 10^6	88,000	38,000	87
							−314	283,000	233,000	12	33	—	31.3	120,000	46,000	
Ni-Cr-Mo	0.34	0.44	2.27	1.88	0.40	1560, OQ; Temp 1040	68	168,000	148,000	17[b]	51	397[c]	—	—	—	93
							−58	182,000	164,000	17[b]	65	337[c]	—	—	—	
							−94	183,000	164,000	18[b]	62	—	—	—	—	
							−297	226,000	204,000	17[b]	63	—	—	—	—	
Ni-Cr-Mo	0.34	0.44	2.27	1.88	0.40	1560, OQ; Temp 1090	68	150,000	128,000	19[b]	69	298[c]	—	—	—	93
							−58	166,000	143,000	19[b]	63	—	—	—	—	
							−297	205,000	185,000	21[b]	51	397[c]	—	—	—	

[a] Permanent Set.
[b] Elongation in 5 diameters.
[c] Brinell.
[d] Full thickness plate specimens, 2-in. gage length.
[e] 45-deg V-notch, .010-in. root radius.
[f] 1.37% Si.

Abbreviations:
OQ = Oil Quenched. T = Tempered.

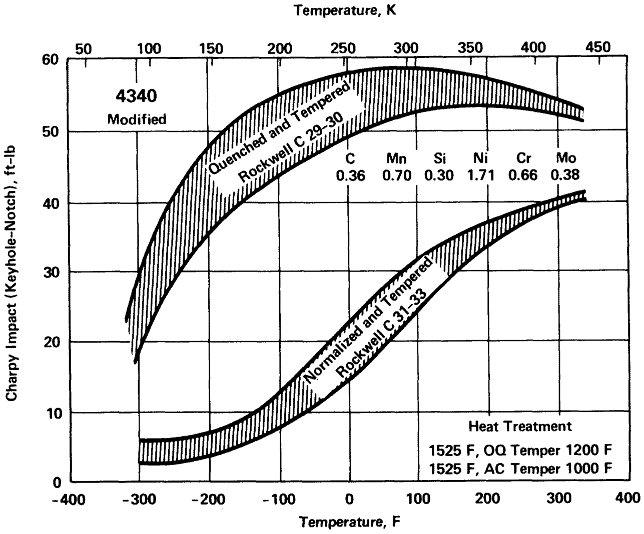


Fig. 35. Effect of heat treatment on impact properties of modified 4340 steel.[30]

TABLE XXIX

Effect of Slack Quenching on Transition Temperature of Six Medium-Carbon Alloy Steels[a]

AISI Steel Type	Transition Temperature, F 15 ft-lb Charpy Impact (V-Notch) Slack Quenched to Rockwell C 40	Quenched to Martensite	Transition Temperature Increase Caused by Slack Quenching, F
2345	−150	Less than −230	More than 170
4340	−100	Less than −320	More than 220
4640	−100	−260	160
4140	−70	Less than −320	More than 250
5145	10	−228	238
1340	135	−175	310

[a] Reference 38.

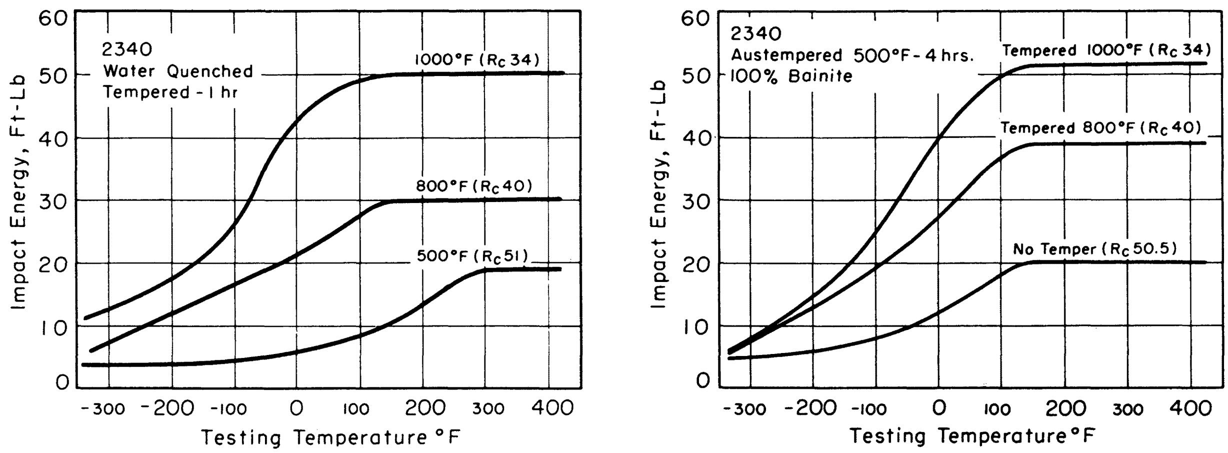


Fig. 36. Transition curves for 2340 steel after quenching and tempering (left) and austempering (right).[89]

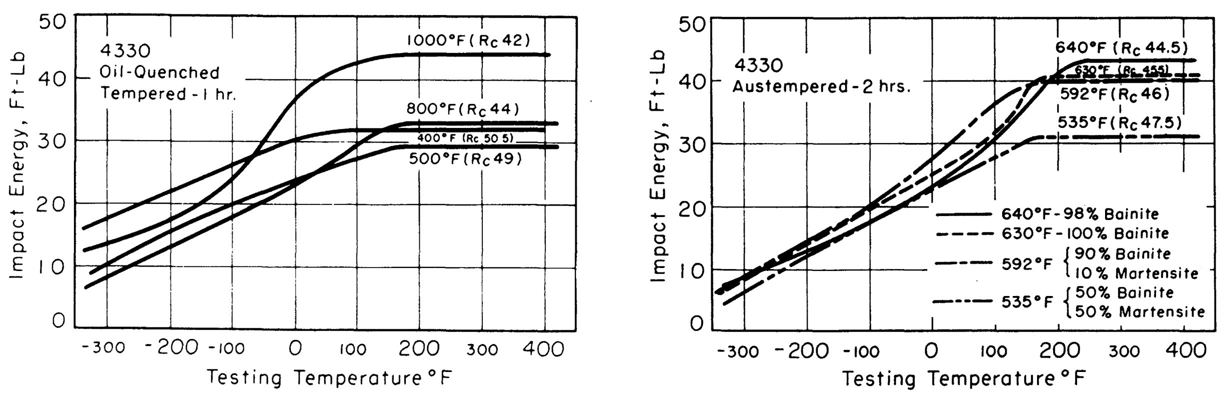


Fig. 37. Transition curves for 4330 steel after quenching and tempering (left) and austempering (right).[89]

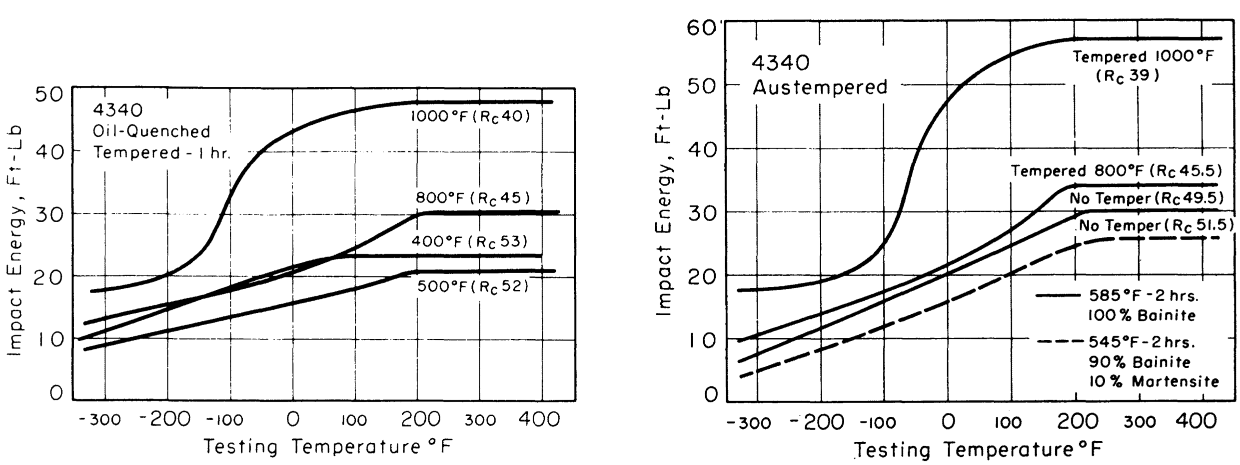


Fig. 38. Transition curves for 4340 steel after quenching and tempering (left) and austempering (right).[89]

TABLE XXX

Low-Temperature Impact Properties of Quenched and Tempered Nickel Alloy Steels[a]

AISI Steel Type	Composition, %					Heat Treatment		Rockwell C Hardness	Charpy Impact (V-Notch), ft-lb, at Temperature Indicated, F[c]					Transition Temperature (50% Brittle) F
	C	Mn	Ni	Cr	Mo	Quenching Temperature[b] F	Tempering Temperature F		−300	−200	−100	0	100	
2320	0.18	0.91	3.47	—	—	1650	300	43.5	17	24	30	30	30	—
							800	30	10	19	35	54	59	−120
							1000	22	19	24	65	75	75	−140
2330	0.33	0.86	3.50	—	—	1575	800	35	15	20	30	41	46	−115
							1000	26	10	24	49	59	60	−160
2340	0.43	0.83	3.38	—	—	1550	800	39	10	18	24	30	35	−65
							1000	30	15	19	37	44	45	−150
2360	0.57	0.91	3.50	—	—	1475	800	40	5	9	10	19	24	—
							1000	32	8	11	18	30	35	−65
2380	0.75	1.00	3.50	—	—	1450	800	45	5	6	10	12	14	—
							1000	35	8	10	12	14	20	40
3120	0.23	0.75	1.26	0.58	—	1650	300	43	10	15	23	28	30	—
							800	35	11	15	25	44	50	—
							1000	26	5	13	33	76	78	—
							1200	19	13	35	95	96	96	—
3140	0.38	0.77	1.26	0.64	—	1550	800	43	10	15	21	26	30	−185
							1000	30	13	16	35	45	48	−200
							1200	25	14	25	55	63	66	−200
3180	0.72	0.92	1.34	0.63	—	1450	800	47	4	5	10	14	14	—
							1000	40	10	10	12	16	20	—
							1200	31	—	18	19	40	45	—
4320	0.21	0.74	1.53	1.09	0.19	1650	400	43	9	17	25	27	28	—
							800	37	5	10	16	25	30	30
							1000	33	8	16	28	40	45	−65
							1200	21	19	35	80	90	90	−175
4330	0.30	0.84	1.69	1.10	0.20	1575	400	50	5	14	16	20	20	—
							600	47	5	6	10	14	17	—
							800	43	6	10	14	19	21	70
							1000	35	17	17	23	30	34	−110
							1200	27	17	35	45	53	56	−185
4340	0.38	0.77	1.65	0.93	0.21	1550	400	52	11	15	20	21	21	—
							600	48	10	14	15	15	16	—
							800	44	9	13	16	21	25	—
							1000	38	15	18	28	35	36	−130
							1200	30	15	28	55	55	55	−185
4360	0.57	0.87	1.62	1.08	0.22	1475	800	48	5	6	10	11	14	—
							1000	40	9	10	13	18	23	−10
							1200	30	12	15	25	42	43	−110
4380	0.76	0.91	1.67	1.11	0.21	1450	800	49	4	5	8	9	10	—
							1000	42	8	8	10	12	15	60
							1200	31	5	11	19	33	38	−50
4620	0.20	0.67	1.85	0.30	0.18	1650	300	42	14	20	28	35	35	—
							800	34	11	16	33	55	55	—
							1000	29	16	34	55	78	78	—
							1200	19	17	48	103	115	117	—
4640	0.43	0.69	1.78	0.29	0.20	1550	800	42	16	17	20	25	27	—
							1000	37	17	22	35	39	39	−190
							1200	29	17	30	55	67	67	−180
4680	0.74	0.77	1.81	0.30	0.21	1450	800	46	5	8	13	15	16	—
							1000	41	11	12	15	19	22	—
							1200	31	11	13	17	39	43	—
8620	0.20	0.89	0.60	0.68	0.20	1650	300	43	11	16	23	35	35	—
							800	36	8	13	20	35	45	−20
							1000	29	25	33	65	76	76	−150
							1200	21	10	85	107	115	117	−195
8630	0.34	0.77	0.66	0.62	0.22	1575	800	41	7	12	17	25	31	0
							1000	34	11	20	43	53	54	−155
							1200	27	18	28	74	80	82	−165
8640	0.45	0.78	0.65	0.61	0.20	1550	800	46	5	10	14	20	23	—
							1000	38	11	15	24	40	40	−110
							1200	30	18	22	49	63	66	−140
8660	0.56	0.81	0.70	0.56	0.25	1475	800	47	4	6	10	13	16	—
							1000	41	10	12	15	20	30	−10
							1200	30	16	18	25	54	60	−90
8680	0.76	0.81	0.67	0.60	0.22	1450	800	50	3	4	5	9	10	—
							1000	42	4	5	10	14	17	—
							1200	32	3	6	11	25	40	−30

[a] References 90, 91 and 92. Induction furnace laboratory heats normalized before quenching.

[b] Quenched in oil as 0.45-inch square bars. (Oversize Charpy blanks).

[c] Values scaled from curves.

TABLE XXXI

Low-Temperature Impact Properties of Cast Nickel Steels[a]

Composition, %				Heat Treatment	Charpy Impact (V-Notch), ft-lb, at Indicated Temperature, F							
C	Mn	Si	Ni	F	−320	−160	−120	−80	−40	0	40	70
0.13	0.65	0.35	0.0	Norm 1650	—	—	3	13	29	44	59	68
0.13	0.65	0.35	1.03	Norm 1650	—	3	8	17	32	48	62	71
0.13	0.65	0.35	2.02	Norm 1650	—	7	12	21	34	48	60	72
0.13	0.65	0.35	3.50	Norm 1650	—	15	24	35	46	56	67	74

[a] Reference 94.

TABLE XXXII

Requirements of Nickel and Nickel Alloy Steel Castings for Low-Temperature Service

Steel ASTM A 352 and ASME SA-352	2½% Nickel Grade LC2	Ni-Cr-Mo Grade LC2-1	3½% Nickel Grade LC3	4½% Nickel Grade LC4
Chemical Composition				
Carbon, max, %	0.25	0.22	0.15	0.15
Manganese, %	0.50-0.80	0.55-0.75	0.50-0.80	0.50-0.80
Phosphorus, max,%	.040	.040	.040	.040
Sulfur, max, %	.045	.045	.045	.045
Silicon, max, %	0.60	0.50	0.60	0.60
Nickel, %	2.0-3.0	2.5-3.5	3.0-4.0	4.0-5.0
Chromium, %	—	1.35-1.85	—	—
Molybdenum, %	—	0.30-0.60	—	—
Heat Treatment[a]	NT or QT	NT or QT	NT or QT	NT or QT
Tensile Properties				
Tensile Strength, min, psi	70,000	105,000	70,000	70,000
Yield Point, min, psi	40,000	80,000[b]	40,000	40,000
Elongation (2 in.), min, %	24.0	18.0	24.0	24.0
Reduction of Area, min, %	35.0	30	35.0	35.0
Charpy Impact (V-Notch)				
Energy Value, min, ft-lb[c]	15	30	15	15
Test Temperature, F	−100	−100	−150	−175

[a] Heat treatment: Normalized and tempered (NT) or quenched and tempered (QT). Castings shall be tempered at a minimum of 1100 F except Grade LC 4 which shall be 1050 F. [b] Yield Strength. [c] Average of three specimens.

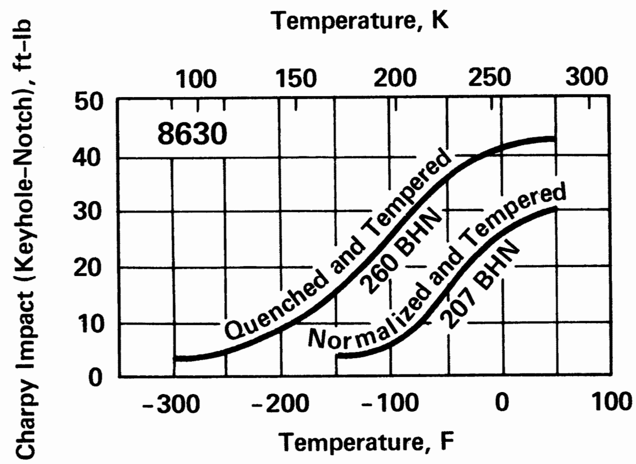
TABLE XXXIII

Impact Properties of Cast Nickel Alloy Steels[a]

AISI Steel	Nominal Composition, %						Charpy Impact (V-Notch), ft-lb, at Indicated Temperature, F							
Type	C	Mn	Si	Ni	Cr	Mo	−250	−200	−150	−100	−50	0	40	70
						Normalized and Tempered								
2330	0.30	0.70	0.28	3.50	—	—	—	8	8	9	13	21	30	42
3130	0.30	0.70	0.28	1.25	0.65	—	—	3	4	5	7	14	23	32
4330	0.30	0.70	0.28	1.82	0.80	0.25	—	—	8	11	15	21	25	28
4630	0.30	0.70	0.28	1.82	—	0.25	—	2	8	21	27	32	33	34
8640	0.40	0.88	0.28	0.55	0.50	0.20	—	—	4	7	14	21	25	27
						Quenched and Tempered								
2330	0.30	0.70	0.28	3.50	—	—	—	12	13	17	27	33	35	35
3130	0.30	0.70	0.28	1.25	0.65	—	—	10	12	15	25	35	38	40
4330	0.30	0.70	0.28	1.82	0.80	0.25	—	9	15	22	27	30	32	32
4630	0.30	0.70	0.28	1.82	—	0.25	—	9	21	33	39	43	45	46
8640	0.40	0.88	0.28	0.55	0.50	0.20	5	11	20	32	39	43	45	45

[a] Steel Castings Handbook.[96]

Fig. 39. Low temperature impact properties of water-quenched and tempered and normalized and tempered nickel-chromium-molybdenum cast steel (8630).[95]



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