# 3½ % NICKEL STEEL FOR LOW TEMPERATURE SERVICE

A PRACTICAL GUIDE TO THE USE OF NICKEL-CONTAINING ALLOYS

Nº 278

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**Nickel Institute**

communications@nickelinstitute.org
www.nickelinstitute.org

# $3\frac{1}{2}$% NICKEL STEEL
## For Low Temperature Service

### Introduction

$3\frac{1}{2}$% Ni steels have a useful combination of strength and excellent low temperature properties and find applications in process equipment and structures operating at temperatures down to −150 F. They are available as plate, pipe, tubes, forgings, castings, bolting, flanges, fittings and valves.

### Specifications for Low Temperature Service

| Material | ASTM Designation[1] |
|---|---|
| Plate | A 203 Grade D* and E* |
| Pipe (Seamless & Welded) | A 333 G-3 |
| Tubes (Seamless & Welded) | A 334 G-3 |
| Forged or Rolled Flanges, Fittings & Valves | A 350 G-LF3 |
| Welded Fittings | A 420 G-WPL3 |
| Forgings† | A 336 Class F31 |
| Castings | A 352 G-LC3 |
| Bolting | A 320 G-L10‡ |

*When to be used as pressure vessels, should conform to A 20-70a—"General Requirements For Delivery Of Steel Plates For Pressure Vessels."

†Drum Forgings.

‡Not included in 1973 Issue of ASTM Standards. See 1970 Issue.

**Composition Specifications** (In accordance with ASTM 1973 Specifications)[1]

| Element | Plate* Grade D | Plate* Grade E | Pipe & Tube | Castings | Forgings | Flanges, Fittings, Valves |
|---|---|---|---|---|---|---|
| Carbon, max | .17 | .20 | .19 | .15 | .35 | .20 |
| Manganese | .70 max | .70 max | .31-.64 | .5-.8 | .5-.9 | .90 max |
| Phosphorus, max | .035 | .035 | .05 | .04 | .04 | .04 |
| Sulfur, max | .04 | .04 | .05 | .045 | .04 | .05 |
| Silicon | .15-.30 | .15-.30 | .18-.37 | .60 max | .10-.40 | .15-.35 |
| Nickel | 3.25-3.75 | 3.25-3.75 | 3.18-3.82 | 3.0-4.0 | 2.25-3.00 | 3.25-3.75 |

*Chemistry varies according to thickness. Values given are for plates up to 2 in. in thickness. Refer to ASTM specifications for chemistry of heavier plate.

**Tensile Requirements**

***Plate* (Normalized)***

| | A 203 Grade D | A 203 Grade E |
|---|---|---|
| Tensile Strength, ksi | 65-77 | 70-85 |
| Yield Point, min, ksi | 37 | 40 |
| Elongation in 8 in., min, % | 19* | 17* |
| Elongation in 2 in., min, % | 23 | 21 |

*See ASTM A 20 for testing methods to be used.

***Pipe and Tubes* (Seamless and Welded)**

| | | |
|---|---|---|
| Tensile Strength, min, ksi | 65 | |
| Yield Point, min, ksi | 35 | |
| | **Longi-tudinal** | **Trans-verse** |
| Elongation in 2 in., min, %* | 30 | 20 |

***Castings* (Quenched and Tempered)**

| | |
|---|---|
| Tensile Strength, min, ksi | 70 |
| Yield Strength, min, ksi | 40 |
| Elongation in 2 in., min, % | 24 |
| Reduction of Area, min, % | 35 |

***Forgings* (A 336 Class F31—Quenched and Tempered)**

| | |
|---|---|
| Tensile Strength, min, ksi | 95 |
| Yield Strength, min, ksi | 70 |
| Elongation in 2 in., min, %, tangential | 18 |
| Reduction of Area, min, %, tangential | 35 |

***Flanges, Fittings and Valves* (May be normalized, normalized and tempered or quenched and tempered but must meet following mechanical properties)**

| | |
|---|---|
| Tensile Strength, min, ksi | 70 |
| Yield Point or Yield Strength, min, ksi | 40 |
| Elongation in 2 in., min, % | 25 |
| Reduction of Area, min, % | 50 |

### Low Temperature Tensile Properties

The effect of heat treatment on the low temperature tensile properties is demonstrated in Figures 1 (as-rolled), 2 (normalized) and 3 (quenched and tempered) for A 203 Grade D plate.[2] At −150 F not much difference is shown by normalizing over as-rolled plate (both 90,000 psi tensile strength and 62,000 psi yield strength). Definite added strength at −150 F is obtained by quench and temper heat treatment (100,000 psi tensile strength and 75,000 psi yield strength).

*Basic minimum elongation for walls 5/16″ and over in thickness, strip tests, and for all small sizes tested in full section. For wall thicknesses less than 5/16″, see A 333 specification for elongation requirement.

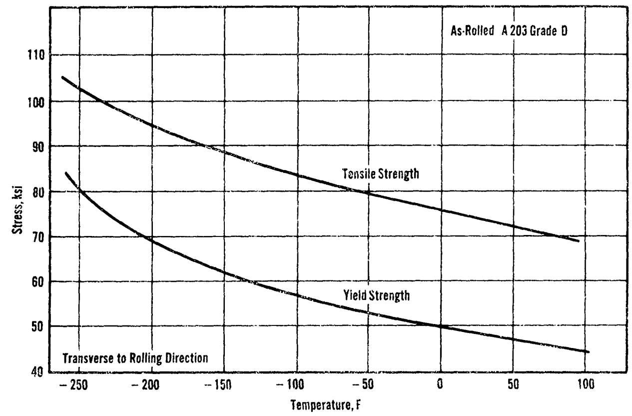


Fig. 1. Effect of temperature on tensile data of as-rolled A 203 Grade D material.

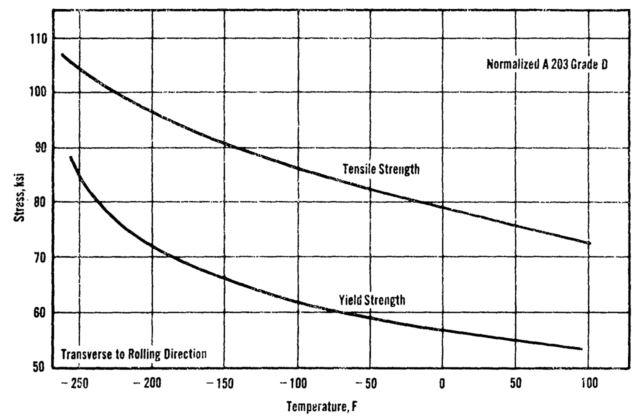


Fig. 2. Effect of temperature on tensile data of normalized A 203 Grade D material.

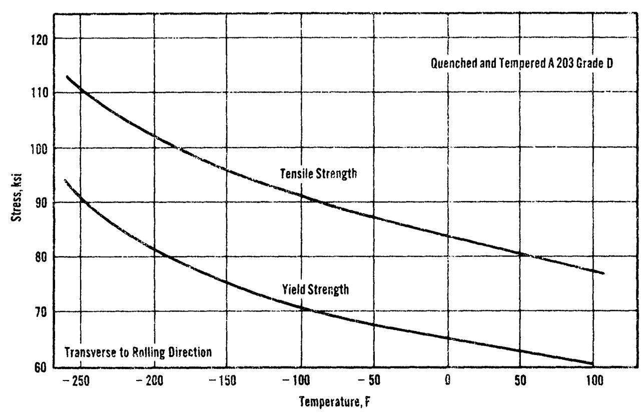


Fig. 3. Effect of temperature on tensile data of quenched and tempered A 203 Grade D material.

## Impact Requirements

Charpy V-notch testing requirements for thermally treated steel plates for pressure vessels are given in ASTM A 593-72.[1] Table I of this specification (A 593-72) gives grade/thickness/minimum test temperature combinations meeting Charpy V-notch requirements indicated for normalized or quenched and tempered condition. For Grade D plates up to 2 in. thick the test temperature is –150 F and for plates 2-3 in. thick the test temperature is –125 F for the minimum 13 ft-lb impact value for the average of three tests. For Grade E this minimum impact value for three tests must average 15 ft-lb.

## Impact Properties

The effect of heat treatment on the low temperature impact properties is shown in Figures 4 (as-rolled), 5 (normalized) and 6 (quenched and tempered) for A 203 Grade D plate.[2] In the transverse direction, the material in the normalized condition had a 15 ft-lb transition temperature of –170 F while the quenched and tempered material had a transition temperature of –225 F.

Other Charpy V-notch tests of quenched and tempered material showed superior notch toughness to normalized material.[3,4]

Effects of various heat treatments and section sizes on impact properties are shown in Figures 7 and 8.[5,6] The reason for heat treatment becomes apparent from results of the as-rolled specimens.

### *Fracture Toughness Tests*

Figure 9 shows both Charpy V-notch and keyhole-notch transition curves and also the NDT temperature determined by the drop weight test.[7] Half-inch plate, normalized and tempered and 1 inch bar just normalized was used for this test. Tempering the 1 inch bar did not change the NDT temperature in the drop weight test.

Further tests using quarter section as-rolled, normalized and quenched and tempered plate gave results shown in Table II.[2] The quenched and tempered Grade D materials' NDT at –130 F was far superior to the as-rolled condition and better than the normalized condition at –110 F by 20 F.

The low and cryogenic temperature static fracture toughness data for A 203 Grade D plate are given in Table III. Dynamic fracture toughness data are given in Table IV.[2]

***Impact properties of welds*** using matching 3½% nickel steel electrodes (E8015-C2) give properties shown in Figures 10 and 11 which show effect stress relief has on areas such as heat affected zone and fusion line.[3]

Other results show this in tabular form (Table V) where ½ in. plate normalized and then tested in the as-welded and the stress relieved conditions are given.[8] These welds were performed with E-8016-C2 electrodes.

## Fracture Toughness of Welded 3½% Ni Steels

In addition to drop weight tests on base metals, fracture toughness of welded wide plate tests (Wells wide plate) shows no brittle fracture at applied stresses below general yield in ½ in. welded plates down to –211 F. These tests were performed without post-weld heat treatment. The original plate was supplied as normalized and tempered.

**Table I**

**Generally Available Grade/Thickness/Minimum Test Temperature Combination Meeting ASTM-ASME Charpy V-Notch Requirements Indicated (Normalized or Quenched and Tempered Condition)**

| Class[a] | Acceptance Criteria Charpy V-Notch, Energy Absorption: Average for three specimens ft-lb min | Acceptance Criteria Charpy V-Notch, Energy Absorption: Minimum for one specimen ft-lb | Specification and Grade | Test Temperature, F, for Plate Thicknesses (Unless Otherwise Agreed Upon): 1 in. and under | Over 1 to 2 in. incl | Over 2 to 3 in. incl |
|---|---|---|---|---|---|---|
| III | 13 | 10 | A 203 Grade D | –150 | –150 | –125 |
| IV | 15 | 12 | A 203 Grade E | –150 | –150 | –125 |

[a] Class III is Fully Killed with a specified minimum tensile strength of 65,000 psi or lower.
Class IV is Fully Killed with a specified minimum tensile strength of over 65,000 to 75,000 psi.

Tests at –148 F on 11/16 in. welded plate show failure does not occur until after 2% plastic strain with the Wells wide plate test. The failure initiated at the pair of sawcuts located in the transverse weld metal. The plastic strain is measured over the full plate length.

Details of Wells wide plate specimens are given in Figure 12.[9]

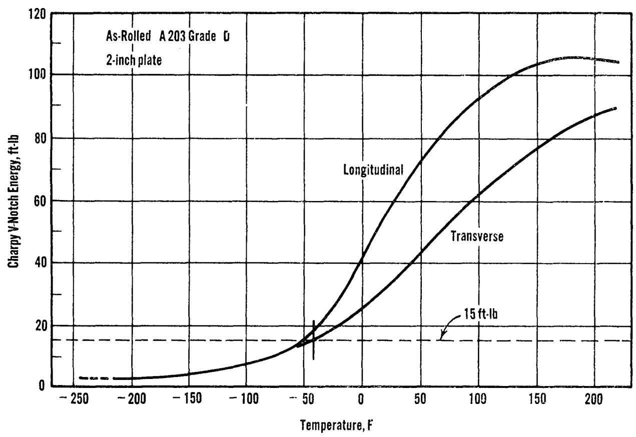


Fig. 4. Charpy V-notch impact test transition temperature curves for as-rolled A 203 Grade D material.

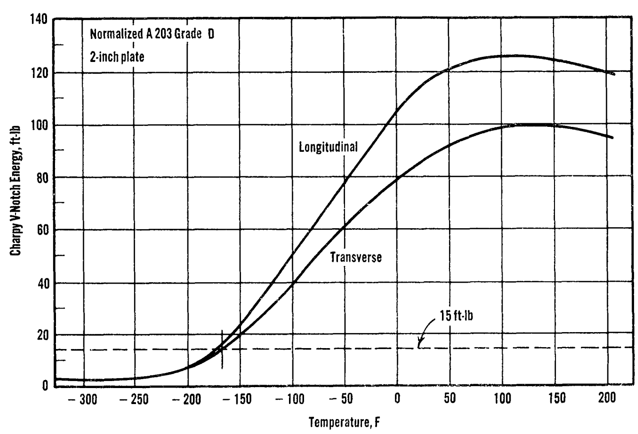


Fig. 5. Charpy V-notch impact test transition temperature curves for normalized A 203 Grade D material.

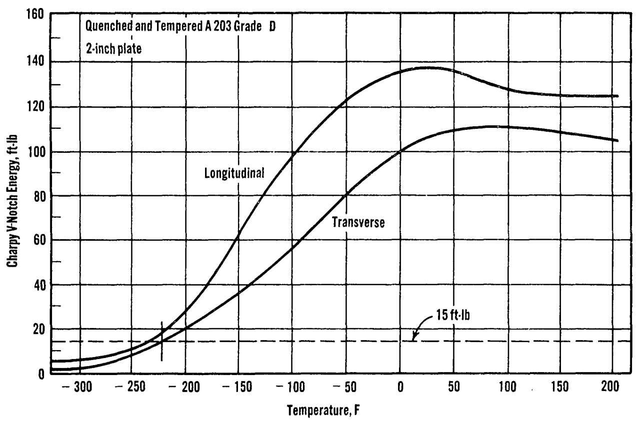


Fig. 6. Charpy V-notch impact test transition temperature curves for quenched and tempered A 203 Grade D material.

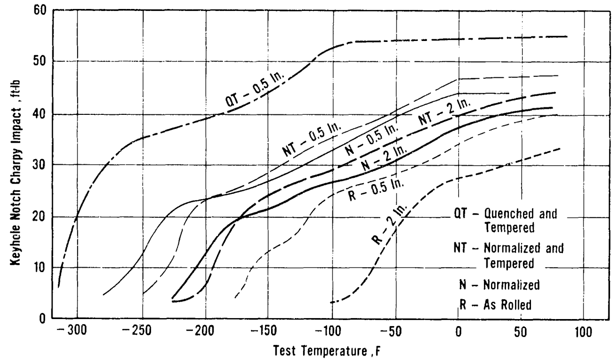


Fig. 7. Effect of heat treatment and plate thickness on keyhole-notch-impact properties of low carbon, 3½ per cent nickel steel plate. Longitudinal specimens.

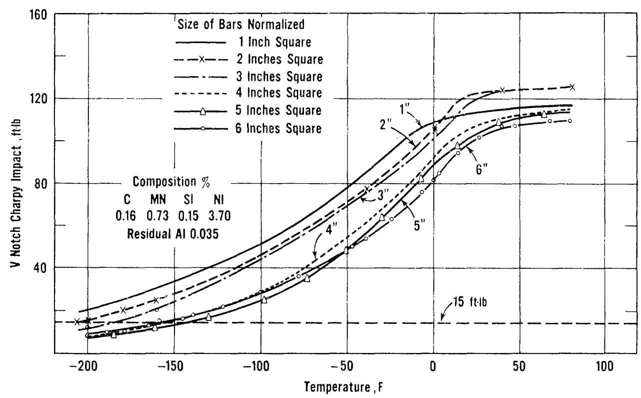


Fig. 8. Effect of section size on impact properties of normalized 3½ per cent nickel steel.

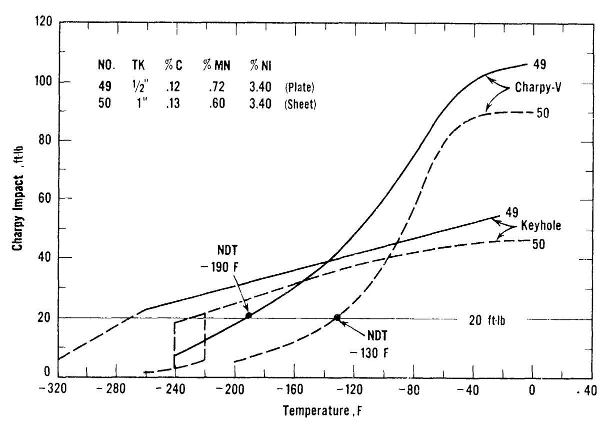


Fig. 9. Charpy and drop-weight test results of normalized A 203 Grade D steels.

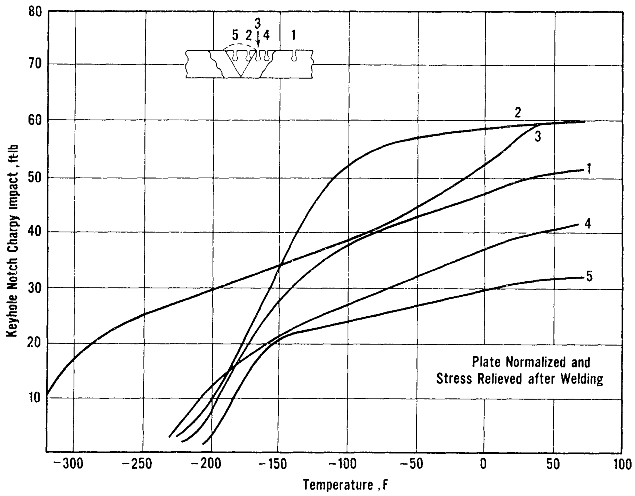


Fig. 10. Group of impact curves for one condition of welding and heat treatment of 3½ per cent nickel steel plate.

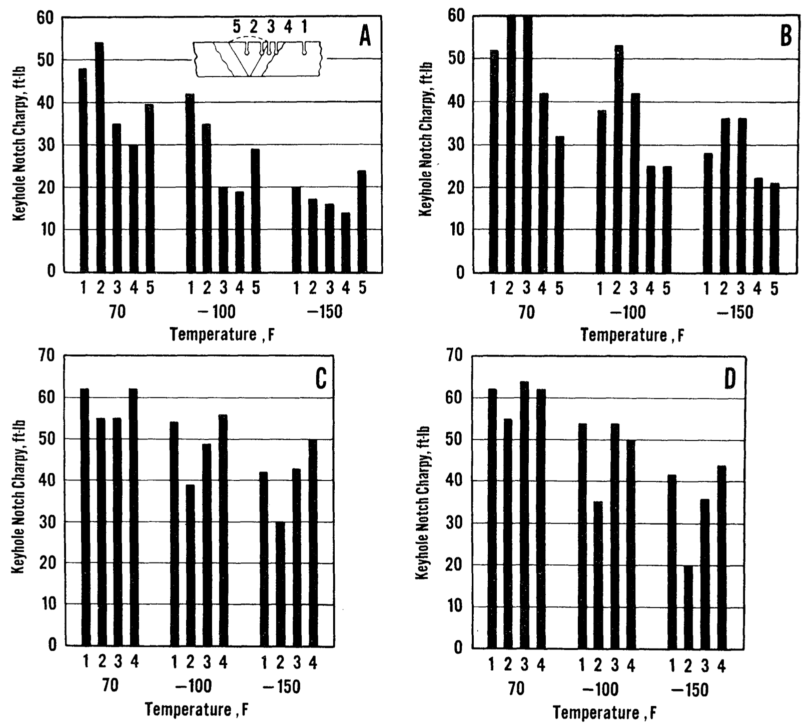


Fig. 11. Effect of welding on impact properties of low-carbon, 3½ per cent nickel steel.

A—Plate normalized and tested as welded.

B—Plate normalized and stress-relieved at 1150 F after welding.

C—Plate quenched and tempered. Tested as welded.

D—Plate quenched and tempered. Stress-relieved 1150 F after welding.

## Table II

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

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

**Table III**

**Static Fracture Toughness Data**

| Specimen No. | ASTM A 203 Grade | Testing Temperature, F | $K_{max}$[a] ksi $\sqrt{in.}$ | $K_{Ic}$[b] ksi $\sqrt{in.}$ |
|---|---|---|---|---|
| 1HR7 | D | –50 | 88.5 | — |
| 1HR8 | D | –50 | 80.1 | — |
| 1HR10 | D | –75 | 79.1 | — |
| 1HR5 | D | –100 | 61.4 | — |
| 1HR6 | D | –100 | 57.2 | — |
| 1HR9 | D | –125 | 42.6 | 42.6 |
| 1HR3 | D | –150 | 52.4 | 36.3 |
| 1HR4 | D | –150 | 39.3 | 39.3 |
| 1HR1 | D | –200 | 39.4 | 39.4 |
| 1HR2 | D | –200 | 36.4 | 36.4 |
| 2HR7 | D | –50 | 99.2 | — |
| 2HR8 | D | –50 | 75.7 | — |
| 2HR5 | D | –100 | 50.7 | — |
| 2HR6 | D | –100 | 62.5 | — |
| 2HR10 | D | –125 | 47.6 | 47.6 |
| 2HR3 | D | –150 | 63.5 | — |
| 2HR4 | D | –150 | 43.6 | 43.6 |
| 2HR9 | D | –150 | 57.5 | — |
| 2HR1 | D | –200 | 42.4 | 42.4 |
| 2HR2 | D | –200 | 36.0 | 36.0 |
| N5 | D | –125 | 116.3 | — |
| N8 | D | –125 | 131.5 | — |
| N1 | D | –150 | 126.2 | — |
| N2 | D | –150 | 118.7 | — |
| N9 | D | –175 | 105.8 | — |
| N10 | D | –175 | 105.7 | — |
| N3 | D | –200 | 68.9 | 68.9 |
| N4 | D | –200 | 68.1 | 68.1 |
| N6 | D | –250 | 48.1 | 48.1 |
| N7 | D | –250 | 47.3 | 47.3 |
| QT7 | D | –150 | 150.7 | — |
| QT8 | D | –150 | 155.2 | — |
| QT1 | D | –200 | 148.2 | — |
| QT2 | D | –200 | 125.1 | — |
| QT6 | D | –225 | 97.5 | — |
| QT3 | D | –250 | 65.5 | — |
| QT4 | D | –250 | 86.9 | — |
| QT5 | D | –275 | 75.7 | 75.7 |
| QT9 | D | –300 | 38.5 | 38.5 |
| QT10 | D | –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.

### Table IV

**Dynamic Fracture Toughness Data**

| Specimen No. | ASTM A 203 Grade | Testing Temperature, F | $K_{max}$[a] ksi $\sqrt{in.}$ | $K_{1c}$[b] ksi $\sqrt{in.}$ |
|---|---|---|---|---|
| N7 | D | −100 | 63.2 | — |
| N8 | D | −100 | 62.4 | — |
| N5 | D | −150 | 46.9 | 46.9 |
| N6 | D | −150 | 43.5 | 43.5 |
| QT7 | D | −100 | 103.9 | — |
| QT8 | D | −130 | 66.4 | 66.4 |
| QT2 | D | −150 | 77.3 | — |
| QT3 | D | −150 | 60.3 | 60.3 |
| QT4 | D | −200 | 40.8 | 40.8 |
| QT5 | D | −250 | 38.3 | 38.3 |

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

### Table V

**Properties of Welded ½ in. Plate, Notched as Indicated. Base Plate as Normalized at 1600 F. Welds Made with E8016-C2 Electrodes.**

| Condition | Notch Location | Keyhole Charpy Impact Values 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 |

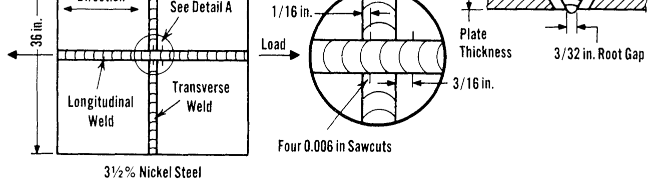


Fig. 12. Wells wide plate fracture toughness test specimens.

### Allowable Stress Values for 3½% Nickel Steel Components

The ASME Boiler and Pressure Vessel Code, Section VIII, Table UCS-23, lists the following allowable stresses for 3½% nickel steel plate:

| Temperature, F | Maximum Allowable Stress, psi SA203D | SA203E |
|---|---|---|
| −20 to +650 | 16200* | 17500* |
| 700 | 15500 | 16600 |
| 750 | 13800 | 14700 |
| 800 | 11400 | 12000 |
| 850 | 8900 | 9200 |
| 900 | 6500 | 6500 |
| 950 | 4500 | 4500 |
| 1000 | 2500 | 2500 |

Values for Pipe and Tubes are:
−20 to +650 F—16200*

Values for Castings are:
−20 to +650 F—16200*

Values for Forged or Rolled Flanges, Fittings and Valves are:
−20 to +650 F—17500*

### Effect of Cold Working

Cold working has the effect of raising the NDT temperature of the 3½% nickel steels. Usually this plastic deformation is performed by cold bending pressure vessel heads, shells, etc., and does not exceed 5% total reduction. This raises the transition temperature slightly but stress relieving at 1100-1175 F will restore the original low temperature properties.

### Corrosion Resistance

Long-term atmospheric corrosion tests show attractive corrosion resistance for 3½% nickel steel generally matching low alloy high strength weathering steels (Figure 13).[10] Where protective coatings are used, the extended coating life generally realized with corrosion resistant steels can provide added benefits.

### Fatigue Properties

Room temperature polished rotating beam endurance limit: 49,000 psi.

Smooth bar endurance-tensile ratio: 0.61. These values were obtained from tests on normalized ½ in. thick commercial plate made to ASTM Specification A 203 Grade D.

*Value also applies for temperatures below −20 F.

### Welding

The 3½% nickel steels, which are classified by the ASME Code as P-9B and P-12A materials, have been welded with alloys of matching composition, with various austenitic stainless steels and with nickel base filler metals. Welding processes used include Shielded Metal Arc, Tungsten Inert Gas (TIG), Metal Inert Gas (MIG) and Submerged Arc.

Preheat and interpass temperatures of 200 F minimum are usually used depending on electrodes and welding process employed. Also post weld heat treatment is recommended for material thicker than ⅝ in. The ASME Code calls for post heating at 1100 F minimum and 1175 F maximum with holding times of one hour per inch of thickness as a minimum. Exception to the thickness requirements is when welded structures will contain lethal sub-

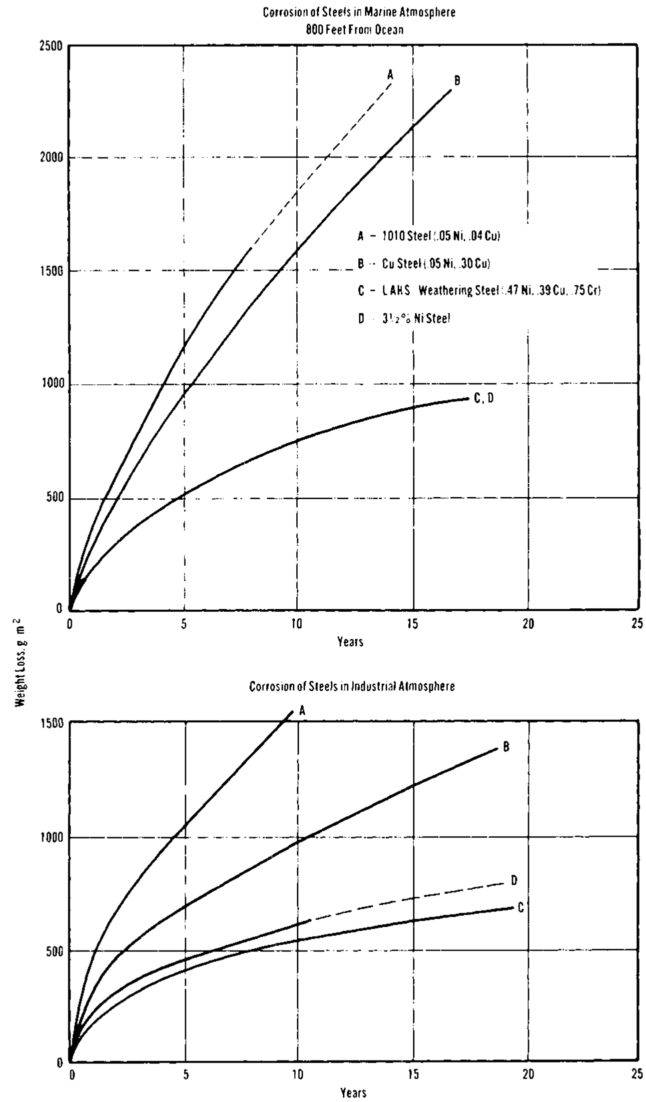


Fig. 13. Atmospheric corrosion of carbon and low alloy steels.

stance, either liquid or gaseous (see ASME Code, Section VIII, paragraph UW-2). In this case, post weld heat treatment is mandatory for ***all*** butt welded joints.

### *A 203 Plate Welding*

The following electrodes can be used after water quenching the plate from about 1600 F and tempering at 1100 to 1175 F (this treatment will produce a proeutectoid ferrite and fine pearlite structure which is readily welded):

| Welding Process | Filler Metal |
|---|---|
| SMA | 68 Ni-15 Cr-3 Ti-9 Fe |
| Sub-Arc | 65 Ni-27 Mo wire and neutral flux |
| TIG and MIG | 70 Ni-15 Cr-9 Fe wire with Helium-Argon Gas |

Normalized A 203 plate is welded with filler metals mentioned above for quenched and tempered plate. These plates in the normalized condition can also be welded with matching composition electrodes (AWS A5.5 E8015-C2, E8016-C2 and E8018-C2) and austenitic stainless steel filler metals.

Nickel base filler metal is preferred by many fabricators because of the excellent impact values and low temperature fracture properties exhibited by the weld metal. Some of the filler metals that are used not mentioned previously are:

AWS A5.14 Class ERNiCrMo-5
(HASTELLOY* alloy W)
AWS A5.14 Class ERNiCr-3
(INCONEL† Filler Metal 82)
AWS A5.14 Class ERNiCrFe-6
(INCONEL Filler Metal 92)
AWS A5.11 Class ENiCrFe-3
(INCONEL Welding Electrode 182)
AWS A5.11 Class ENiCrFe-2
(INCO-WELD† A Electrode)

### *Pipe and Tube Welding*

Favorite electrodes for both shop and field welding of 3½% nickel steel pipe and tube are the austenitic stainless steels (AWS A5.4 E308-16 and ER308). These filler metals will meet the mechanical property requirements of ASTM A 333 and A 334 Grade 3, which include a minimum tensile strength of 65,000 psi and a minimum notched bar impact value of 15 ft-lb at –150 F (10 mm by 10 mm specimen). Where service conditions and specifications permit, backing rings can be used to reduce the time and welder skill needed to make the root pass. The root pass is made without a backing ring when internal obstructions are not allowed. Care must be used to insure full root penetration.

Automatic submerged-arc welding can be used for all passes except the root pass. It is not suitable for the root pass because drop-through would occur if no backing ring were used, or the welding flux could be trapped between the backing ring and the pipe which could cause incomplete fusion and other defects. The root pass is made by shielded metal-arc welding with ⅛ in. diameter E308-16 electrodes. Although no preheat is used, interpass temperature is held in the range of 150 to 350 F to avoid overheating and subsequent cracking.

Details of both the manual root pass welding and the automatic submerged arc welding are given in Figure 14.[11]

### *Welding Forgings, Fittings, Flanges, Valves*

These are welded similar to pipe and tube with any of the electrodes (i.e. nickel base, austenitic stainless steel, or matching composition) used.

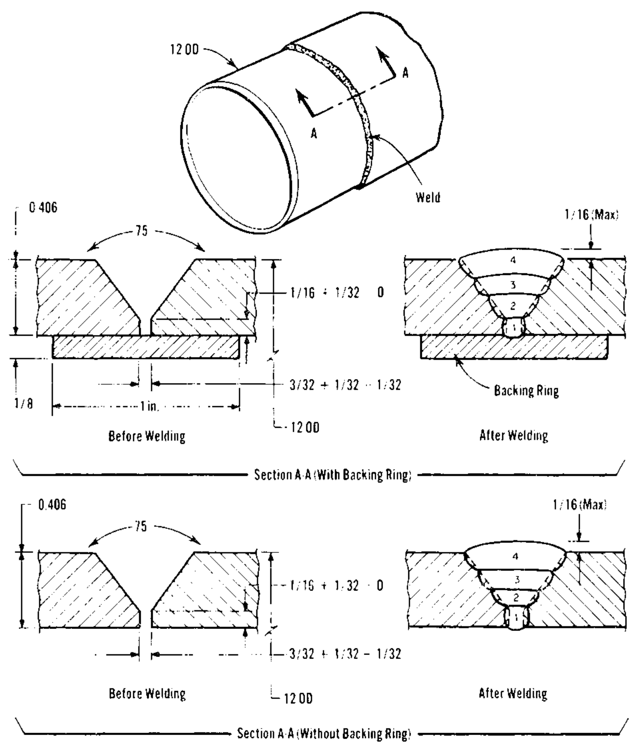


Fig. 14. Circumferential welding of .406 in. thick 3½ per cent nickel steel pipe for low temperature service, showing joint designs for welding with and without backing ring.

*Registered trademark of Cabot Corporation.
†Registered trademark of The International Nickel Company, Inc.

### *Welding Castings*

When it is necessary to repair weld castings, the nickel base electrodes are preferred using the same procedures mentioned for welding 3½% nickel steel plate.

## Physical Properties

### *Physical Constants*

Modulus of Elasticity (68 F), psi . . . . . . . $30 \times 10^6$
Modulus of Elasticity (–148 F), psi . . . . . $31 \times 10^6$
Density, lb/cu in. . . . . . . . . . . . . . . . . . . . 0.284
g/cu cm . . . . . . . . . . . . . . . . . . . . 7.85

## Thermal Properties

### *Thermal Expansion:*

| Temperature, F | Mean Coefficient of Thermal Expansion per °F |
|---|---|
| 0 to +200 | $6.15 \times 10^{-6}$ |
| 0 to –150 | 5.5 |

### *Thermal Conductivity:*

| Temperature, F | Btu/ft²/in./hr/°F |
|---|---|
| –150 | 214 |
| +68 | 253 |
| +200 | 270 |
| +212 | 290 |

### *Specific Heat:*

| Temperature, F | Mean Specific Heat Btu/lb/°F |
|---|---|
| –150 to +80 | 0.0798 |
| +80 to +1000 | 0.147 |

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