

## Plate

### 9% Nickel Steel: For use at cryogenic temperatures

#### Introduction

Iron, carbon steel and most ferritic alloy steels undergo a change from ductile to brittle behavior through a temperature range which varies with chemistry, heat treatment and thickness. This natural characteristic of most ferritic materials prevents their use for pressure vessels below approximately  $-150^{\circ}\text{F}$  ( $-101^{\circ}\text{C}$ ). However, more than 50 years ago, the International Nickel Company laboratories found that a low-carbon 9% Nickel alloy steel, when appropriately heat treated, retained notch ductility at temperatures to  $-320^{\circ}\text{F}$  ( $-196^{\circ}\text{C}$ ) and below.

9% Nickel steel has been recognized by the ASME Code for cryogenic use since 1954 and has been widely used for storage of oxygen, nitrogen and other liquefied gases in competition with stainless steel, other austenitic alloys and aluminum.

#### Chemical Composition

Element (%)	A353 and A553 Type 1
Carbon (max.)	.13
Manganese (max.)	.90
Phosphorus (max.)	.015
Sulfur (max.)	.015
Silicon	.15/.40
Nickel	8.50/9.50

#### Specifications and Codes

Material specifications for ArcelorMittal USA 9% Nickel plate (UNS K81340) intended for cryogenic pressure vessels are ASTM A353 (double normalized); ASTM A553 Type I (quenched and tempered); ASME Section II, Part A, SA353 and SA553; and API Standard 620 Appendix Q, A353 and A553.

Rules for design, fabrication and testing of pressure vessels are given by the ASME Code Section VIII, Divisions 1 and 2 (including applicable Code Cases 2214, 2335 and 2345), Section III Class 3 Components, and API Standard 620 Appendix Q.



#### Heat Treatment

ArcelorMittal USA 9% Nickel steel is heat treated either by double normalizing and tempering (NNT) or quenching and tempering (Q&T). The tempering is conducted within a restricted range, that results in the formation of a small amount (5-15%) of metallurgically stable retained austenite, which is very important in developing the superior cryogenic toughness of the steels.

#### Heat Treatments for 9% Nickel Steel

Double normalized and tempered (A353)	1650°F + 1450°F + (1050-1125°F) 899°C + 788°C + (566 - 607°C)
Quenched and tempered (A553)	1475°F + (1050 - 1125°F) 802°C + (566 - 607°C)

#### Size Availability

ArcelorMittal USA provides a wide range of plate sizes for 9% Nickel plate steel. Thicknesses from .1875 to 2 in. (4.8 to 51 mm), widths to 132 in. (3.4 m), and lengths to 540 in. (13.7 m) are available depending on grade and property requirements. Consult ArcelorMittal USA for sizes outside these ranges, in particular widths to 186 in. (4.7 m).

## Mechanical Properties

### Tensile Properties (ASTM, ASME, API Requirement)

	Tensile Strength ksi [MPa]	Yield Strength ksi [MPa], min.	Elongation in 2" [50mm](%)
(S)A353/ (S)A353M	100 – 120 [690 – 825]	75 [515]	20
(S)A553/ (S)A553M Type I	100 – 120 [690 – 825]	85[585]	20

### Recommended Radius for Cold Bending (A20/A20M)

Thickness of Material	Ratio of Bend Diameter To Thickness of Specimen
1 in. [25 mm] and under	1.5
Over 1 in. [25 mm] to 2 in. [50 mm] incl.	2-1/2
Over 2 in. [50 mm]	3

### Mandatory Impact Properties – Charpy V-Notch ASTM\*, ASME\* and API Requirement – Lateral Expansion

0.015 in. [0.381 mm] at -320°F(-196°C)	Transverse orientation (axis of notch parallel to major rolling direction)
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\* The Charpy V-Notch energy absorption values, as well as fracture appearance in percentage shear, are required to be recorded by ASME Code, Section VIII, Division 1 and Division 2, and Section III.

### API Requirement – Charpy V-Notch Impact Values<sup>3</sup>

Size of Specimen (mm)	Transverse Value Required <sup>1</sup> (Minimum Single Value) <sup>2</sup> ft-lb [J]	Longitudinal Value Required <sup>1</sup> (Minimum Single Value) <sup>2</sup> ft-lb [J]
10 x 10	20 (16) [27(22)]	25 (20) [34(27)]
10 x 5.0	10 (8) [14(11)]	13 (10) [17(14)]

<sup>1</sup> Average of three specimens

<sup>2</sup> Only one specimen of a set

<sup>3</sup> Subsize specimens use ratio of size

### ASTM Added Supplementary Requirements & ASME Supplementary Requirements

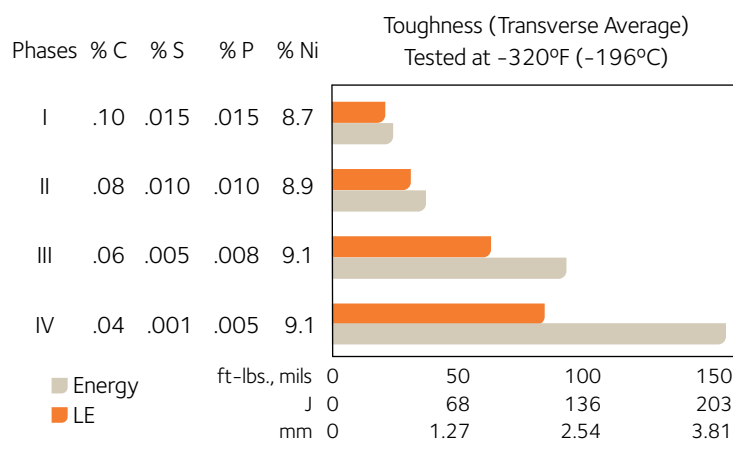
Charpy V-Notch Energy Absorption Requirement at  
-320°F(-196°C) (A353, SA353, A553, SA553)

Orientation	Impact Value Required (Average of 3 Specimens)	Minimum Impact Value Required (One Specimen Only)
Longitudinal	25 ft-lbs. [34 J]	20 ft-lbs. [27 J]
Transverse	20 ft-lbs. [27 J]	15 ft-lbs. [20 J]

## Selected Property Information

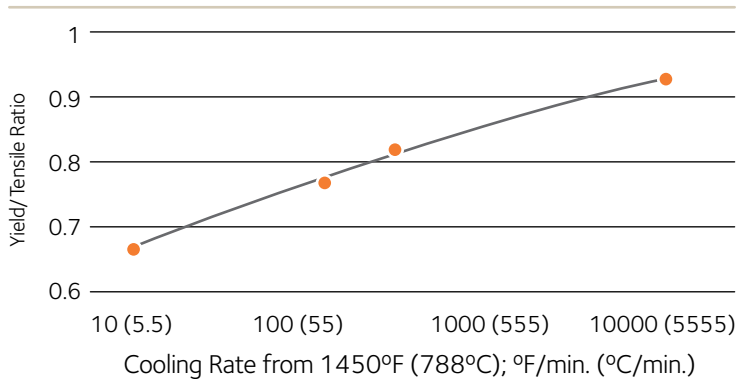
Over the years, the properties of 9% nickel steels have evolved as a function of the technology in melting and refining used to produce them. The improvements enabled designers to raise minimum material requirements to take advantage of the increased properties, and in particular toughness, to enhance their specifications. Today, while many of the standard requirements remain the same, many worldwide specifications are requiring improved Charpy-V notch performance, such as 75 ft-lbs (100J) at minus 320°F(-196°C), a level that heretofore would not have been achievable. These enhanced requirements can be achieved with clean steel technological advances, as illustrated below. The benefit of lower carbon, sulfur, phosphorus and higher nickel levels is shown with the improvement in toughness. ArcelorMittal USA 9% nickel steel can be ordered with 0.002% S and 0.005% P maximums when required.

### 9% Nickel Steel Process Improvements

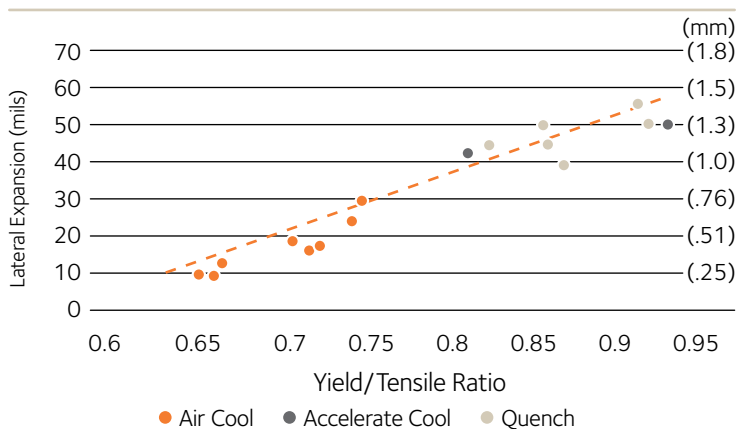


Other factors contribute to the improved toughness of 9% nickel steels. Traditionally, toughness improves with quenched and tempered material over that produced in the normalized condition. Cooling rate plays a major role in determining Charpy toughness for 9% nickel steels. Experimental work has shown that lateral expansion and the ratio of yield to tensile for A353 and A553 are directly correlated, and the higher the yield to tensile ratio, the more lateral expansion is expected. This is shown in the figures below. Consideration must be given then to choosing A353, a NNT product with generally lower Y/T, or A553, a Q&T product with higher Y/T and considerably higher Charpy and lateral expansion values. The cooling rate has a major affect on the resultant yield to tensile ratio, as illustrated below in ArcelorMittal USA laboratory studies. This information may be important when considering heat treatments other than as provided from the steel mill.

## Yield/Tensile Ratio as a Function of Cooling Rate



## Variance of Lateral Expansion with Yield/Tensile Ratio



## Design and Engineering Data

### Maximum Allowable Stress Value – Welded (-20 to 100°F)[-29 to 38°C]

	Section VIII Division 1 <sup>1</sup>	Section VIII Division 2	Section III Class 3	API 620
(S)A353/A553	28.6 ksi (197 MPa) 27.1 psi (187 MPa) *	33.3 ksi (230 MPa) 31.7 ksi (219 MPa)*	28.6 ksi (197 MPa)	Based on weld metal strength

<sup>1</sup> Section VIII Division 1 provides for the use of higher allowable stresses in tension at low temperatures. Consult Table ULT-23 for specifics.

\* Welded, with the tensile strength of the Section IX reduced tension test less than 100 ksi (690 MPa), but not less than 95 ksi (655 MPa)

## Physical Properties

### Modulus of Elasticity

At 70°F (21°C)	27 x 10 <sup>6</sup> psi (185,000 MPa)
At -320°F (-196°C)	30 x 10 <sup>6</sup> psi (209,000 MPa)

### Mean Coefficient of Expansion

-320 to 70°F (-196 to 21°C)	4.9 x 10 <sup>-6</sup> in./in./°F (8.8 x 10 <sup>-6</sup> K <sup>-1</sup> )
-200 to 70°F (-129 to 21°C)	5.5 x 10 <sup>-6</sup> in./in./°F (9.9 x 10 <sup>-6</sup> K <sup>-1</sup> )
-100 to 70°F (-73 to 21°C)	5.9 x 10 <sup>-6</sup> in./in./°F (10.6 x 10 <sup>-6</sup> K <sup>-1</sup> )
-100 to 200°F (-73 to 200°C)	6.2 x 10 <sup>-6</sup> in./in./°F (11.2 x 10 <sup>-6</sup> K <sup>-1</sup> )

## Thermal Conductivity

Temp. °F(°C)	Thermal Conductivity Btu in./hr ft <sup>2</sup> °F [W/(m K)]
-320(-196)	91[13.1]
-296(-176)	112[16.1]
-275(-170)	120[17.3]
-243(-153)	134[19.3]
-189(-122)	149[21.0]
-99(-72)	172[24.8]
-9(-22)	190[27.4]
81(27)	203[29.2]
261(128)	226[32.5]
441(228)	236[34.0]
621(328)	238[34.3]
801(428)	232[33.4]
981(528)	224[32.3]

## Fabrication

For general fabrication information refer to [“Guidelines for Fabricating and Processing Plate Steel”](#).

### Cutting

ArcelorMittal USA 9% Nickel is flamecut very much like mild steel, employing only minor adjustments of fuel and oxygen. The steel is characterized by having an adherent scale. This should be popped off prior to setting the cut in order to avoid clogging the tip. Pre-heating for cutting is generally unnecessary.

Because of its high strength and toughness, the thickness, which can be sheared by a given machine, will be approximately 2/3 of that of mild steel. Rake angles higher than those of mild steel are advantageous.

## Forming

In most circumstances, it is desirable to cold form rather than hot form this steel, whether double normalized and tempered or quenched and tempered. It should be noted that 9% Nickel steel has a high yield strength and requires approximately three times the forming capacity of mild steel.

It is advisable to round-off corners in tension and smooth, rough cut edges.

The following bending limits are suggested:

### Die Span: 12 x Thickness

Plate Thickness	Min. Radius
To 3/4 in. [19 mm]	4 x thickness
Over 3/4 in. to 1-1/4 in. [31 mm]	5 x thickness
Over 1-1/4 in. [31 mm] to 2 in. [50 mm]	6 x thickness

For roll forming: minimum inside diameter = 30 x thickness

The ASME Code requires post heat treatment where outer fiber elongation in cold forming exceeds 5% by the formula:

$$\% E = \frac{(70 \times t)}{R_f} \times (1 - R_f/R_o)$$

% E – percent extreme fiber elongation

t – plate thickness

R<sub>f</sub> – final radius

R<sub>o</sub> – original radius (equals infinity for flat plate)

In addition, cold forming of 9% Nickel steel may cause the transformation of retained austenite into untempered martensite due to cold work. This may have a deleterious effect on toughness, but may be partially restored by an intercritical post heat treatment. Fabricators are urged to determine the effect of forming practices on final material properties.

The post heat treatment, where necessary, is conducted in accordance with the rules of Section VIII Division 1 UHT-56 within the range of 1025-1085°F(551-583°C), but not exceeding the tempering temperature, holding at temperature for one hour per inch of thickness, followed by cooling at a rate no less than 300°F(167°C) per hour. Slower cooling rates may reduce the notch toughness of the steel.

In some cases, it may be desirable to form hot. The formed part must be either completely reheat treated or in the case of the double normalized and tempered specification, A353, the forming operation may be conducted at 1650 - 1750°F(899-954°C) and treated as the first normalizing operation. The ASME Code requires that tests be made by the fabricator to verify the heat treatment. It is suggested that hot forming be limited to non-welded plate, unless it is first demonstrated that the weld metal is capable of meeting required mechanical properties after being heat treated.

## Welding

Welding Qualification 9% Nickel steel welding procedures are qualified under Section IX of the ASME Code. For qualification purposes, the double normalized (A353) and quenched grades (A553) are P-No. P11A Group 1. Additional tension tests at or below the vessel minimum allowable temperature are required for Section VIII Div 1 ULT applications.

Section VIII, Divisions 1 and 2, Section III and API Standard 620 Appendix Q specify that the weld metal and heat affected zone of procedure qualification tests shall meet the Charpy V-Notch requirements for the plate. Production impact testing may be exempt for welding under certain conditions in Section VIII, and for API 620 Appendix Q after the initial tank construction.

**Energy Input** As with other low temperature steels, the welding energy input for ArcelorMittal USA 9% Nickel steel must be controlled to preserve notch toughness in the heat affected zone.

Generally, the steel is welded at low energy inputs – even sub-merged-arc welds with Inconel are best made with 1/16 in. (1.6mm) wire. However, caution is advised for plate under about 0.5 in.(13mm) both because light plate chills the weld less rapidly and because transverse plate Charpy values tend to be lower initially for thin plate.

Data from laboratory tests suggest the following guide for preparing the qualification test plate.

Approximate Thickness	Kilojoules/in.(KJ/mm), max.
9/16 in. [14 mm] and under	35(1.4)
Over 9/16 in. [14 mm] to 3/4 in. [19 mm]	40(1.6)
3/4 in. [19 mm] and over	50(2.0)

Note: 9% Nickel is seldom welded at over 50 KJ/in.(2.0 KJ/mm) in any thickness.

**Preheat** Joints in ArcelorMittal USA 9% Nickel steel made with austenitic weld metals are relatively immune to cold cracking difficulties. Nevertheless, it is suggested that plate over 1 in.(25mm) in thickness be preheated to about 100°F(35°C) and that lighter plate not be welded below the dew point. Section VIII Code Case 2214 provides additional information on preheat requirements in special situations.

**Special Precautions** Because of its high nickel content, 9% Nickel steel is susceptible to the retention of magnetism of enough intensity and permanence to affect arc welding. Care should be taken in exposing the plate to lifting magnets or to strong direct current fields after the austenitizing heat treatments. ArcelorMittal USA 9% Nickel steels are handled without magnets in the finishing operations. As an added insurance, when requested, ArcelorMittal USA can furnish its plates demagnetized to a maximum residual level of 50 gauss as measured on the plate edges.

Once induced, magnetism may be reduced or removed by wrapping or sweeping with alternating current cables or electromagnets. For heavy plate, it may be necessary to use special demagnetizing equipment that utilize decreasing and reversing currents strong enough to realign any magnetic domain fields to neutral. In extreme cases, residual magnetism can be removed by reheat treating.

Shielded Metallic Arc Welding with alternating current and interrupted-arc MIG welding are less affected by magnetism than other processes. Isolated magnetic poles at the seam may be temporarily neutralized by strong permanent magnets. Care should be taken, particularly in MIG welding, that magnetic shop dirt adhering to weld chamfers does not lead to weld porosity.

In submerged-arc welding of ArcelorMittal USA 9% Nickel steel, particularly of thick plate and restrained joints, it is desirable to use low energy inputs to avoid the possibility of hot cracking of weld beads, particularly the initial ones in the groove. With both the submerged-arc and MIG processes used at high energy inputs, the fabricator should be careful to establish by procedure tests that the desired weld strength (usually 95 ksi (655 MPa)) can be attained.

**Post Weld Heat Treatment** Except as provided by the fabrication requirements of ULT-79, the ASME Code requires no post weld heat treatment for 9% Nickel up to 2 in. (51 mm) inclusive in thickness. See AF630.1 (Division 2) and UHT56 (Division 1). Where post weld heat treatment is performed, it is necessary to control the temperature within the range of 1025-1085°F (551-583°C) but not over the tempering temperature and to cool at a rate not less than 300°F (167°C) per hour to avoid possible reduction in notch toughness of the steel.

### Further Information

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Continuing updates of this information can be found on our website at: <http://usa.arcelormittal.com>

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