ArcelorMittal USA

ArcelorMittal

Plate

A516 and A387 Pressure Vessel Steels: A Technical Overview

Introduction

ArcelorMittal is the major producer of carbon, alloy and roll-bonded clad plate for the petroleum, petrochemical and chemical processing industries in the United States. We operate four facilities in Pennsylvania and Indiana for the production of plate.

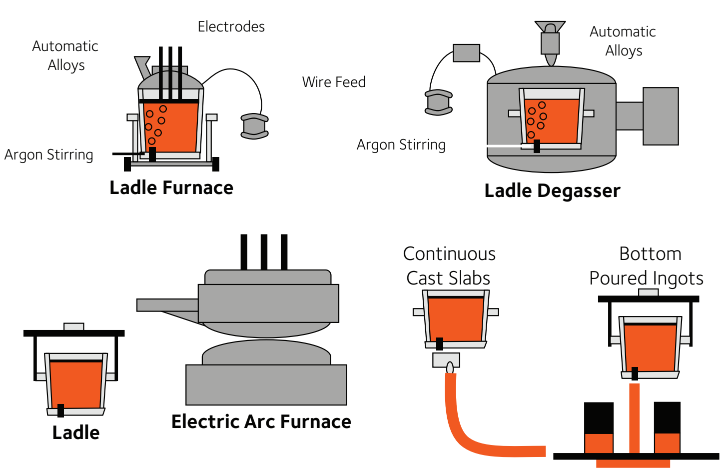
Many of the more than 450 grades of carbon and alloy plate steels produced by ArcelorMittal are pressure vessel quality (PVQ) grades used in the design and fabrication of process vessels. In addition, we offer the thinnest, thickest, widest and heaviest plates available in North America. For a comprehensive list of PVQ grades and availability, refer to our Plate Steel Specification Guide.

Two pressure vessel plate steel specifications comprise, by far, the most popular process vessel applications. Based on ArcelorMittal's experience, ASME SA516 (ASTM A516) carbon steel and ASME SA387 (ASTM A387) alloy steel are detailed technically in this brochure.

Production Practices

ArcelorMittal's PVQ steels are manufactured to stringent metallurgical practices in steelmaking shops located in Burns Harbor, IN and Coatesville, PA. Plate products manufactured at our Coatesville electric arc furnace (EAF) facility (Figure 1) provide the basis for all the information described in this brochure.

Figure 1
Coatesville Steelmaking Process Plan



- PVQ steels at ArcelorMittal that are melted in an electric arc furnace meet specification requirements using scrap that is among the most carefully selected in the world.
- The molten steel is then refined in a ladle metallurgy station that includes a ladle furnace (LRF). A tank degasser is available for additional removal of undesirable gases when required.
  - High levels of cleanliness are available. When specified, 0.002% maximum sulfur, 0.005% maximum phosphorus and 0.002% maximum oxygen can be achieved for certain grades. The lowest sulfur levels are achieved through Finleline® processing that includes calcium treatment for inclusion shape control.
  - Improved accuracy and precise control of chemical composition is achieved, making it possible to offer the stringent carbon equivalent (CE) maximums required by our customers.
  - Microalloying elements (B, Ti, Cb, V) are not intentionally added to PVQ steels, unless required by customer specification. This practice addresses industry concerns about the unpredictable response of hard heat affected zones containing these elements during welding and subsequent post weld heat treatment (PWHT) of fabricated process vessels. However, when specifically approved by our customer, microalloying additions may be considered to achieve special properties.
- PVQ steels are bottom-poured into ingots or continuously cast into slabs, depending on plate size and weight. Based on final product dimensions, our PVQ steels are rolled on our, 110, 140, 160 or 206-inch wide rolling mills.
- Depending on specification requirements, PVQ steel can be heat treated in car-bottom or continuous furnaces. If the steel is intended for hot forming applications, ArcelorMittal will perform a capability test on laboratory heat treated samples from the as-rolled plates in accordance with the provisions of A20.

A516 Carbon Steels

ArcelorMittal produces the full range of A516 plate steels in grades 55, 60, 65, and 70. Plate thicknesses to 18 inches, widths to 195 inches, lengths to 1525 inches and pattern weights up to 50 tons can be produced, depending on a combination of specification and size requirements. Our advanced facilities make possible the production of A516 to a variety of customer and industry specifications, including rigorous hydrogen- induced cracking (HIC) testing requirements.

There are no heat lot ordering requirements for any of the quality levels of A516 produced by ArcelorMittal.

Carbon Equivalent Controls

Due to the concern for weldability, ArcelorMittal produces A516 steels to restricted carbon and CE levels when requested. The carbon equivalent maximums we can offer will vary by grade, thickness and post-weld heat treatment requirements.

As shown by the data in Figure 2, carbon and other elements that comprise the most commonly used CE formula [C + Mn/6 + (Cu+Ni)/15 + (Cr+Mo+V)/5} are important for providing strength. Tensile strength rises linearly as CE increases, generally at the rate of 1,000 psi per 0.01 increase in CE. Thus, while it may be important to restrict CE, certain amounts of carbon, manganese and other elements need to be present in order to achieve minimum mechanical properties. This is especially true for Grade 70 as thickness increases. Figure 3 shows the CE levels that can be achieved for the various grades of A516, while still maintaining the required strength levels as a function of plate thickness.

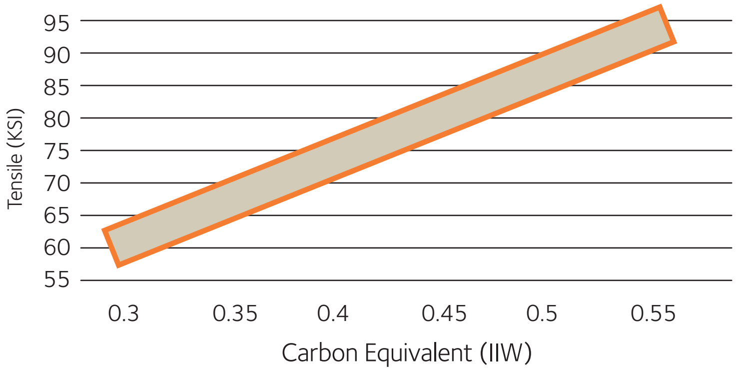
Employing special melting practices can control both carbon and CE. Improvements can be achieved with special melting for individual situations depending on thickness, other unique chemical restrictions (such as Pcm), toughness requirements or PWHT considerations. Furthermore, if even more aggressive requirements are desired, quench and temper (Q&T) heat treatment will allow even lower carbon and CE levels. Quenching and tempering also improves toughness and resistance to degradation of properties due to post-weld heat treatment (PWHT).

The improvement in CVN toughness realized by Q&T is illustrated in Figure 4.

Figure 2

Tensile Strength of Normalized A516

The Effect of Carbon Equivalent



80% of all results for plates 1.5” to 3” thick fall within shaded area.

Figure 3

Available CE Maximums for Normalized A516

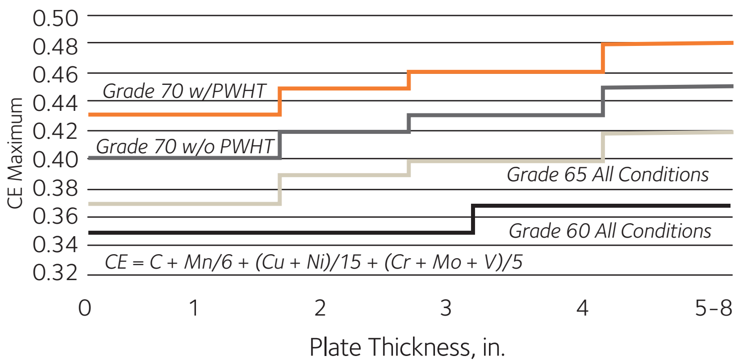
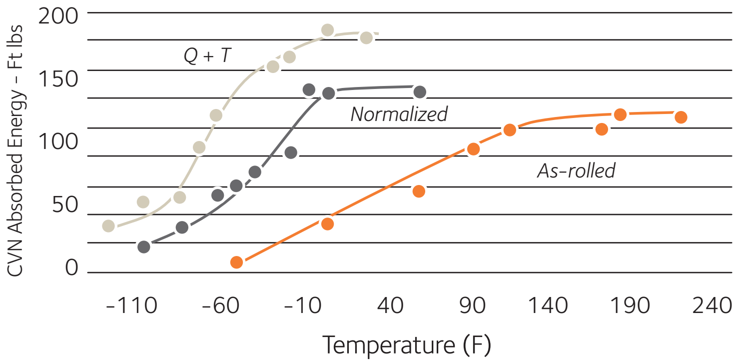


Figure 4

Effect of Heat Treatment on Transverse CVN Toughness of A516



Post-Weld Heat Treatment (PWHT)

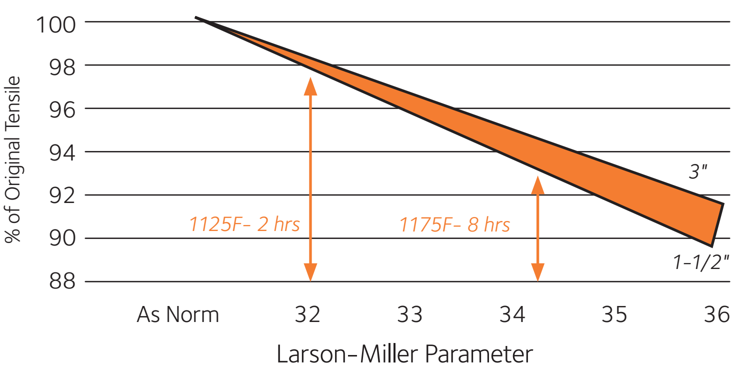
In general, a PWHT cycle of 1150 degrees F for eight hours will create the need for nearly four additional points of CE to achieve the same strength as in a plate of the same thickness without PWHT. This is shown by the matrix found in Figure 5 which is based on the accumulation of thousands of data points as well as the result of specific heat treat studies by ArcelorMittal. The effect of PWHT on lowering strength levels is shown in Figure 6.* In this example, the reduction of tensile properties is shown as a percentage of the starting as-normalized tensile strength. As a result, and given the predictable relationship between CE, thickness and strength for normalized plate typified in Figure 2, an approximation of the effects of PWHT can easily be derived.

Figures 7-9 further summarize the results of testing on 1-1/2 and 3 inch thick A516 Grade 70 plate and show the degradation of toughness as PWHT severity increases. Figure 7 depicts the actual absorbed energy values but a more dramatic representation of the data is illustrated in Figure 8. In this example, toughness at –50ºF is shown to drop by as much as 75 percent from the as-normalized condition when subjected to a PWHT cycle of 1175ºF for 8 hours. Figure 9 displays the effects when measured by the 35 ft-lb transition temperature and shows a shift of over 60ºF from the same PWHT cycle.

Figure 5
Guidelines for Adjusting CE Requirements Due to the Effects of PWHT

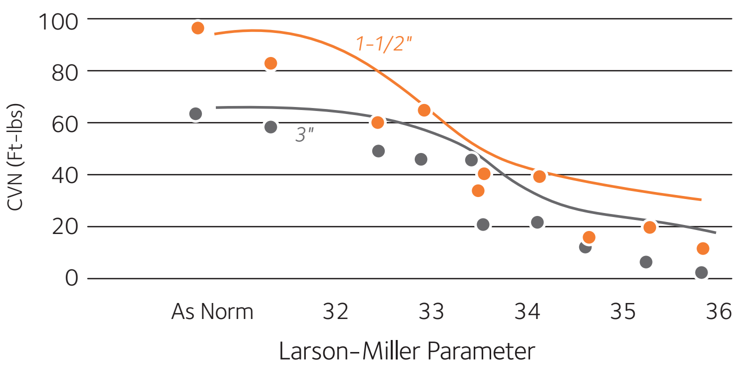
TEMP	Hours of PWHT							
(F)	1	2	3	4	5	6	7	8
1125	0.010	0.013	0.016	0.019	0.02	0.025	0.028	0.030
1150	0.018	0.021	0.024	0.027	0.030	0.033	0.036	0.038
1175	0.026	0.029	0.032	0.035	0.038	0.041	0.044	0.046
1200	0.034	0.037	0.040	0.043	0.041	0.049	0.052	0.054
1225	0.042	0.045	0.048	0.051	0.049	0.057	0.060	0.062
1250	0.050	0.053	0.056	0.059	0.065	0.065	0.068	0.070

Figure 6
The Effects of PWHT on Tensile Properties*
As a % of Original Strength



** ArcelorMittal uses the Larson-Miller time-temperature parameter to assist in identifying the effects of PWHT on properties.*

Figure 7
The Effects of PWHT on Impact Properties*
LMP vs. CVN Energy @ -50ºF



We will consider multiple certification of A516 to Grades 60, 65 and 70 on normalized plates from 3/8 to 3-inches thick. The necessary chemistry controls can be achieved in our ladle metallurgy facilities.

Figure 8
The Effects of PWHT on Impact Properties
LMP vs. % of Original Energy @ -50ºF

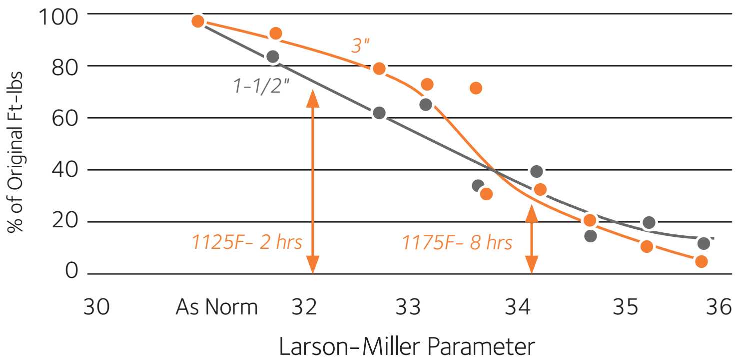
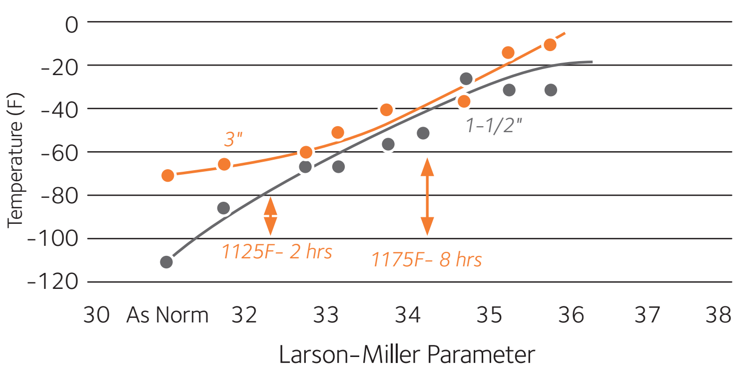


Figure 9
The Effects of PWHT on Impact Properties
LMP vs. 35 Ft-lb Transition Temperature



Results of 1-1/2" and 3" plates

A516 Steels for Sour Service Applications

Pressure vessel steels, and more commonly A516, for use in refinery environments that are subject to certain operating conditions can be susceptible to hydrogen-assisted cracking. This cracking can come in the form of blistering on the surface, step-wise cracking through the thickness (HIC), or sulfide stress cracking (SSC). More recently there has been attention to a phenomenon termed stress-oriented hydrogen-induced cracking (SOHIC). Blistering and HIC cracking can occur without the presence of external stresses, while SSC and SOHIC require the combination of hydrogen activity in the presence of external stress.

As shown schematically in Figure 10, hydrogen ions generated by the reaction of steel with a sour process environment (wet H_2S) attempt to pass through the steel shell containment boundary. If there is an absence of inclusions in the steel, this is done harmlessly while creating an iron-sulfide scale at the reaction interface. However, if inclusions are present, the ions nucleate at these "voids" and form hydrogen gas pockets, appearing as blisters on the steel's surface. High internal pressure can eventually cause the inclusions to be initiation sites for further "hydrogen -induced", or stepwise cracking (HIC) in the steel.

The facility at the Coatesville plant for ArcelorMittal has produced HIC-Tested A516 plate steels since 1990 for use in a variety of process vessels where there is a concern for HIC in aqueous hydrogen sulfide service or other hydrogen charging environments.

To meet HIC testing requirements, it is imperative to have very clean steels with low inclusion contents. All HIC-Tested A516 steels are produced to our exclusive Fineline® process, which reduces sulfur levels to 0.002% or less and employs calcium treatment for inclusion shape control. Maximum levels of phosphorus and oxygen may also be accepted.

Besides cleanliness, we have found heat treating to be very important in attaining satisfactory results with HIC tests. ArcelorMittal will not perform HIC tests on unheat-treated products. Both normalizing and Q&T heat treatments are available and help meet other properties as well.

The use of HIC-Tested steels is one approach used in dealing with potential sour service applications. Other approaches, depending on the anticipated severity of the sour environment include the use of stainless or stainless clad steels. Where less severe conditions are expected, use of simply lower sulfur steels with restrictive CE and prohibitions against the use of microalloys may suffice. A more detailed review of this subject is contained in NACE Publication 8X194, *Materials and Fabrication Practices for New Pressure Vessels Used in Wet H_2S Refinery Service.*

ArcelorMittal's HIC-Tested A516 can be produced in plate thicknesses from 3/8 through 6 inches and plate weights to 55,000 pounds. Other thicknesses and weights will be considered on an individual basis. HIC testing of these steels is performed as outlined in ArcelorMittal's HIC-01 series of specifications found in Figure 11.

- HIC testing is performed according to NACE TM0284.
- Figure 12 depicts the orientation and size of three test specimens to be cut from one plate of each thickness rolled from each heat of steel. The formulae used to determine various HIC test parameters are also shown.
- Note that requirements are based on average values of all specimens. ArcelorMittal recognizes that there are increasingly more corporate specifications requiring individual specimen or crosssection maximums. To accommodate these more restrictive standards, we may impose additional quality extras or employ the use of Q&T heat treatment.
- The Testing Solution A of NACE TM0284 (the low pH solution, 2.75 ±0.1 pH) is the standard used for the test. Testing Solution B of TM0284 (high pH) is also available.
- Test reports for all HIC-Tested A516 steels include values for CLR, CTR, and CSR, and other information specified by the purchaser. Examples of CLR values obtained from testing HIC-Tested A516 are illustrated in Figure 13. ArcelorMittal's HICTested A516 steels are also available from select service centers nationwide.

Figure 10
Stepwise Cracking Mechanism

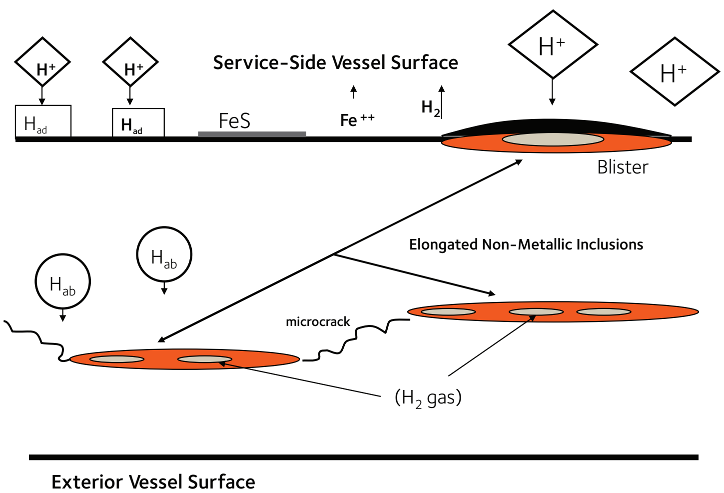


Figure 11
Available Sour Service-Testing Criteria

ArcelorMittal Specification	Test Method/ Solution	Test Criteria, Average of	CLR	% CTR	CSR
HIC-A-15	TM0284/A	Overall	15	5	5
HIC-B-15	TM0284/B	Overall	15	5	5
HIC-A-5	TM0284/A	Overall	5	1	0.375
HIC-A-15S	TM0284/A	Specimen	15	3	1
HIC-A-10S	TM0284/A	Specimen	10	2	0.5
HIC-A-15CS	TM0284/A	Cross-section	15	5	1
HIC-A-10CS	TM0284/A	Cross-section	10	2	1
SSC-A-01	ASTM G39	Visual, no cracks	na	na	na
SSC-A-02	TM0177 Method A	@ 70% SMYS	na	na	na

HIC-A-15 is the default testing scheme, additional quality extras apply for more restrictive requirements. SSC-01-A requires Q+T. Cross-sectional testing, depending on plate thickness, may also require Q&T.

Testing frequency is on a per melt/thickness basis for HIC tests and on heaviest thickness ordered for SSC tests unless otherwise specified by a customer's specification.

Figure 12
Determining Hydrogen Induced Cracking (HIC) Resistance NACE Specification TM-02-84

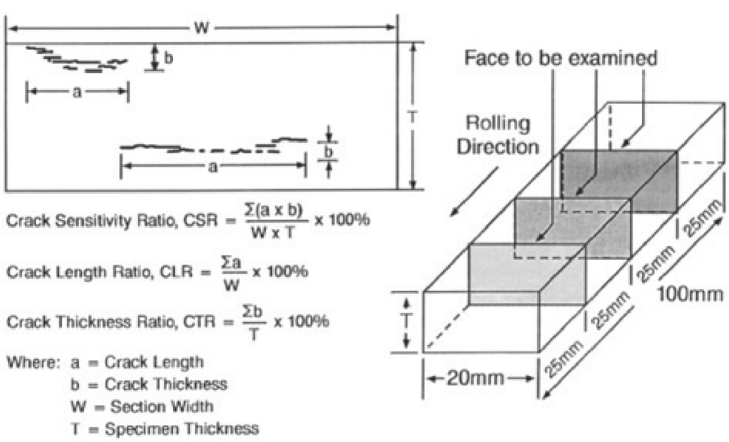
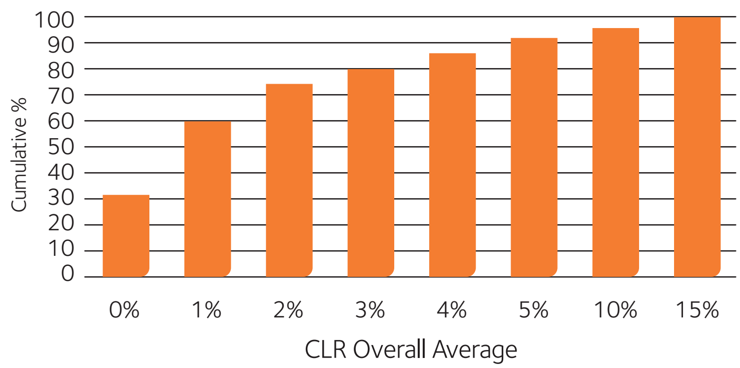


Figure 13
HIC-Test Performance (TM0284, Solution A) Cumulative Results Since 1995



Applicable NACE documents besides TM0284 *(Evaluation of Pipeline and Pressure Vessel Steels for Resistance to Hydrogen-Induced Cracking)* and 8X194 include ISO15156/MR0175 which is sometimes cited as a specification to be invoked when assurance from hydrogen-assisted cracking is required. However, this standard applies to oilfield equipment and for carbon steel, adds little or nothing in the way of special controls commonly associated with HIC-resistant steel. More appropriate for refining applications is NACE MR0103 *(Material Resistant to Sulfide Stress Cracking in Corrosive Petroleum Refining Equipment)*. However, even this by itself does not guarantee that steel meeting its general requirements is immune from environmental damage from sulfide stress cracking (SSC). To evaluate susceptibility for SSC, ASTM G39 *(Preparation and Use of Bent-Beam Stress-Corrosion Test Specimens)*, the four-point bent beam test, and NACE TM0177 Method A (NACE tensile test) are sometimes called out, though traditionally these are used to evaluate steels much higher in strength than A516.

Another perceived control for steels in sour service involves the application of ASTM E1268 *(Standard Practice for Assessing the Degree of Banding or Orientation of Microstructures)*. This is a metallographic procedure for determining what is loosely referenced as a "banding index" (AI), and has recently been associated with steels for sour service. ArcelorMittal will perform this test, when required, for information only. Figures 14 and 15 show representative microstructures of HIC-Tested A516 Grade 60 steel along with the anisotropy index and relative performance in HIC (Figure 16) and SSC tests.

Another recent test recognized more for its ability to screen classes of material more than for production testing is NACE TM0103 *(Laboratory Test Procedures for Evaluation of SOHIC Resistance of Plate Steels Used in Wet H_2S)*. ArcelorMittal does not accept requirements for this test method and offers TM0177 Method A in its place.

Figure 14
General Microstructure of "Clean" A516-60

- No HIC Cracking
- No SSC Failures
  - through 110% SMYS
  - 80.4% actual YS

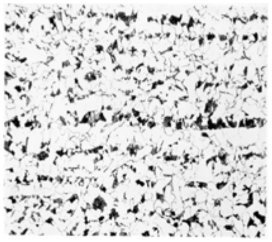
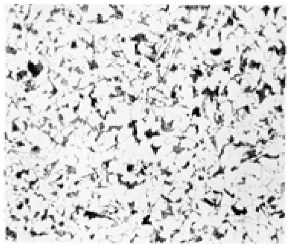
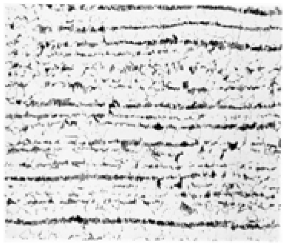


Figure 15
The Effect of Microstructural Banding on HIC and SSC Test Performance of A516-60



Anisotropy Index = 1.12
No HIC cracking
SSC OK at 80%, 90%, and 110%
Failed after 480 hr. at 100%



Anisotropy Index = 1.48
0.11% CLR
No SSC failures through 110%

Figure 16
HIC Test Results (TM0284 Solution A) - A516-60

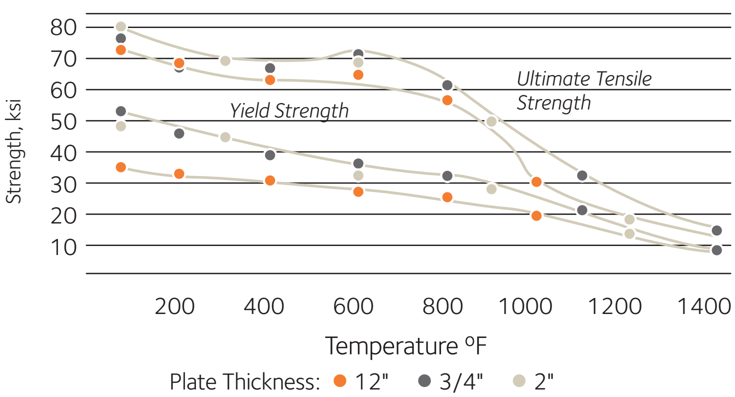
Melt	Thickness(in/mm)	CLR, %	CTR, %	CSR,%
D3861	1.62(41)	0	0	0
C3866	1.62(41)	0	0	0
C3818	1.75(44)	0	0	0
D3822	1.75(44)	0	0	0
D3826	1.12(30)	0	0	0
D3905	1.62(41)	0	0	0
D3818	1.62(41)	0	0	0
D3871	1.62(41)	0	0	0
D3826	1.18(29)	0.11	0.01	0.0001
D3826	1.31(33)	0.12	0.01	0.0001
D3894	1.62(41)	0.78	0.10	0.0029
D3822	1.62(41)	1.22	0.10	0.0029

Other Available Testing

A variety of additional property controls for A516 steels are available from ArcelorMittal . Some of these require more restrictive chemistry control and/or heat treatment.

- Ultrasonic internal quality requirements, such as ASTM A578/ ASME SA578 Level C may be specified. Depending on plate size, this specification requires a minimum of ArcelorMittal Fineline® with .010% max. sulfur processing, or if modified for 1/2-in. diameter, requires Fineline® with 0.002% max. sulfur. More restrictive requirements will be considered on request.
- The most aggressive CVN impact properties for A516 steels can be met using a variety of sulfur controls, chemistry adjustments and heat treatments. Please inquire your specific requirements.
- Through-thickness tensile properties may be specified per A770 for plates up to 6-inches thick, including reduction of area (RA) up to 50%, when purchased to Fineline® with 0.002% max. sulfur. 40% RA and 25% RA are available with Fineline® with 0.005% max. sulfur or Fineline® 0.010% max. sulfur, respectively. For plate thicknesses over 6 inches, please inquire.
- The weldability of A516 is primarily addressed through the control of carbon and carbon equivalent levels that may permit the use of lower preheat levels. A516 steels, whether HIC tested or otherwise, can be welded with conventional welding techniques.
- High temperature tensile properties are not usually specified for A516 steels. However, for reference purposes, Figure 17 shows test results for three plates of various thicknesses.

Figure 17
Elevated Temperature Tensile Strength of A516-70



A387 Alloy Steels

ArcelorMittal is the major supplier of A387 PVQ alloy steels in North America producing a full range of A387 grades, including Grades 11, 12, 22, 22L, 5, 9 and 91. Other less commonly specified grades such as 2, 21, 21L and 22L are also available if ordered in sufficient quantity, usually greater than 100 tons.

Grades 11, 12 and 22 are most commonly used in process vessels and are the primary focus of this review. All grades of A387 are melted at our Coatesville, PA location. Plates up to 12-inches thick, 186-inches wide and 600-inches long, with weights up to 100,000 pounds can be produced, depending on the combination of specification and size required.

Chemistry

In applications where improved toughness, temper embrittlement resistance, or concern over reheat-cracking in Grade 11 are needed, restricted levels of tramp elements considered impurities may be specified. These restrictions can normally be obtained by taking special care in scrap selection and subsequent treating of the molten steel at our ladle metallurgy facility. The following controlled impurity levels are available for fine grain A387 steels.

Heat Analysis, Guaranteed Maximum Levels (When Specified)*

	Grades 11 and 12	Grade 22
Antimony	0.0025%	0.0025%
Tin	0.010%	0.010%
Phosphorus	0.005%	0.008%
Sulfur	0.002%	0.005%
Arsenic	0.010%	0.010%

* Inquire if more restrictive levels are required.

Concern about temper embrittlement, discussed in more detail later, is normally addressed by specifying limits on one of two chemical factors, J and X bar defined by the following equations:

$$J = (\%\,Si + \%\,Mn)(\%\,P + \%\,Sn) \times 10^4$$

$$X\ bar = \frac{(10P + 5Sb + 4Sn + As)}{100} \quad \{\text{elements in ppm}\}$$

X bar is normally considered only appropriate for welding consumables not base plate, but can be offered when so desired. The maximum levels available by grade are:

Grades	J Factor	X Bar
12	110	12
11	150	12
22	90	15

The distributions of J and X bar data for Grade 22 are shown in Figures 18 and 19. More restrictive levels of individual tramp elements, or J and X bar factors, will be considered on a case-by-case basis.

Figure 18
Distribution of J Factors for A387 Grade 22 Utilizing Melting Practices to Control Tramp Elements

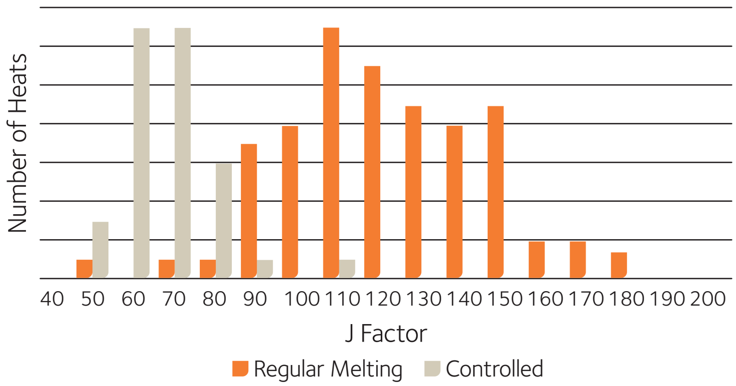
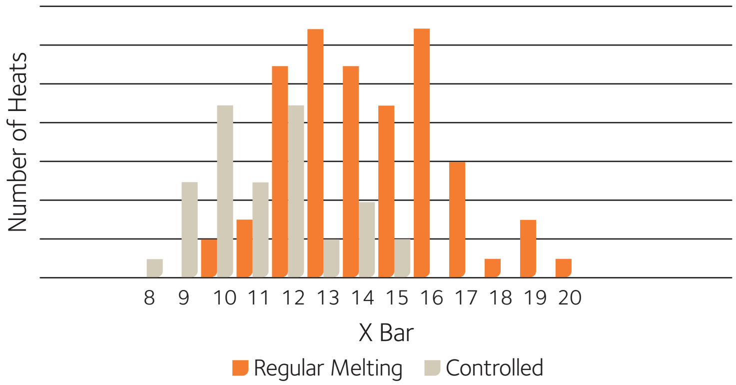


Figure 19
Distribution of X bar for A387 Grade 22 Utilizing Melting Practices to Control Tramp Elements



The application of J factor for Grade 11 is often misunderstood and as a result, somewhat higher J factors for Grade 11 may be required to allow for higher Mn and minimum silicon levels required to meet strength levels in thicker plates and/or when extensive PWHT is required. The effect of chemistry balance on strength is illustrated in Figure 20. In this example, tensile strength of Grade 11 plate, 1-3/8 inch thick in the normalized and tempered condition, is plotted against Larson-Miller Parameter (LMP). ArcelorMittal has found that there is an excellent correlation between strength, thickness, chemistry and time-temperature parameters such as Larson-Miller $\{P = T(C + \log t) \times 1000\}$. In the chart, the effects of both additional chemistry, represented by a conventional carbon equivalent, as well as more stress relief, represented by higher LMP factors, are shown. Clearly, when trying to achieve Class 2 properties of 75 KSI minimum tensile strength, chemistry and PWHT must be considered carefully. More will also be said about this in the section on toughness. Distribution for J and X bar factors for Grade 11 are depicted in Figures 21 and 22.

Figure 20
The Effect of Time - Temperature on Tensile
Strength of N+T 1-3/8" A387-11

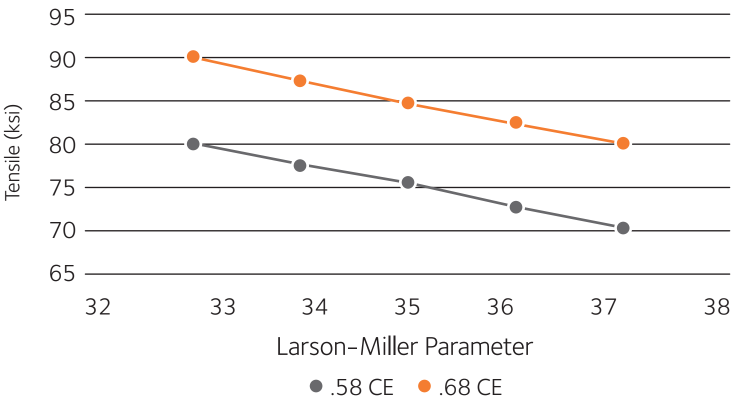


Figure 21
Distribution of J Factors for A387 Grade 11 Utilizing Melting Practices to Control Tramp Elements

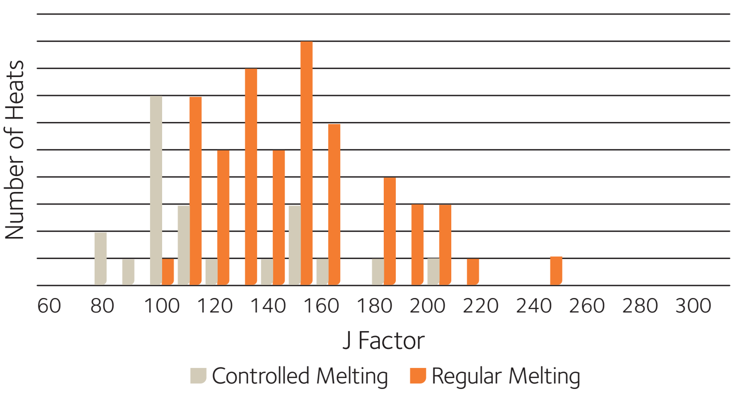


Figure 22
Distribution of X bar for A387 Grade 11 Utilizing Melting Practices to Control Tramp Elements

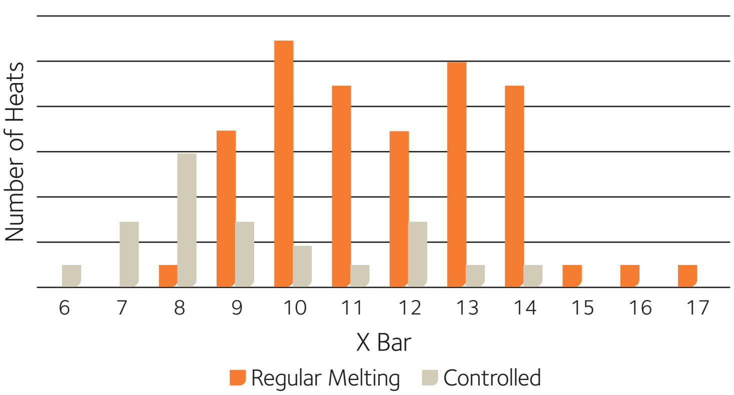
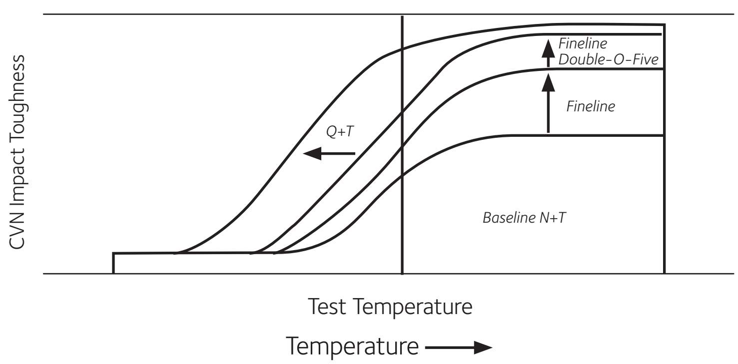


Figure 23
Influence of Processing on the Toughness of A387 Steels

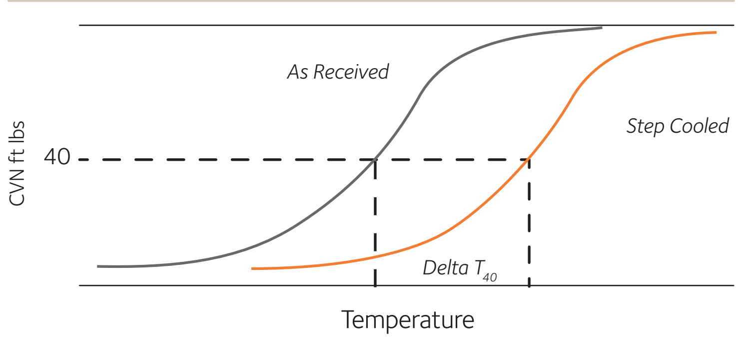


Charpy V-Notch Toughness

Improved Charpy V-notch toughness properties can be met for A387 steels with Fineline processing, including vacuum degassing and calcium treatment for inclusion shape control. When thick plates are specified with high CVN toughness requirements or when PWHT requirements demand it, a quench and temper heat treatment may be required. Multiple austenization may also be utilized to meet increased toughness requirements. The general effects of Fineline processing and heat treatment on toughness are shown in Figure 23. PWHT also has a significant effect on notch-toughness that will be discussed later. In all cases, we highly recommend that our Specification Metallurgy Department be contacted for CVN capabilities before specifying design criteria.

Tramp elements may cause degradation of CVN toughness over time in vessels with long-term service, a phenomenon known as temper embrittlement. The effect is shown schematically in Figure 24. As previously discussed, certain tramp elements, but particularly phosphorus and tin, are restricted to minimize the temper embrittlement susceptibility of A387 steels.

Figure 24
Effect of Temper Embrittlement on 40 Ft-Lb Transition Temperature



Some specifications, such as described by API 934, additionally stipulate that a laboratory step-cooling simulation be performed to determine the steel's susceptibility to temper embrittlement. ArcelorMittal will perform stepcooling treatment and meet commonly specified requirements that limit the amount of shift in the 40 ft.-lb. CVN transition temperature (ΔTT_{40}). Test results for A387 Grade 22 steels shown in Figures 25 and 26 demonstrate these capabilities for transverse orientation testing. In particular, the excellent toughness prior to step cooling and the low susceptibility to temper embrittlement after step cooling is shown in Figure 26. Results for Grade 22 repeatedly have shown that it is an overly conservative requirement, adding only additional cost and extended delivery with no perceived benefit. Designers are strongly urged to remove the step-cooling requirement.

Additional testing has been completed on A387 Grade 5 material subjected to step-cooling treatments in the normalized and tempered condition and is illustrated in Figure 27. While exhibiting some shift as a result of the stepcool cycle, T_{40} results approach –180ºF and such requirements for this grade are seldom seen.

Post Weld Heat Treatment (PWHT)

End users and fabricators typically impose various post-weld heat-treatment (stress relief) requirements when specifying A387 steels that are driven by the applicable ASME construction code. Extended time at the PWHT stabilizes and softens the microstructure of the aswelded heat affected zone after fabrication. The number of cycles applied to the tests representing the plates usually will account for any subsequent weld repairs that may be made during the life of the vessel. However, as PWHT temperatures and hold times are increased, the ability of the chemistry of each grade to achieve the tensile strength requirements of the specification is limited, particularly when using normalize and temper heat treatment.

Extensive stress relief treatments are also found to have a dramatic deleterious influence on notch-toughness in A387 steels. This is illustrated in Figure 28, which summarizes the influence of increasing PWHT cycles on longitudinal CVN toughness of a 2-inch thick A387 Grade 22 plate by showing the resultant "shift" in the transition curve. In this example, the shift in the 40 ft.-lb. transition temperature is 43ºF as the result of a PWHT cycle of 1350ºF for 4 hours. Looking back on the step-cooled data from Grade 22, this shift, due to the coarsening of carbides at the grain boundaries as shown in the photomicrographs (Figure 29) is more than is normally encountered when evaluating for temper embrittlement.

Figure 25
A387-22 7.6" Plates, Q & T
Shift of 40TT after Step Cooling

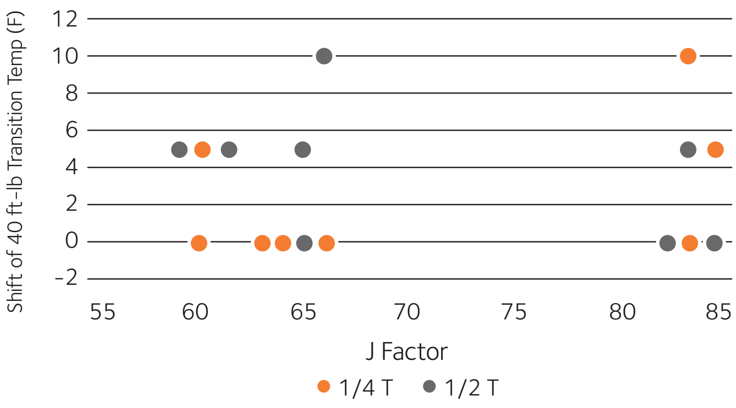
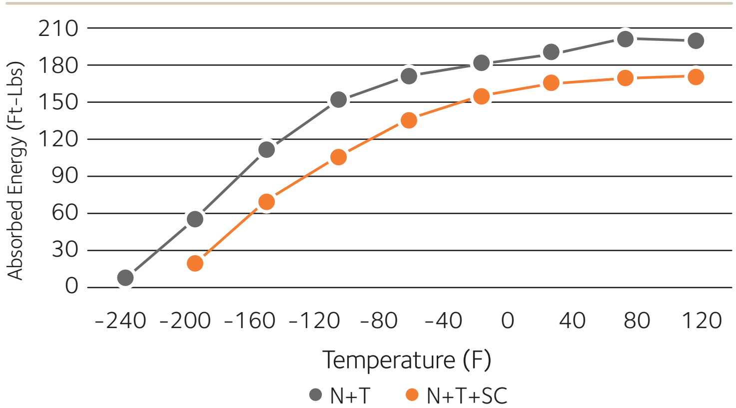


Figure 26
Effect of Step-Cooling on Q+T A387-22
Transverse 40 Ft-Lb Transition Temperature

Heat No.	T (in.)	Loc	T_{40} (F)	Delta T_{40} (F)	T_{40} + 2.5 Delta T_{40} (F)
U3566-5	2.62	1/2t	-120	15	-83
U3566-9	2.375	1/4t	-185	10	-160
C8200-4D	2.375	1/4t	-185	**-30**	-185
C8713-6G	2.25	1/2t	-151	3	-143
U6037-6	2.625	1/2t	-162	4	-158
U2821-4	1.85	1/2t	-126	21	-105
U2821-5	2.25	1/2t	-145	7	-138
U2840-7	2.56	1/2t	-122	**0**	-122
U2840-1	4.187	1/2t	-160	10	-135
U2840-2	3.56	1/2t	-125	30	-50
U3566-10	2.25	1/2t	-133	**-11**	-133
U5504-1	3.56	1/2t	-145	**-5**	-145
U5598-1	3.56	1/2t	-155	15	-113
U7514-1	1.84	1/4t	-170	**0**	-170
U7521-6	3.04	1/4t	-185	25	-110
Average			**-151**	**6**	**-130**

Based on average of 3 specimens.

Figure 27
The Effect of Step-Cooling on A387 Grade 5



As footnoted earlier, one measure of the severity of a particular PWHT cycle is the Larson-Miller Parameter (LMP). The effect of extended stress relief on Grade 11 is illustrated in Figure 30 and shows the drop in tensile strength by increasing the normal tempering temperature and PWHT by 100ºF, a common request from design engineers. The differences are sometimes not apparent but the combination of such increases to accommodate either hardened HAZ's or to address reheatcracking concerns is evident in Figure 31. In Figure 32, the effects of the extended heat treatment on toughness are illustrated, showing the increase in 40 ft.-lb. transition temperature. What is also demonstrated is the improvement in resistance to PWHT property degradation with quenched and tempered Grade 11. Figure 33 shows the microstructural damage that progresses with increasing LMP.

Figure 28
The Effect of PWHT on N & T A387-22

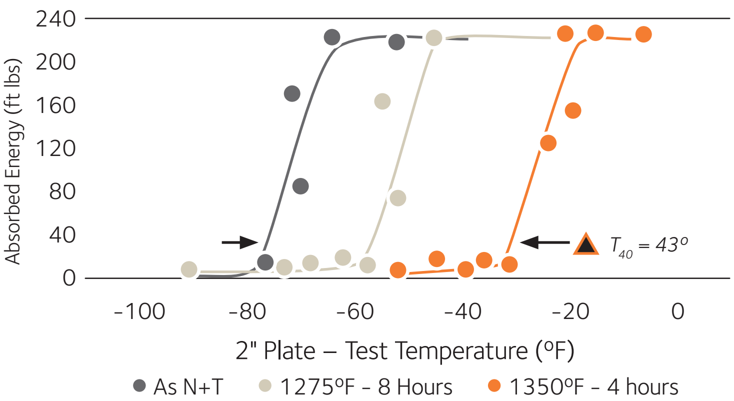
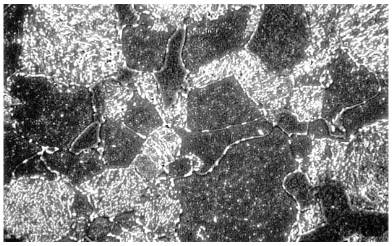
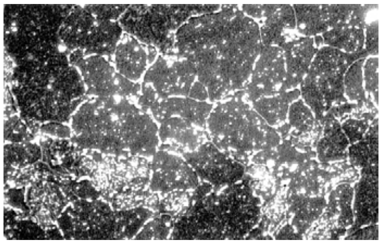


Figure 29
Grain Boundary Embrittlement A387-22



Normalized and Tempered

Coalescence of carbides in grain boundaries of A387-22 after excessive exposure to time-temperature.



Normalized and Tempered & PWHT 1325ºF for 20 hours.

Figure 30
The Effect of a 100ºF Increase in Tempering Temperatures on N & T A387-11

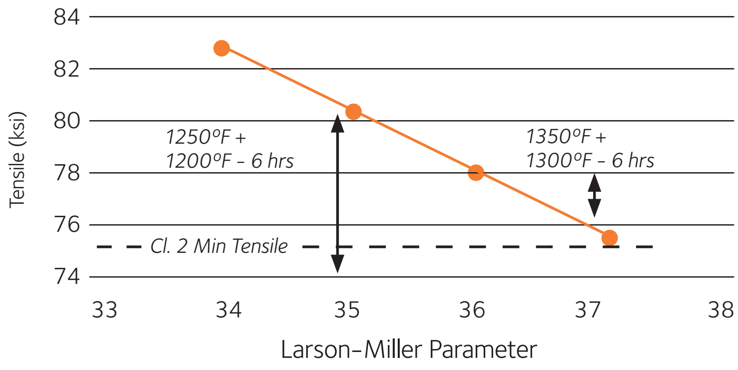


Figure 31
Time Temperature Parameter - Illustrative Example

Past Practice	Current Trends
1250ºF for 1 hour tempering	1350ºF for 1 hour tempering
+	+
1200ºF for 6 hours PWHT	1300ºF for 6 hours PWHT
The combination of tempering and PWHT =	
34.86 LMP	**36.94 LMP**

Figure 32
The Effect of LMP on Toughness of A387-11

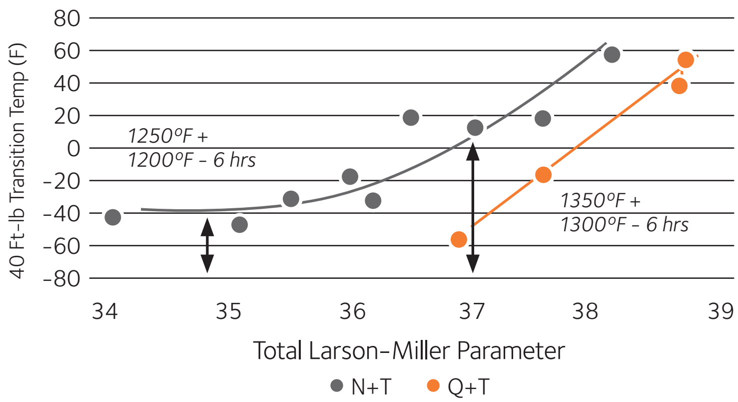


Figure 33
Microstructural Effects of Time-Temperature in N+T A387-11

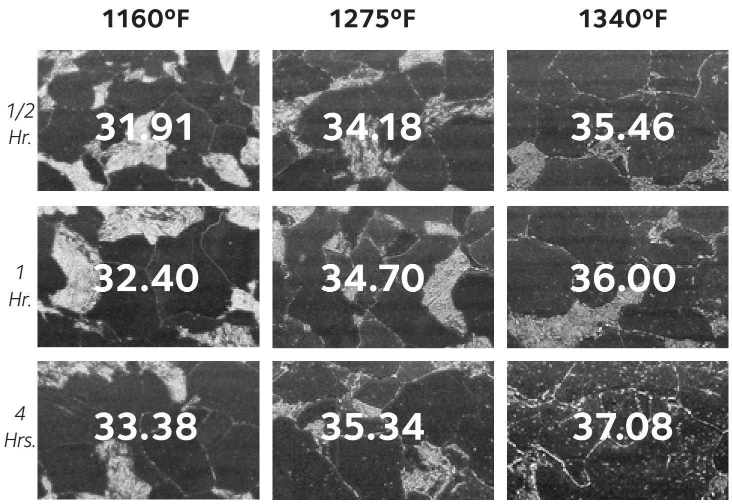
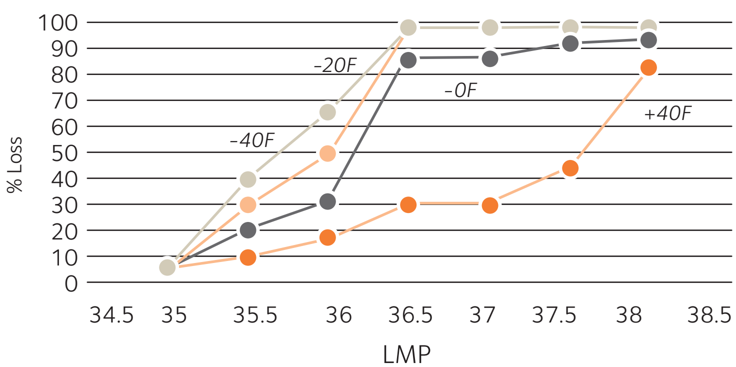


Figure 34
Percentage Loss of Original CVN Toughness with Increasing PWHT After Initial N + T as f(test temperature): A387-11 2" Plate



ArcelorMittal's experience is that loss of toughness as the result of extended PWHT time and temperature is also dependent on the CVN test temperature. Figure 34 illustrates the reduction in overall absorbed energy for Grade 11 that is subjected to increasing time-temperature (LMP) as a function of percentage loss and test temperature. It is clear that for test temperatures below 0ºF, the degradation of toughness is accelerated, making it even more difficult to achieve minimum requirements when sub-zero impact test temperatures are required, something that is becoming more prevalent in the industry.

As toughness requirements become even more restrictive, the PWHT cycle will dictate that plates will need to be quenched and tempered to maintain toughness as well as strength. Due to the increasing demand for improved resistance to creep embrittlement and concerns for reheat cracking, higher PWHT temperatures are being specified, especially for Grade 11. To improve performance, Class 1 strength levels are also being specified. This allows lower carbon and CE levels to be achieved, particularly when quench and tempered heat treatment is specified.

Ultrasonic Quality

A387 plates to 6-inches thick and over 50,000 pounds can be ordered to meet the requirements of A578 Level C, when the steel is produced with Fineline® processing. For plates thicker than 6 inches, please inquire.

Introducing a New Cr-Mo-W-V Steel – ASTM A1041

In 2004, a new variety of Cr-Mo steel was introduced. ASTM A1041 is the first domestically inspired new grade of steel for elevated temperature service in over twenty years. ArcelorMittal has worked with Oak Ridge National Laboratories and a consortium of private companies to bring this grade to the marketplace and have an ASTM specification established. Containing tungsten and vanadium, A1041 Grade 315 provides decided improvement in other grades of A387 and A1017 through its very high strength and excellent creep properties. As a result, many of the specialized vessels for high temperature pressure applications will be able to more easily be fabricated by taking advantage of thinner walls. Another significant advantage is that this material is capable of being fabricated without post-weld heat-treatment when used in conjunction with TIG, MIG or SMAW welding processes. This can mean that repairs made downstream can be made without cumbersome and costly PWHT.

While ASTM has adopted a new specification, ASME is still in the process of approving this material through the use of a Code Case. Consult ArcelorMittal metallurgists for updated status, but it is expected that approval will occur in 2009.

ASTM A1041-04

	Grade 315 (Composition, %)
Carbon	0.08 - 0.12
Tungsten	1.35 – 1.65
Vanadium	0.20 – 0.30
Molybdenum	0.65 – 0.85
Chromium	2.8 – 3.2
Manganese	0.25 – 0.45

ASTM A1041-04
Tensile Requirements

	Grade 315
Tensile Strength, ksi [MPa]	105 to 135 (725 to 930)
Yield Strength, Min ksi [MPa]	85 (585)
Elongation in 2 in. [50 mm], Min	16

Technical Literature

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3. "Performance Characteristics of Special Clean Pressure Vessel Steel Subjected to SSC and HIC Testing", Kenneth E. Orie and Fred B. Fletcher, Paper No. 632, Corrosion 99, April 1999, NACE, Houston, TX
4. "The Effect of PWHT on Normalized Base- Metal Properties of ASTM A516 Steel", Ken Orie and Charles R. Roper, Welding Research Council Bulletin 481, May 2003

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1. "Improvements of the Mechanical Properties of 1 Cr-1/2 Mo Steel," R. A. Swift, ASME Petroleum Mechanical Engineers Conference, Mexico City, Mexico, 1976
2. "High Toughness 2-1/4 Cr – 1 Mo Steel for Hydrocarbon Process Pressure Vessels," K. J. Benusa and R. A. Swift, API Mid-Year Meeting, May 1981
3. "Evaluation of A387-22 Steel Modified for Improved Toughness," R. A. Swift and J. A. Gulya, MPC-ASME Symposium "Advanced Materials for Pressure Vessel Service with Hydrogen at High Temperatures and Pressures," June 1982
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5. "Effects of Composition and Heat Treatment on the Mechanical Properties of 300 mm gauge 2- 1/4 Cr – 1 Mo Steel Plate," R. A. Swift, ASTM STP 755, 1982
6. "Fineline A387-11 Data," J. A. Gulya, Lukens Steel Company Report RPR 86-1, February 1986
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8. "Fineline A387-11 Data," J. A. Gulya, Lukens Steel Company Report RPR 86-1, February 1986
9. "Properties and Behavior of Modern A387 Cr- Mo Steels," A. D. Wilson, C. R. Roper, K. E. Orie and F. B. Fletcher, ASME PVP Vol. 239, 1992
10. "Tougher Steels Improve Pressure Vessel Performance," A. D. Wilson, Advanced Materials & Processes, Vol. 143, April 1993

More Information

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Important

The information provided herein is based on testing or ArcelorMittal experience and is accurate and realistic to the best of our knowledge at the time of publication. However, characteristics described or implied may not apply in all situations. ArcelorMittal reserves the right to make changes in practices which may render some information outdated or obsolete. In cases where specific properties are desired, ArcelorMittal should be consulted for current information and/or capabilities.

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