

# Duplex Stainless Steel

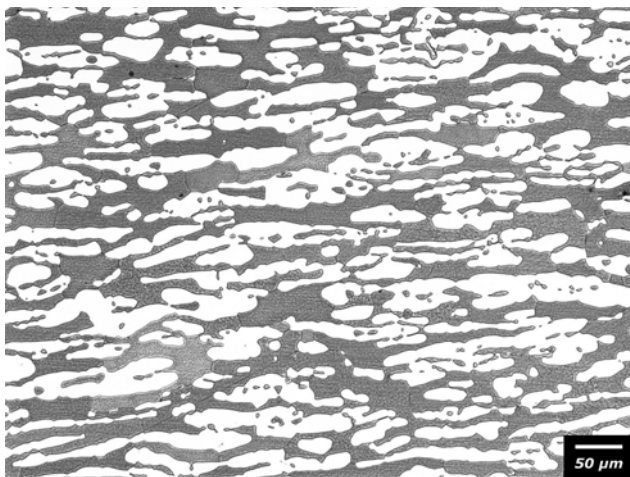
## ATI 2003™ Alloy

### (UNS S32003)

#### GENERAL PROPERTIES

The ATI 2003™ (UNS S32003) alloy is a nitrogen-enhanced, proprietary duplex stainless steel alloy. Cr, Ni, Mo, and N are controlled to give a phase balance similar to that of ATI 2205™ alloy, while reducing costs. The alloy fills a gap between Type 316 and ATI 2205 duplex alloy in terms of corrosion resistance, while possessing the higher mechanical properties characteristic of a duplex stainless steel. ATI 2003 alloy can be an economic alternative to Type 316L stainless steel, providing enhanced strength and corrosion resistance.

When heat-treated properly, the nominal 20% chromium, 3% nickel, 1.7% molybdenum, and 0.17% nitrogen in the ATI 2003 alloy produce a microstructure that consists of a nearly equal mixture of the austenite and ferrite phases as shown in the photo-micrograph below. The microstructure and composition of the ATI 2003 alloy provide stress-corrosion cracking resistance that is superior to that of Types 316 or 317, and a yield strength that is more than double that of conventional austenitic stainless steels.



Duplex microstructure of ATI 2003™ alloy. The ferrite phase appears darker than the austenite due to a KOH etch.

The microstructure and phase balance of ATI 2003 alloy have been designed to facilitate the production of pipe and tube products, as well as sheet, strip, plate, and long products, including rod. With reduced levels of Cr and Mo, the ATI 2003 alloy is more resistant than ATI 2205™ material to detrimental phases such as sigma. The ATI 2003 alloy was created for use in environments where resistance to general corrosion and chloride stress corrosion cracking is important.

Because of its superior corrosion resistance and strength, ATI 2003 alloy can be an economic alternative to Types 316 and 317 for a variety of applications, including:

- Desalination
- Storage Tanks
- Bridge Decking
- Architectural Structures
- Oil & Gas
- Water Heaters
- Home Appliances
- Power Generation
- Heat Exchangers
- Potable Water Systems
- Pressure Vessels
- Chemical Processing
- Pulp & Paper
- Transport Tanks
- Water Treatment Facilities

#### CHEMICAL COMPOSITION

Element	ASTM A240 Specifications for UNS S32003 Material
C	0.030% Maximum
Mn	2.00% Maximum
P	0.030% Maximum
S	0.020% Maximum
Si	1.00% Maximum
Cr	19.5% to 22.5%
Ni	3.0% to 4.0%
Mo	1.50% to 2.00%
N	0.14% to 0.20%
Fe	Balance

## SPECIFICATION COVERAGE

ASTM specification coverage exists for A240 (plate, sheet and strip), A270 (sanitary tube), A480, A789 (tube), A790 (pipe), and A928 (pipe welded with filler). ATI 2003 material is approved for ASME Boiler and Pressure Vessel Code use under Code Case 2503-1 for Section VIII Division 1 use. ATI 2003 alloy is certified as an acceptable material for use in drinking water treatment and distribution systems by NSF International in Appendix C of NSF/ANSI Standard 61:2005. ATI Allegheny Ludlum has been qualified as a producer of ATI 2003 alloy under NORSOK standard M-650. ATI 2003 alloy is included in Appendix X of API Standard 650, Welded Steel Tanks for Oil Storage.

## PHYSICAL PROPERTIES

### Density

0.28 lb/in<sup>3</sup> (7.8 g/cm<sup>3</sup>)

### Specific Heat at 73-212°F (23-100°C)

0.12 BTU/lb-°F (0.51 kJ/kg-K)

### Thermal Conductivity at 73-212°F (23-100°C)

10 BTU-ft/hr-ft<sup>2</sup>-°F (17 W/m-K)

### Thermal Coefficient of Expansion

Range	Average TCE
68-400°F (20-204°C)	8.0x10 <sup>-6</sup> /°F (14.4x10 <sup>-6</sup> /°C)
68-200°F (20-93°C)	7.7x10 <sup>-6</sup> /°F (13.8x10 <sup>-6</sup> /°C)
-100-68°F (-73-20°C)	7.3x10 <sup>-6</sup> /°F (13.1x10 <sup>-6</sup> /°C)
-150-68°F (-101-20°C)	7.1x10 <sup>-6</sup> /°F (12.8x10 <sup>-6</sup> /°C)

### Modulus of Elasticity in Tension

30.5 x 10<sup>6</sup> psi (210 GPa)

### Magnetic Permeability

Ferromagnetic

## CORROSION RESISTANCE

### Chloride Stress Corrosion Cracking Resistance

The nickel-free ferritic steels are essentially immune to chloride stress corrosion cracking. Nickel-containing austenitic stainless steels such as Type 304 and Type 316, on the other hand, are highly susceptible to stress corrosion cracking. Duplex alloys behave in a manner that is a combination of the characteristics of the austenitic and ferritic phases that make up the alloy. Consequently, the ferrite phase in ATI 2003 alloy provides resistance to chloride stress corrosion cracking, making it substantially better than the standard 300 series austenitic stainless steels.

### Stress Corrosion Cracking Performance in Boiling 26% NaCl

Austenitic Type 304L	Failed (850 Hours)
Austenitic Type 316L	Failed (530-940 Hours)
Austenitic Type 317L	Failed (1000 Hours)
Duplex ATI 2003™	Passed (1000 Hours)
Duplex ATI 2205™	Passed (1000 Hours)

Additional testing was performed in a saturated chloride solution at 82, 100, and 115°C for periods up to 2200 hours. The salt mixture and was designed to be comparable to conditions expected from sea spray on an offshore oil and gas production system. At the highest temperature, some general surface corrosion was evident on the ATI 2003 material, but no cracking occurred. Type 316L material was limited to 60°C in this test, while the 2205 duplex alloy was limited to 100°C. ATI 2003 alloy thus demonstrated good CSCC resistance in comparison to alloys commonly used for these applications.

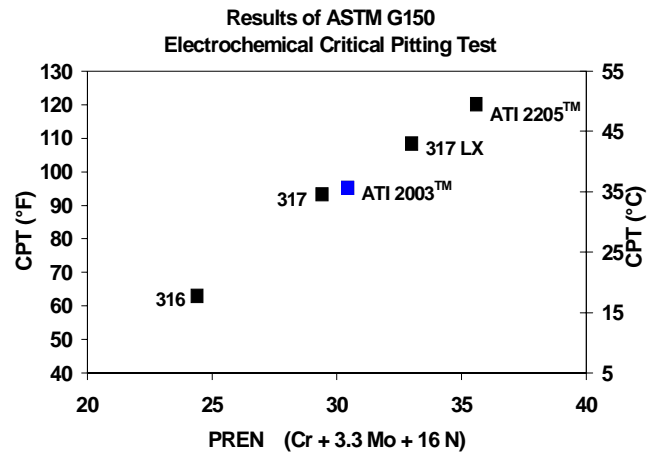
### Sulfide Stress Cracking (SSC) & Stress Corrosion Cracking (SCC)

Resistance to SSC and SCC was determined using the Four Point Bend (FPB) test method in accordance with EFC 17. Triplicate testing was carried out for 30 days at a load equal to 100% of the yield stress under the conditions shown in the table below. These conditions were chosen to simulate various well streams encountered in offshore oil and gas production. Under these conditions, no cracking or pitting was observed on any of the as-welded or base metal samples of ATI 2003 material that were tested. All welds were made using AWS E2209 filler metal.

Temp.	pH <sub>2</sub> S	pCO <sub>2</sub>	pH <sub>2</sub> O	pH	Solution
194°F (90°C)	0.1 bar	1.9 bar	0.7 bar	3.5	20% NaCl (120,000 ppm Cl <sup>-</sup> )
194°F (90°C)	0.1 bar	39.9 bar	0.7 bar	3.0	1000 ppm Cl <sup>-</sup> and 500 ppm CH <sub>3</sub> COOH
320°F (160°C)	0.01 bar	7.4 bar	6.1 bar	5.8	87.4g/l NaCl and 1.26 g/l NaHCO <sub>3</sub>

**Pitting and Crevice Corrosion Resistance**

A relative ranking of the resistance to chloride-ion pitting and crevice corrosion can be made by following ASTM Standard G150 and increasing the test temperature until the onset of pitting is observed. The temperature at which attack is first observed is called the critical pitting temperature (CPT) and can be used as a relative measure of pitting corrosion resistance. The critical pitting temperature criterion is useful for ranking alloys, but does not necessarily indicate an absolute limiting temperature for the use of a particular alloy in chloride-bearing solutions. Test data shows that ATI 2003 alloy has a CPT of 95°F (35°C), which is slightly better than that of Type 317L material.



The CPT was determined for as-welded ATI 2003 material in an acidified ferric chloride solution in accordance with ASTM G48, Practice C. Results after 72 hours showed that the as-welded samples of ATI 2003 alloy passed the test at 5°C and failed at 10°C. In comparison, Type 316L would fail in this test at approximately 0°C.

**General Corrosion Resistance**

The ATI 2003 alloy is resistant to dilute reducing acids and moderate concentrations of oxidizing acids. The alloy is resistant to low concentrations of organic acids.

**Intergranular Corrosion**

ATI 2003 alloy was tested in accordance with ASTM Standard A 262, Practices B, C, and E. Test results indicate that the alloy resists intergranular corrosion in the welded condition. Due to its compositional balance, ATI 2003 alloy will reform austenite in the weld zone. This austenite-forming ability, in combination with low carbon content, minimizes grain boundary precipitation and gives ATI 2003 alloy excellent resistance to intergranular attack (IGA).

**Corrosion Resistance in Boiling Solutions and ASTM Tests**

Test Solution	Corrosion Rate in Mils per Year (mm/y) for Cited Alloys			
	Type 316L	Type 317L	ATI 2003™	ATI 2205™
20% Acetic Acid*	0.10 (<0.01)	0.48 (0.01)	0.02 (<0.01)	0.01 (<0.01)
45% Formic Acid	23.4 (0.59)	18.4 (0.47)	14.9 (0.38)	0.50 (0.01)
10% Oxalic Acid	48.0 (1.22)	44.9 (1.14)	3.77 (0.10)	7.80 (0.20)
20% Phosphoric Acid	0.20 (<0.01)	0.72 (0.02)	0.34 (0.01)	0.80 (0.02)
10% Sulfuric Acid*	636 (16.2)	298 (7.57)	259 (6.58)	206 (5.23)
1% Hydrochloric Acid*	226 (5.47)	54.2 (1.38)	49.9 (1.27)	0.80 (0.02)
ASTM A262 Practice B (Fe <sub>2</sub> (SO <sub>4</sub> ) <sub>3</sub> •H <sub>2</sub> SO <sub>4</sub> )	26.0 (0.66)	20.8 (0.53)	20.8 (0.53)	19.9 (0.51)
ASTM A262 Practice C (65% HNO <sub>3</sub> )	22.3 (0.57)	19.7 (0.50)	30.9 (0.78)	20.6 (0.53)
ASTM A262 Practice E (Cu•CuSO <sub>4</sub> •H <sub>2</sub> SO <sub>4</sub> )	Pass	Pass	Pass	Pass

\* Samples Activated

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**MECHANICAL PROPERTIES**

**Mechanical Properties at Room Temperature**

Typical mechanical properties for annealed ATI 2003 alloy material at room temperature are listed below:

**Plate (>0.1875" or 5 mm)**

Property	ASTM A240 Specification	Typical
Yield Strength (0.2% Offset)	65,000 psi (450 MPa) (Minimum)	75,000 psi (515 MPa)
Ultimate Tensile Strength	95,000 psi (655 MPa) (Minimum)	105,000 psi (725 MPa)
Elongation in 2" (50.8 mm)	25% (Minimum)	40%
Hardness	293 Brinell (Maximum) 31 Rc (Maximum)	223 Brinell

**Sheet (≤0.1875" or 5 mm)**

Property	ASTM A240 Specification	Typical
Yield Strength (0.2% Offset)	70,000 psi (485 MPa) (Minimum)	80,000 psi (550 MPa)
Ultimate Tensile Strength	100,000 psi (690 MPa) (Minimum)	110,000 psi (760 MPa)
Elongation in 2" (50.8 mm)	25% (Minimum)	40%
Hardness	31 Rc (Maximum)	20 Rc

**Minimum Specified Mechanical Properties, Various Product Forms**

Property	Sheet ksi (MPa)	Plate ksi (MPa)	Tube ksi (MPa)	Pipe ksi (MPa)
Yield Strength (0.2% Offset)	70 (485)	65 (450)	70 (485)	65 (450)
Ultimate Tensile Strength	100 (690)	95 (655)	100 (690)	90 (620)

**Effect of Temperature on Mechanical Properties**

The chart shows the effect of high and low temperatures on the tensile properties of ATI 2003 alloy from -130 to 600°F (-90 to 316°C). An upper temperature limit of 650°F (343°C) has been placed on the use of S32003 duplex stainless steel in the ASME Boiler and Pressure Vessel Code to prevent "885°F (475°C) Embrittlement." The ferrite phase of duplex stainless steels may be embrittled after exposure to temperatures from 650 to 1000°F (343-530°C).

885°F (475°C) embrittlement is reversible by heat treating the alloy at a temperature above 1100°F (590°C) and air cooling. For more highly alloyed duplex alloys, such as ATI 2205 alloy, another embrittling range exists from about 1000°F (530°C) to 1830°F (1000°C) due to the precipitation of excess phases that are detrimental to both impact and corrosion properties. To a lesser extent, these phases may also form in ATI 2003 alloy. After extended periods of exposure to temperatures in the embrittling range, a full anneal and air or water cooling is sufficient to prevent the latter form of embrittlement and is also the preferred manner of relieving forming stresses and 885°F (475°C) embrittlement. 885°F (475°C) and sigma phase embrittlement of ATI 2003 alloy during welding are not a problem when using conventional techniques.

**ATI 2003™ Alloy Tensile Properties**

Temperature		Yield Stress		Tensile Stress		Elongation
°F	°C	ksi	MPa	ksi	MPa	Percent in 2"
-130	-90	113	779	155	1069	57
-94	-70	103	710	140	965	61
-58	-50	96	662	129	889	67
-4	-20	89	614	119	820	54
70	21	76	524	107	738	41
200	93	66	455	95	655	32
300	149	62	427	88	607	27
400	204	56	386	87	600	26
500	260	56	386	85	586	22
600	316	56	386	87	600	22

**Effect of Cold Reduction on Tensile Properties**

Cold working of ATI 2003 alloy results in an increase in its strength and an accompanying decrease in its elongation before fracture. The chart below shows the effect of cold reduction on the tensile properties of ATI 2003 sheet.

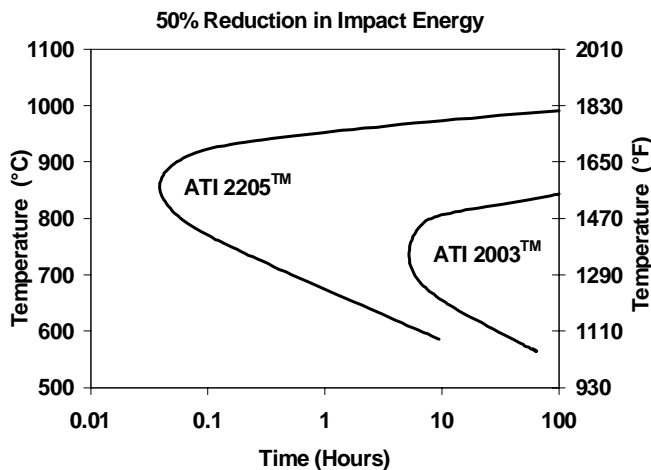
**ATI 2003™ Alloy Tensile Properties for Cold Worked Material**

Reduction	Yield Stress		Tensile Stress		Elongation
Percent	ksi	MPa	ksi	MPa	Percent in 2"
0.0	79	545	108	745	34
1.7	88	607	110	758	32
3.0	98	676	114	786	29
9.4	120	827	133	917	15
12.3	129	889	142	979	11
18.8	136	938	151	1041	12
27.6	148	1020	169	1165	10
38.2	165	1138	190	1310	5
47.2	187	1289	204	1407	2
67.3	214	1476	235	1620	1

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**Impact Properties**

Duplex ATI 2003 alloy will undergo a transition from a ductile mode of fracture at higher temperatures to a brittle mode of fracture at lower temperatures when subjected to impact loading. For properly annealed plate, this transition temperature is well below 70°F (21° C), at which the impact energy is in excess of 300 ft-lbs (400 J). However, by exposing the alloy for extended periods of time at temperatures in the range from 650 to 1000°F (343-530°C), the brittle transition temperature will be increased. Improper welding procedures, such as welding with straight chromium stainless steel filler metals, will also increase the susceptibility of the weld to brittle impact behavior. At higher temperatures, embrittlement of duplex alloys may result from the formation of intermetallic phases such as sigma or chi. Due to its reduced alloy content, ATI 2003 alloy resists embrittlement at these temperatures for much longer exposure times than traditional duplex alloys such as 2205. The T-T-T curves below compare the time required to embrittle ATI 2003 alloy between 1100 and 1800°F (600 and 1000°C) with that for ATI 2205 alloy.

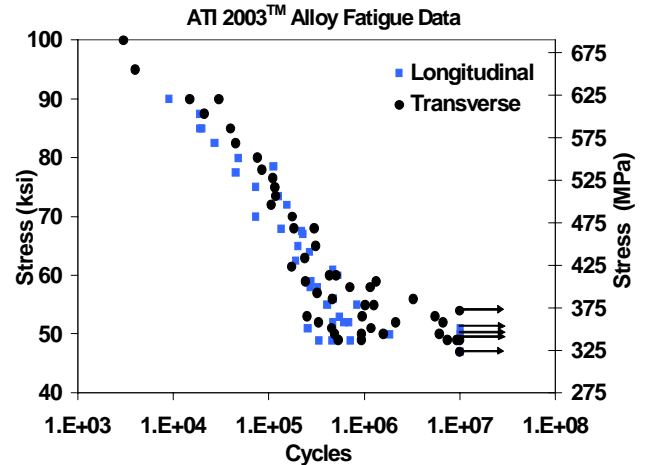


As seen in the Table below, ATI 2003 alloy will exhibit average Charpy impact energies (for full size specimens) much greater than the 40 ft-lb (54 J) at -40°F (-40°C) that is commonly specified.

ATI 2003™ Alloy Impact Energy (L-T Orientation)	
Temperature	Impact Energy
68°F (20°C)	>300 ft-lbs (>400 J)
-4°F (-20°C)	179 ft-lbs (243 J)
-58°F (-50°C)	93 ft-lbs (126 J)
-94°F (-70°C)	78 ft-lbs (106 J)
-130°F (-90°C)	70 ft-lbs (95 J)

**Fatigue**

Flexural fatigue testing was performed on samples of annealed 0.035"-thick AL 2003 alloy in both the longitudinal and transverse orientations with respect to the rolling direction. The results, as shown in the accompanying S-N curve, indicate a fatigue endurance limit of just under 50,000 psi.



**Forming**

The ATI 2003 alloy can be successfully cold-bent and expanded. Greater loads will be required to deform the alloy because of the higher strength of this duplex alloy in comparison to conventional austenitic materials. Due to the lower ductility of the ferrite phase, the alloy should be bent to more generous bend radii than fully austenitic materials. It is suggested that bend radii of at least two times the metal thickness be used when forming ATI 2003 duplex stainless steel.

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### Welding

The ATI 2003 alloy can be welded by most methods used to weld stainless steels. Autogenous welding will increase the amount of ferrite present in the weldment and adjacent areas of the base metal. Subsequent annealing will tend to restore the balance of phases in the base metal. A nitrogen addition is recommended with autogenous welding to preserve corrosion resistance and strength.

Commercially available overmatched filler metals are suggested for welding the ATI 2003 alloy. Such filler metals (AWS E2209) contain more nickel than the base metal in order to produce a phase balance within the weld that is approximately the same as the base metal. When ATI 2003 alloy is welded to different metals, a filler metal should be chosen that contains a quantity of austenite forming elements that is sufficient to produce a fully austenitic weld. Non-filler metal welds should be heat treated for optimum corrosion resistance and formability.

ASME Code Case 2503-1 states that for welding performance qualifications, ATI 2003 alloy shall be considered P-No. 10H, Group 1.

For more information, please request the publication "ATI 2003™ (S32003) Weld Procedures & Evaluation."



### Heat Treatment

The ATI 2003 alloy should be annealed between 1850 and 2010°F (1010-1100°C) and cooled quickly. Annealing near 2010°F (1100°C) will increase the amount of ferrite present in the microstructure compared to that resulting from annealing near 1850°F (1010°C). Cold-bent sections in excess of 10% deformation should be fully annealed after forming. Stress relief heat treatments in the 750 to 1650°F (400-900°C) range adversely affect the properties of the alloy and should not be considered.



### Contact Information

Visit the ATI Allegheny Ludlum Web page shown below for a list of sales offices.

<http://www.alleghenyludlum.com/ludlum/pages/contact/sales.asp>