

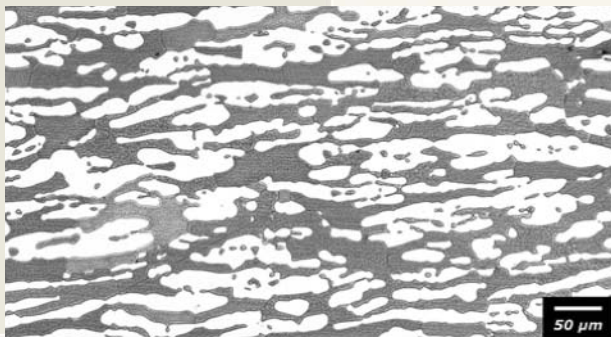
ATI 2003®

ATI 2003® (UNS S32003) Lean Duplex Stainless Steel with Molybdenum

GENERAL CHARACTERISTICS

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

When heat-treated properly ATI 2003 LDSS will have a microstructure that consists of a nearly equal mixture of the austenite and ferrite phases as shown in the image below. The microstructure and composition of ATI 2003 LDSS 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.



This image shows the duplex microstructure of ATI 2003® LDSS. The ferrite phase appears darker than the austenite due to a KOH etch.

The microstructure and phase balance of ATI 2003 LDSS have been designed to facilitate the production of sheet, strip, plate, pipe and tube products. With reduced levels of Cr and Mo, ATI 2003 LDSS is more resistant than ATI 2205™ material to detrimental phases such as sigma. ATI 2003 molybdenum-enhanced lean duplex stainless steel 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 LDSS can be an economic alternative to Types 316 and 317 for a variety of applications, including:

- Pipes and Tubes
- Subsea Flowlines
- Bridge Decking
- Architectural Structures
- Desalination
- Water Heaters
- Home Appliances
- Heat Exchangers
- Water Treatment Facilities
- Potable Water Systems
- Power Generation
- Chemical Processing
- Pressure Vessels
- Transport Tanks
- Pulp & Paper Production

Chemical Composition of ATI 2003® LDSS (ASTM A240 Limits for S32003)

Element	Weight Percent
Carbon	0.030 max
Manganese	2.00 max
Phosphorus	0.030 max
Sulfur	0.020 max
Silicon	1.00 max
Chromium	19.50 - 22.50
Nickel	3.00 - 4.00
Molybdenum	1.50 - 2.00
Nitrogen	0.14 - 0.20
Iron	Balance

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SPECIFICATION COVERAGE

ATI 2003 alloy (S32003) is covered in ASTM specifications 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 LDSS 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 LDSS is included in Appendix X of API Standard 650, Welded Steel Tanks for Oil Storage.

PHYSICAL PROPERTIES

Density	0.280 lb/in ³ (7.78 g/cm ³)
Elastic Modulus	30 x 10 ⁶ psi (210 GPa)
Magnetic Permeability	Ferromagnetic
Specific Heat 73-212°F (23-100°C)	0.12 BTU/lb-°F (0.51 kJ/kg-K)
Thermal Conductivity 73-212°F (23-100°C)	10 BTU-ft/hr-ft ² -°F (17 W/m-K)

Thermal Expansion (mean coefficient over range)			
Temperature Range			
°F	°C	in/in/°F x 10 ⁻⁶	mm/mm/°C x 10 ⁻⁶
-150 to 68	-101 to 20	7.1	12.8
-100 to 68	-73 to 20	7.3	13.1
68 to 200	20 to 93	7.7	13.8
68 to 400	20 to 204	8.0	14.4

ROOM TEMPERATURE MECHANICAL PROPERTIES

ASTM A240 specification limits for annealed ATI 2003 (S32003) sheet, strip, and plate material are shown in the table below.

Minimum Room Temperature Tensile Properties for S32003 per ASTM A240							
Product	Ultimate Strength		0.2% Yield Strength		Elongation in 2" or 50 mm %	Hardness (Max.)	
	ksi	MPa	ksi	MPa		BHN	R _C
Sheet / Strip (≤ 0.187" or 5 mm)	100	695	70	485	25	293	31
Plate (>0.187" or 5 mm)	95	655	65	450	25	293	31

Typical tensile properties for ATI 2003 sheet, strip, and plate material are shown in the table below. Sheet and strip products will typically have higher strength than plate due to refinement of the microstructure that occurs during cold working.

Typical Room Temperature Tensile Properties of ATI 2003® LDSS							
Product	Ultimate Strength		0.2% Yield Strength		Elongation in 2" or 50 mm %	Hardness	
	ksi	MPa	ksi	MPa		BHN	R _C
Sheet / Strip (≤ 0.187" or 5 mm)	110	760	80	550	40	—	20
Plate (>0.187" or 5 mm)	105	725	75	515	40	223	—

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Minimum Room Temperature Tensile Properties Required by ASTM Specifications for ATI 2003® LDSS in Various Product Forms

	Sheet (ASTM A240)		Plate (ASTM A240)		Tube (ASTM A789)		Pipe (ASTM A790)	
	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa
0.2% Yield Strength	70	485	65	450	70	485	65	450
Ultimate Tensile Strength	100	695	95	655	100	695	95	655

EFFECT OF TEMPERATURE ON MECHANICAL PROPERTIES

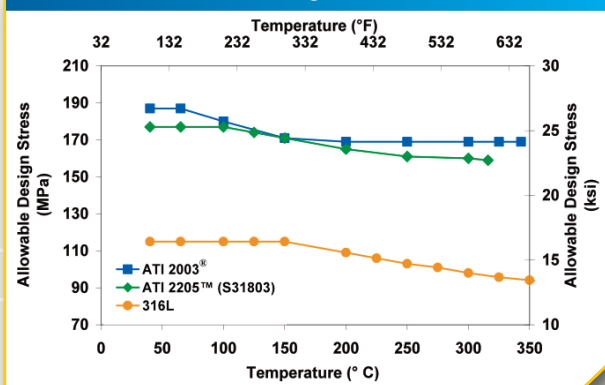
The chart shows the effect of high and low temperatures on the tensile properties of ATI 2003 alloy from -130 to 500°F (-90 to 260°C).

Tensile Properties of ATI 2003® LDSS at Various Temperatures

Temperature		Yield Strength		Tensile Strength		% Elongation
°F	°C	ksi	MPa	ksi	MPa	
-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

The accompanying figure shows the allowable design stresses for ATI 2003 LDSS per the ASME Boiler and Pressure Vessel Code as permitted by Code Case 2503-1 for Section VIII Division 1 use. Also shown are the allowable stresses for T 316L and ATI 2205 DSS as listed in Section VIII Division 1 of the BPV Code. The figure shows that the design strength of ATI 2003 LDSS is much greater than that for Type 316L and is comparable to that of ATI 2205 DSS. An upper temperature limit of 650°F (343°C) has been placed on the use of ATI 2003 LDSS 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 DSS, another embrittling range exists from about 1000°F (530°C) to 1830°F (1000°C) due to the precipitation of undesirable phases such as sigma 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 LDSS during welding are not a problem when using conventional techniques.

ASME BPV Allowable Design Stresses for Plate



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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.

Tensile Properties of Cold-Worked ATI 2003® LDSS					
Percent Reduction	Yield Strength		Tensile Strength		% Elongation
	ksi	MPa	ksi	MPa	
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

FORMABILITY

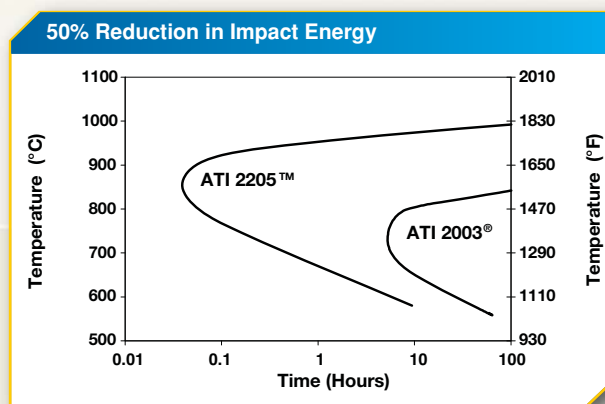
ATI 2003 LDSS can be successfully cold-bent and expanded to the same extent as other duplex stainless steels. Because of the higher strength of duplex grades, greater loads and more generous bend radii are required for forming compared to conventional austenitic materials. It is suggested that bend radii of at least two times the metal thickness be used when forming duplex stainless steels. Allowances may also need to be made for a larger springback than is seen with lower strength materials.

IMPACT PROPERTIES

ATI 2003 LDSS can 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). Exposing the alloy for extended periods of time at temperatures in the range from 650 to 1000°F (343-530°C) will increase the transition temperature. The use of proper duplex stainless steel welding procedures will result in excellent low-temperature impact resistance down to at least -58°F (-50°C).

Higher temperature exposures can embrittle some duplex alloys as a result of the formation of intermetallic phases such as sigma or chi. Due to its reduced alloy content, ATI 2003 LDSS resists embrittlement at these temperatures for much longer exposure times than traditional duplex alloys such as ATI 2205 DSS. The T-T-T curves to the right compare the time required to embrittle ATI 2003 alloy between 1100 and 1800°F (600 and 1000°C) with that for ATI 2205 DSS. While ATI 2205 DSS loses half of its impact resistance following only a few minutes of exposure near 1600°F (870°C), several hours of exposure are required to reduce the impact energy of ATI 2003 LDSS to the same extent.

As seen in the table to the right, 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.



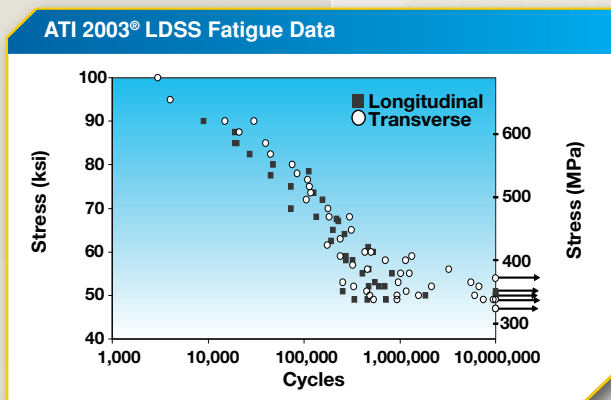
ATI 2003® LDSS Impact Energy (L-T Orientation)			
Temperature		Impact Energy	
°F	°C	ft-lbs	J
68	20	>300	>400
-4	-20	179	243
-58	-50	93	126
-94	-70	78	106
-130	-90	70	95

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FATIGUE

Flexural fatigue testing was performed on samples of annealed 0.035"-thick ATI 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 less than 50 ksi (345 MPa).



HEAT TREATMENT

ATI 2003 molybdenum-enhanced lean duplex stainless steel 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.

WELDING

ATI 2003 LDSS 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 ATI 2003 LDSS. 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 LDSS 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 LDSS shall be considered P-No. 10H, Group 1.

For more information, please see the publication "ATI 2003 (S32003) LDSS Weld Procedures & Evaluation," which may be downloaded from <http://www.alleghenyludlum.com>.



ATI 2003®

CORROSION RESISTANCE

General Corrosion Resistance

ATI 2003 LDSS is resistant to dilute reducing acids and moderate concentrations of oxidizing acids. The alloy is also resistant to low concentrations of organic acids. Corrosion rates in several solutions are shown in the Table below.

Test Solution	Corrosion Rate in Mills per Year (mm/y)			
	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 ₂ (SO ₄) ₃ •H ₂ SO ₄)	26.0 (0.66)	20.8 (0.53)	20.8 (0.53)	19.9 (0.51)
ASTM A262 Practice C (65% HNO ₃)	22.3 (0.57)	19.7 (0.50)	30.9 (0.78)	20.6 (0.53)
ASTM A262 Practice E (Cu•CuSO ₄ •H ₂ SO ₄)	Pass	Pass	Pass	Pass

* Sample Activated

Plain and welded samples of ATI 2003 alloy were exposed for over 1000 hours in a salt fog cabinet per ASTM B117. No signs of rust or pitting were observed.

Intergranular Corrosion

ATI 2003 LDSS was tested in accordance with ASTM Standard A262, 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 LDSS excellent resistance to intergranular attack (IGA).

Chloride Stress Corrosion Cracking (CSCC) 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 LDSS provides resistance to chloride stress corrosion cracking, making it substantially better than the standard 300 series austenitic stainless steels.

Alloy	Result
Type 304	Failed (850 Hours)
Type 316	Failed (530-940 Hours)
ATI 2102™	Passed (1000 Hours)
ATI 2003®	Passed (1000 Hours)
ATI 2205™	Passed (1000 Hours)

CSCC test results for U-Bend immersion testing in a boiling 26% sodium chloride solution.

Additional testing was performed in a saturated chloride solution at 82, 100, and 115°C for periods up to 2200 hours. The salt mixture 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. In this test, ATI 2003 alloy demonstrated good CSCC resistance in comparison to alloys commonly used for these applications.

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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.

Temperature	pH ₂ S	pCO ₂	pH ₂ O	pH	Solution
68°F (20°C)	0.01 bar	7.4 bar	6.1 bar	5.8	87.4g/l NaCl and 1.26 g/l NaHCO ₃
194°F (90°C)	0.1 bar	1.9 bar	0.7 bar	3.5	20% NaCl (120,000 ppm Cl ⁻)
194°F (90°C)	0.1 bar	39.9 bar	0.7 bar	3.0	1000 ppm Cl ⁻ and 500 ppm CH ₃ 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 ₃

Four-point bend test conditions. No cracking or pitting of ATI 2003® LDSS was observed after 30 days.

Pitting Corrosion Resistance

A relative ranking of the resistance to chloride-ion pitting 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 LDSS 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 LDSS passed the test at 41°F (5°C) and failed at 50°F (10°C). In comparison, Type 316L would fail in this test at approximately 32°F (0°C).

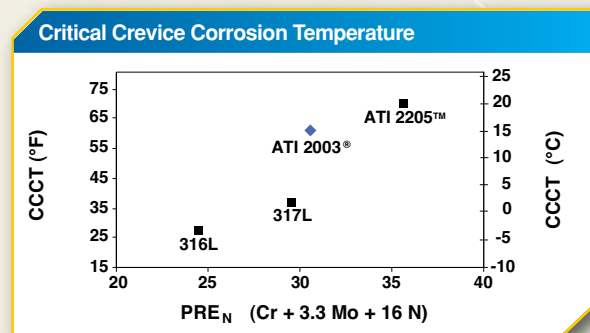
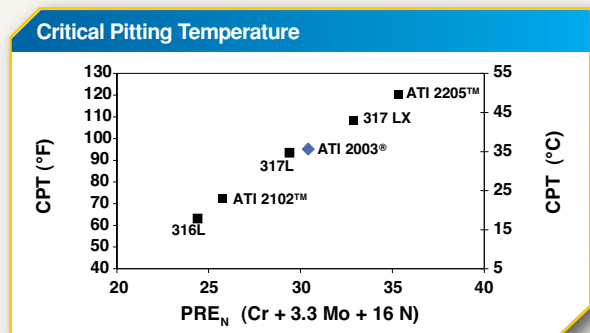
Crevice Corrosion Resistance

The critical crevice corrosion temperature (CCCT) of ATI 2003® LDSS base metal was determined using the ASTM G48, Practice B test. The CCCT was measured to be 61°F (16°C), which is between that measured for Type 317L and ATI 2205 DSS.

CONTACT INFORMATION

Please visit the following ATI Allegheny Ludlum web page for current sales contact information.
www.alleghenyludlum.com/ludlum/pages/contact/sales.asp

For general information on ATI and ATI Allegheny Ludlum products and technology, visit:
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