

# Development of a new "lean" duplex stainless steel, AL 2003™ Alloy (UNS S32003)

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## INTRODUCTION

Duplex stainless steels, so named because their microstructures consist of a mixture of austenite and ferrite, were discovered in the 1920's. However, the original duplex alloys suffered from brittleness and low ductility. It wasn't until the 1970's, when modern steelmaking practices allowed much more precise control of the composition, that steels resembling today's duplex alloys could be produced.<sup>1</sup> The most popular of the duplex grades to be developed in that era is the 22Cr alloy known as 2205. The 2205 alloy contains approximately 22% Cr, 5% Ni, 3% Mo and 0.16% N. When properly annealed, modern duplex alloys consist of a microstructure with roughly 50% ferrite and 50% austenite (Figure 1). These attributes give them a combination of strength and corrosion resistance that is superior to those of conventional austenitic stainless steels for many applications. However, the cost of the 2205 alloy is significantly higher than commonly used austenitic steels such as types 304 and 316. Also sigma phase precipitation can be a concern when 22Cr duplex has been exposed to heat from welding, annealing and stress relieving. In one instance in 1996, a 22Cr duplex valve broke during installation in a piping system in the North Sea.<sup>2</sup>

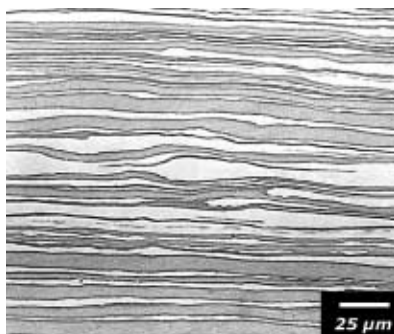


Figure 1. Typical microstructure of the annealed S32003 alloy

Grade	UNS Number	Cr	Ni	Mo	N	PREN
304 L	S30403	18.2	8.1	0.1	0.06	19.5
316 L	S31603	16.2	10.1	2.2	0.06	24.4
317 L	S31703	18.2	11.1	3.1	0.06	29.4
S32003	S32003	21.5	3.3	1.8	0.16	30.0
317 LX	S31725	18.5	14.0	4.1	0.06	33.0
317 LXN	S31726	19.5	16.5	4.1	0.16	35.6
2205	S32205	22.5	5.5	3.3	0.16	36.0

Table 1. Compositions and pre<sub>N</sub> numbers of several alloys.

Impact testing at -46°C gave values of 3-4 Joules versus the MDS minimum requirement of 45J average. The cause was found to be a brittle microstructure containing 26% intermetallic phases, as a result of incorrect heat treating. Table 1 lists a familiar group of established stainless steel alloys along with the a new alloy, S32003, which has been recently developed as an economic alternative to the other alloys, based on improved costs and reduced sensitivity to weld embrittlement over standard 22Cr duplex.

## CORROSION RESISTANCE

Of the alloys listed in Table 1, type 316L ranks the lowest in general corrosion resistance. This is supported by a number of ranking criteria including the Pitting Resistance Equivalent Number (PRE<sub>N</sub>), National Association of Corrosion Engineers (NACE) standards, and Stress Corrosion Cracking (SCC) testing<sup>3</sup>. The Nickel Development Institute (NiDI) promotes a pitting and crevice corrosion limit of 1,000ppm chlorides for type 316 in oxygenated water at near neutral pH and ambient temperatures in temperate climates<sup>4</sup>. More aggressive process environments usually call for higher

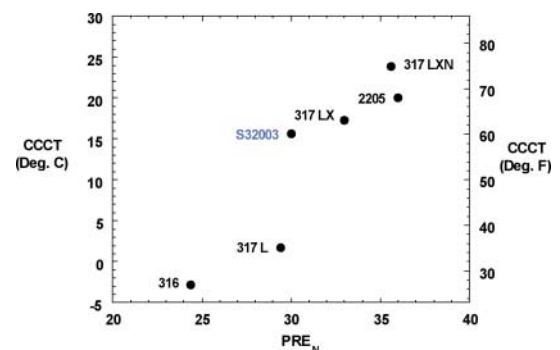


Figure 2. Critical Crevice Corrosion Temperature test results for several alloys, tested, tested in accordance with ASTM G 48 Method B 6.

alloys such as 317, 317LXN, or 2205. Figure 2 compares the Critical Crevice Corrosion Temperature (CCCT) as plotted against the Pitting Resistance Equivalency (PRE<sub>N</sub>). PRE<sub>N</sub> is a good indicator of the relative corrosion resistance to chloride pitting in aqueous environments. It is calculated according to the following formula:

$$PREN = \%Cr + 3.3(\%Mo) + 16(\%N) \quad (1)$$

To verify the expected pitting corrosion resistance, the alloys were tested according to the ASTM Standard G 150 electrochemical critical pitting temperature test<sup>5</sup>. The results of these tests are listed in Table 2.

Another commonly prescribed corrosion test to ascertain the resistance to attack of the 2205 alloy is ASTM Standard A 923 Method C<sup>6</sup>. This tests the alloy's vulnerability to attack due

Grade	CPT °C	CPT °F	PREN
316 L	17	63	24.4
317 L	33	93	29.4
S32003	35	95	30.0
317 LX	42	108	33.0
2205	49	120	36.0

**Table 2. Critical pitting test results in accordance with ASTM G150.**

Alloy	Result
304L	Failed (850 hours)
316	Failed (530-940 hours)
317L	Failed (1000 hours)
S32003	Passed (1000 hours)
2205	Passed (1000 hours)

**Table 3. CSCC test results for various alloys in boiling 26% NaCl.**

to the precipitation of detrimental intermetallic phases. Using this test, three different thicknesses of S32003 alloy were tested by immersion in a 6% by mass ferric chloride solution for 24 hours. All of the samples passed the test at 75°F (24°C) by meeting the test criteria of < 10 mdd corrosion rate.

Since chloride stress corrosion cracking resistance is important in a variety of end uses, AL 2003 alloy was tested by immersing U-bends into boiling solutions of 26% NaCl. The results of these tests for S32003 alloy and some comparative alloys are shown in Table 3. Conclusions from the corrosion test work were that the new lean duplex S32003 compares favorably to 317L and is equally positioned between 2205 and 316L.

**WELDABILITY**

An important consideration in assessing the weldability of an alloy is the need for field repair that is not subsequently heat-treated. For the 300 series, a general rule is that increasing nickel content results in decreasing delta ferrite content. Some ferrite is necessary to avoid cracking from solidification shrinkage. If thin sections are not involved, a filler rod can be obtained that prevents the cracking problem. In the case of duplex stainless steels, the concern is for avoiding the detrimental effects of the precipitation of second phases such as sigma phase. This concern is considered high for superduplex, moderate for

22Cr, and low for lean duplex. Figure 3 shows the time-temperature relationship of how quickly 22Cr duplex loses 50% of its impact strength, compared to the long time period necessary to affect the S32003 lean duplex alloy. This higher tolerance to HAZ embrittlement also allows S32003 to maintain corrosion resistance and low temperature impact strength. Work is currently concluding on low temperature impact testing of welds made on S32003 via GTAW, GMAW with 2209 wire, SAW, and Flux Core Welding, and will be reported later. Additional work is planned for other weld processes including EB, Laser, and Plasma Arc.

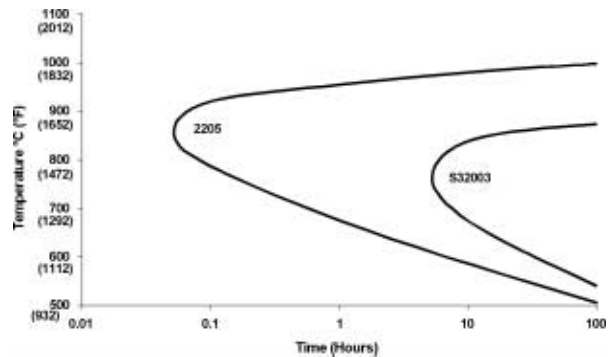
Pitting resistance of welds was also evaluated, per ASTM Standard G48 Method C (72 hours immersion in an acidified ferric chloride solution)<sup>7</sup> on samples of the S32003 alloy that were Gas Metal Arc welded to a dissimilar alloy using 2209 weld wire. The alloy chosen was the 2304 duplex alloy (UNS S32304). The results were that the 2304 heat affected zone (HAZ) pitted at 50°F (10°C) and the 2304 base metal pitted at 60°F (15.5°C), while neither the base metal nor the HAZ of the S32003 alloy were affected at either temperature. 2209 weld wire has performed satisfacto-

rily in the welding of the S32003 alloy.

Gas Tungsten Arc welded S32003 plate material was also tested for intergranular corrosion resistance per ASTM Standard A 262, Practices B, C, and E<sup>8</sup>. The results of these tests are shown in Table 4.

**MECHANICAL PROPERTIES**

In addition to excellent corrosion performance, the mechanical properties of the S32003 alloy make it very useful for fabricators and end users seeking higher strength and corrosion resistance greater than that of T 316L. Table 5 shows the typical strength level of the S32003 alloy compared to those of other alloys. It should be noted that for strip produced for the manufacture of welded tubing, yield strength levels have consistently been measured above 80 ksi (550 MPa), which may be an important consideration for sub sea systems where pressure in deep water limits some material selections.



**Figure 3. TTT Diagram for the S32003 and 2205 alloys, showing exposures that result in a 50% reduction in impact energy.**

Standard	Test Solution	Base Metal	Weld
Practice B	Ferric Sulfate - Sulfuric Acid	0.0027 ipm	0.0072 ipm
Practice C	Nitric Acid	0.0014 ipm	0.0018 ipm
Practice E	Copper - Copper Sulfate - Sulfuric Acid	No Cracking	No Cracking

**Table 4. Results of corrosion tests on welded S32003 materials, ASTM A262.**

Grade	Yield Stress (MPa)	Yield Stress (ksi)	Tensile Stress (MPa)	Tensile Stress (ksi)	Percent Elongation
304 L	207	30	586	85	60
316 L	303	44	607	88	57
317 L	317	46	607	88	50
317 LXN	345	50	621	90	45
S32003	517	77	724	105	40
2205	586	85	862	125	30

**Table 5. Typical tensile properties of selected alloys.**

Reduction Percent	Yield Stress		Tensile Stress		Elongation in 2" Percent
	ksi	MPa	Ksi	MPa	
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

**Table 6. Tensile properties of S32003 alloy as a function of percent cold reduction.**

% Reduction	68°F (20°C)		-40°F (-40°C)		-50°F (-46°C)	
	ft-lbs	J	ft-lbs	J	ft-lbs	J
0	298	404	85	115	78	105
10	98	132	46	62	45	60
20	60	81	35	47	33	44

**Table 7. Tensile properties of S32003 alloy as a function of percent cold reduction.**

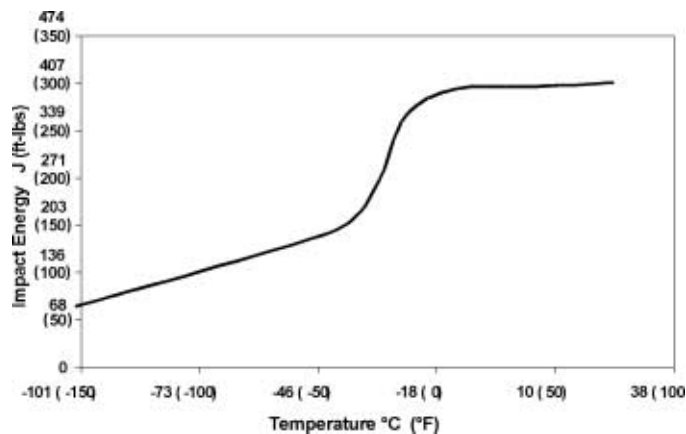
The Charpy impact test data shown for the S32003 alloy in Figure 3 reflect the material's good resistance to HAZ sensitization due to sigma phase formation. This was also reflected in the good corrosion resistance displayed in the ASTM A923 tests of welded material and the ASTM G48 C tests of dissimilar metal welds. Additional impact testing was performed on 0.5 in (1.27 cm) plate samples in accordance with ASTM Standard E 23<sup>9</sup> to measure the effect of sub-zero temperatures on impact strength. A curve plotted through the mean values of impact strength is shown in Figure 4, which shows that the S32003 alloy easily meets the 2205 alloy criterion of 40 ft-lbs (54 J) at -40 to -50°F (-40 to -46°C). The effects of cold working on the mechanical properties of the S32003 alloy were also investigated. Table 6 shows the tensile properties of the S32003 alloy following varying amounts of cold work. Table 7 shows the results of Charpy impact tests performed on plates that had been cold worked to 10 and 20% reductions. Elevated temperature tensile testing of S32003 material was conducted to determine its usefulness at temperatures up to 600°F (316°C). The results of those tests are shown in Table 8. Flexural fatigue tests were performed on S32003 material in both the longi-

tudinal and transverse directions. The results, shown in Figure 5, show an endurance limit of almost 50 ksi (345 MPa).

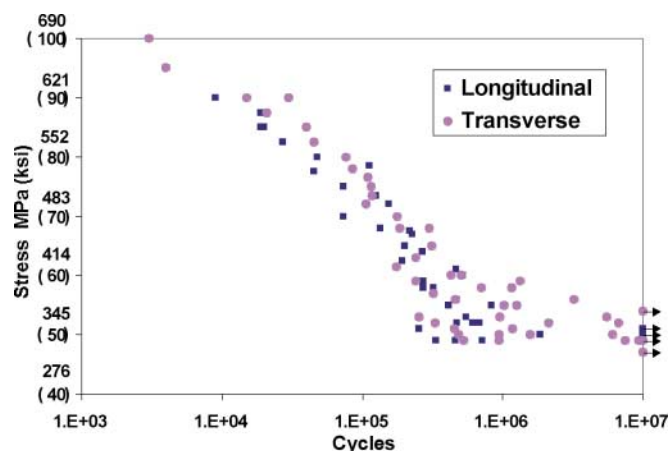
**COSTS**

Raw materials and manufacturing are the main contributors to the cost of a product. The costs of alloying elements such as nickel, chromium and molybdenum have become so volatile that today's price quotes include material surcharges that reflect the raw material's recent market value. Duplex stainless (and particularly lean duplex) are less prone to raw material fluctuations due to lower contents of Ni and Mo. S32003 sat-

isfies the definition of "lean" in terms of reduction of expensive raw materials, while not impairing the attributes of duplex in terms of strength, resistance to SCC and weldability. As shown in Table 1, the composition of the S32003 alloy is similar to that of the 2205 alloy, except that it contains less of the costly elements Cr, Ni, and Mo. Some consequences of being "too lean" are high manufacturing costs due to a material's poor castability, hot and cold formability problems, impaired weldability, and a loss of corrosion resistance and mechanical strength. Manufacturing costs can also be affected by the over-use of lower cost elements, such as manganese, copper and nitrogen as substitutes for nickel, or silicon substitution for chromium or molybdenum. Life-cycle costs are a separate consideration that becomes important to design engineers and end-users. Lean duplex stainless steel alloys are considered economic alternatives to the 300



**Figure 4. Impact energy versus temperature for the S32003 alloy**



**Figure 5. Flexural fatigue test results for the S32003 alloy**

Temperature		Yield Stress		Tensile Stress		Elongation in 2"
°F	°C	ksi	MPa	Ksi	MPa	Percent
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

**Table 8. S32003 alloy elevated temperature tension test results.**

Heat #	C	Mn	Si	Cr	Ni	Mo	N
1	0.021	0.50	0.44	20.25	3.27	1.80	0.167
2	0.018	0.50	0.46	20.13	3.35	1.84	0.161
3	0.018	0.46	0.45	20.18	3.24	1.84	0.166
4	0.017	0.65	0.48	20.40	3.30	1.68	0.162
5	0.016	0.43	0.61	21.61	3.28	1.80	0.157

**Table 9. Compositions of the first five production heats of S32003 alloy.**

series alloys for many end uses due to improved wear resistance, enhanced corrosion resistance, and higher strength, which provide opportunity for thickness reductions. Olsen and Groth reported a 30% weight savings in one application based on ASME design criteria for 22Cr duplex versus 316L.<sup>10</sup>

**ALLOY DEVELOPMENT**

Several 50-lb (22-kg) lab heats were made and processed at ATI. The alloy compositions were chosen based on the results of thermodynamic and empirical models so that their ferrite contents would be between 35 and 65%, and the austenite would be stable with respect to martensite formation. A total of five lean duplex alloys were made, and they were subjected to a number of screening tests to determine which had the optimal combination of mechanical properties and corrosion resistance. The results showed that the best properties were obtained for a specific compositional range. The alloy, UNS S32003, is known commercially as AL 2003™ alloy.

**PRODUCTION EXPERIENCE**

At the time of this submission, five production heats of the S32003 alloy have been made in lots of up to 125 tons. The compositions of these heats are shown in Table 9.

The alloy's response to high productivity processes such as continuous

casting, hot rolling, cold rolling, annealing and pickling, etc. has been very favorable. Thus S32003 lean duplex also attains the ability for lean manufacturing.

**APPLICATIONS**

Production quantities have been supplied to fabricators and end users affiliated with major industries such as power generation, oil and gas, pulp and paper, desalination, chemical processing, and architecture.

*Oil & gas*

Work is under way to obtain NOR-SOK approvals and samples are being evaluated for a number of applications where 316L and 2205 are already used, such as: subsea manifolds and flowlines, subsea piping and umbilicals, and topside hydrocarbon process systems.

*Pulp & paper*

Duplex stainless with minimum 20%Cr are preferred for batch digesters and are finding an increasing number of applications where ever 316 falls short of expectations<sup>11</sup>. Included are steaming vessels, blow tanks and many items of the Chemical Recovery and Air Quality Control sections which experience concerns with SCC, wear and cost due to heavier design wall requirements on lower strength 316L. S32003 samples are currently being evaluated for the potential end uses described.

**Desalination**

Large amounts of 316 and 22Cr duplex are currently used for the desalination of brackish water. Opportunities exist for lean duplex S32003 to be used as an economic alternative for pipe systems, particularly for reverse osmosis plants but also for shells in thermal desalination processes.

**CHEMICAL PROCESSING**

In December 2002, SSW reported the use of over 40,000 tons of 2205 for Stolt Parcel Tankers that transport chemicals ranging from juice concentrates to fertilizer products.<sup>12</sup>

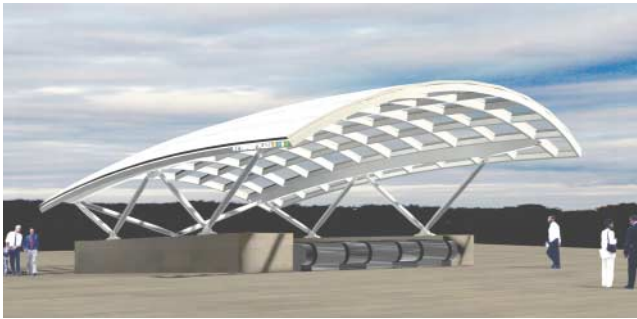
Piping systems for loading and unloading tankers are also using 316 and 22Cr duplex. Advantages of a lean S32003 duplex in this application are the ability to handle a greater variety of chemicals than 316, while being lower cost than 2205. Even high pressure testing and flushing with sea water can be performed with appropriate steps afterwards to sufficiently clean with fresh water.

*Architecture*

Duplex stainless steels are finding greater acceptance in architectural applications over conventional 304/316, especially where structural advantages are realized with reduced weight due to their higher strengths. Figure 6 shows a recent example where S32003 was chosen over tempered 304L for the structural members of the canopies covering the entrances of the Washington D.C. Metro subway system. In addition to the reduced weight advantage and the added corrosion resistance to road salt, chemical cleaners and acid rain pooling, the higher strength provided an added incentive of being more resistant to permanent markings by graffiti artists.

**ADDITIONAL WORK**

In addition to completing the welding work currently in progress, additional testing is planned to obtain data on Chloride Stress Corrosion Cracking (CSCC), and Sulfide Stress Cracking (SSC).



**Figure 6. UNS S32003 Alloy used for the Washington D.C. Metro canopy**

**CONCLUSIONS**

The S32003 alloy has displayed excellent corrosion resistance, mechanical properties, weldability, and low cost process ability, which make it both functionally and economically attractive to a variety of end users and fabricators.

Welding the S32003 alloy with 2209 weld wire produced an acceptable product, with corrosion resistance superior to that of the 2304 alloy in both the HAZ and the base metal. The S32003 alloy can be considered a lean version of the 2205 alloy with a substantially higher resistance to weld zone sensitization from the effects of sigma phase formation, and corrosion resistance generally better than 317L. The S32003 alloy can be considered an economical alternative to the higher alloyed 300 series stainless steels such as 316 and 317, due to its high strength, low life cycle cost and superior corrosion resistance. ◀

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