PRACTICAL GUIDE TO USING 6MO AUSTENITIC STAINLESS STEEL

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Nº 10032

Reprinted from
Materials Performance, Dec 1988

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Practical Guide to Using 6 Mo Austenitic Stainless Steels

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This article gives information on the metallurgy, crevice corrosion, and chloride stress corrosion cracking resistance, design, and fabrication, as well as specifications and commercial product forms available of alloys 254 SMO,™ Al-6X,™ AL-6XN,™ 1925 hMO (25-6MO), and 20 Mo-6.™ ASME Boiler and Pressure Vessel Code design stresses for temperatures up to 800 F (427 C), ASTM Specifications for product forms, and specific welding filler metals and heat treatment requirements are included.

A new level of corrosion-resistant austenitic stainless steels, sometimes characterized as the "6 Mo superaustenitics," has become available over the last few years. A distinguishing characteristic of these highly alloyed grades is that they are produced for the most part on the same equipment with the same scrap and low-cost alloy charge material used for the common grades such as type 316L. Although ladle metallurgy and special processing may be required, these 6% Mo austenitic stainless steels can be delivered at a much lower cost than the nickel-based alloys that have been produced for many years. Furthermore, because nitrogen is used as an alloy addition, the 6 Mo austenitic stainless steels provide increased strength and substantially better corrosion resistance than the common 300 series austenitic stainless steels or some conventional nickel-based corrosion-resistant alloys.

The availability of the 6 Mo austenitics is timely for the operating engineers in the chemical processing, pulp and paper, food and drug, and power industries. In these industries, as in others using stainless steels, trends in operating conditions lead to a need for more corrosion-resistant stainless steels that can be integrated as critical equipment or components with larger constructions of conventional grades of stainless steels.

These trends include: (1) increased production efficiency; (2) reduced risk of costly unscheduled downtime; (3) reduced maintenance costs; and (4) increased severe environmental restrictions. Each of these trends leads to increasingly corrosive operating conditions and the conflicting requirement that the materials of construction be even more resistant to both design operating conditions and possible excursions of conditions that may be reasonably anticipated in practice.

Although there are several austenitic stainless steels with 6% molybdenum, only those offered commercially in the United States are discussed. The list of grades and suppliers should not be considered exhaustive. Minor differences exist among the 6 Mo austenitics. Each producer approached his grade with a highly independent technical development, usually with different production capabilities and experiences, and frequently with different applications in mind. While each producer is able to point to isolated instances where his grade has an advantage, very little difference exists among the grades for the majority of applications. Commercial considerations of availability, price, and technical support are frequently the decisive criteria for selection among the 6 Mo austenitic grades.

The leading 6 Mo austenitic stainless steels are listed in Table 1 with both common names, some of which are trademarks, corresponding UNS numbers, and the ASTM composition ranges. ASTM defines a stainless steel as having at least 50% iron. By this convention, only 254 SMO™ is listed among the ASTM stainless steel specifications. The remaining grades are listed as nickel-based alloys. But this distinction is purely artificial. These 6 Mo

TABLE 1
6 Mo Austenitic Stainless Steels and Other Austenitic Grades

UNS Number	Common Name	Producers	Chemical Composition (wt%)* Cr	Ni	Mo	Cu	N	C
S31254	254 SMO[(1)]	Avesta	19.50-20.50	17.50-18.50	6.00-6.50	0.50-1.00	0.18-0.22	0.020 max
J93254	Cast 254 SMO[(1)] CK-3MCuN	Various licencees	19.50-20.50	17.50-18.50	6.00-6.50	0.50-1.00	0.18-0.22	0.020 max
N08366	AL-6X[(2)]	Allegheny Ludlum	20.00-22.00	23.50-25.50	6.00-7.00	—	—	0.035 max
N08367	AL-6XN[(2)]	Allegheny Ludlum	20.00-22.00	23.50-25.50	6.00-7.00	0.75 max	0.18-.025	0.030 max
N08925	1925 hMo 25-6MO	VDM Technologies Inco Alloys International	19.00-21.00	24.00-26.00	6.0-7.0	0.8-1.5	0.10-0.20	0.020 max
N08026	20Mo-6[(3)]	Carpenter Technology	22.00-26.00	33.00-37.20	5.00-6.70	2.00-4.00	—	0.03 max
S30403	Type 304L	Many	18.00-20.00	8.00-12.00	—	—	0.10 max	0.030 max
S31603	Type 316L	Many	16.00-18.00	10.00-14.00	2.00-3.00	—	0.10	0.030 max
N08904	Alloy 904L	Many	19.00-23.00	23.00-28.00	4.0-5.0	1.0-2.0	—	0.020 max

*ASTM Composition Limits
(1)Registered trademark and patented alloy of Avesta AB.
(2)Registered trademark and patented alloy of Allegheny Ludlum Corp.
(3)Registered trademark and patented alloy of Carpenter Technology Corp.

grades are all produced and marketed through stainless steel manufacturers and distribution channels.

254 SMO evolved from the standard austenitic grades, with the addition of nitrogen. Nitrogen is economical because it decreases the need for nickel to stabilize the austenitic structure. Nitrogen is essential to quality in the 6 Mo austenitics because it delays formation of the chromium-molybdenum intermetallic sigma phase; provides higher strength; and, in particular, improves pitting resistance. The precise control of composition needed for these grades, made possible by modern refining equipment, is demonstrated by the narrow ranges in the ASTM specifications. For 254 SMO, the producer has documented an optimal contribution to both sulfuric acid and chloride resistance by the particular level of copper addition. This grade has pulp bleach plant equipment installations dating from 1977 still in service for replacement of rapidly failed type 317L and alloy 904L. In addition, several thousand tons of 254 SMO have been used in critical piping systems for the North Sea oil production platforms.

AL-6X™ evolved from a nickel-based alloy and relies on nickel to stabilize the austenitic structure. Without a nitrogen addition, AL-6X could be produced only as light gage strip and tubing, with a thickness maximum of about 0.065 in. (1.7 mm), because of its tendency to form sigma phase rapidly. It has found wide use in seawater-cooled condensers for power plants. Since 1973, about 24 million ft (8 million m) of AL-6X condenser tubing has been placed in service.

AL-6XN,™ the nitrogen-enhanced version of AL-6X, was introduced in 1984. AL-6XN has largely replaced AL-6X commercially. The addition of nitrogen allows AL-6XN to be produced over a full range of forms and sizes, with all of the benefits of nitrogen described above. The nickel content is retained at its original high level and provides advantages in some reducing acids. The high strength originally attributed to AL-6XN is being revised to *somewhat* lower values to reflect production experience.

The grade most commonly designated 1925 hMo, and more recently offered as 25-6MO, is a modification of the lower-molybdenum sulfuric acid grade, 904L. Neither 904L nor 1925 hMo—25-6MO—are patented. The nitrogen and copper levels in their specifications are being modified to levels comparable to 254 SMO.

20Mo-6™ is a 6% molybdenum modification of alloy 20. It is significantly higher in chromium and nickel than the other 6 Mo grades. Because of its higher nickel and copper contents, the resistance of 20Mo-6 in reducing acids would be expected to be superior.

Corrosion Resistance

The primary corrosion environments for the application of the 6 Mo austenitics are chlorides.

TABLE 2
Critical Crevice Temperature (CCT) for Some
6 Mo and Other Common Austenitic Stainless Steels

UNS Number	Grade	Critical Crevice Corrosion Temperature in 10% $FeCl_3 \cdot H_2O$ (pH 1) (F)	(C)
S31254	254 SMO	90.5	32.5
N08366	AL-6X	63.5	17.5
N08367	AL-6XN	90.5	32.5
S30403	Type 304L	<27.5	<−2.5
S31603	Type 316L	27.5	−2.5
N08904	Alloy 904L	32	0

TABLE 3
Chloride Stress Corrosion Cracking Resistance of the
6 Mo Austenitics and Common Stainless Steels
(P = Pass, F = Fail)

UNS Number	Grade	Boiling 42% $MgCl_2$	Wick Test	Boiling 25% NaCl
S31254	254 SMO	F	P	P
N08366	AL-6X	F	P	P
N08026	20Mo-6	F	P	P
S30403	Type 304L	F	F	F
S31603	Type 316L	F	F	F
N08904	Alloy 904L	F	P or F	P or F

Many operating engineers think of their chemical processing environments in terms of the major process reaction (or reactions). But for a stainless steel, more often it is correct to focus on *minor constituents* and to think of the operating environment in terms of a strong chloride solution with varying temperature and acidity.

Table 2 shows the critical crevice temperature (CCT) in 10% $FeCl_36H_2O$ (pH 1) for several of the 6 Mo austenitics and some of the more common stainless steels. For a particular environment and crevice geometry, each stainless steel will have a critical temperature above which crevice corrosion initiates. Comparing the 6 Mo austenitics to some common austenitics, a dramatic improvement of corrosion resistance is noted by increasing molybdenum and nitrogen. Among the 6 Mo grades, nitrogen has a powerful effect, but nickel and copper seem to have almost no effect. The ferric chloride test is effective in ranking materials, but the CCT is not necessarily predictive of results in other environments.

The 6 Mo austenitics offer a practical engineering solution to chloride stress corrosion cracking (SCC) in sodium chloride environments. The susceptibility of type 316 to SCC has many engineers concerned about the use of *any* austenitic stainless steel in heat transfer situations in high-chloride environments. As shown in Table 3, the 6 Mo austenitics are not resistant to the standard laboratory test in boiling 42% magnesium chloride, *but this test is far too severe to be representative of practical applications involving environments containing sodium chloride.*

The "Wick Test" and the boiling 25% sodium chloride test correlate well with field experience for both success and failure of austenitic grades in SCC applications. All 6% Mo grades resist cracking *indefinitely* in sodium chloride tests. Alloy 20 and also alloy 2205, a duplex stainless steel, show similar laboratory test behavior and are used successfully to remedy SCC problems. Service experience with 6 Mo austenitics confirms these test results. Thousands of tons of 254 SMO, AL-6X, and now AL-6XN, are in service in pulp and paper bleach plants, seawater applications, and process industry equipment, and no SCC has been reported after more than 10 years' exposure.

Design and Fabrication

The 6 Mo austenitics have strength levels about 50% higher than those of type 316L. As shown in Table 4, these higher strengths are reflected in the allowable design stresses in the ASME Code tables. These values have been confirmed by extensive statistical surveys for commercial production of 254 SMO product forms over a full range of thicknesses. The values for AL-6XN were originally based on experience with light gage product forms, and were overstated in the Code for heavier sections; they are being revised downward. The values shown for 1925 hMo/25-6MO are conservative, especially once the nitrogen level is formally increased to be comparable to the level of 254 SMO and AL-6XN. There appears to be no basis to suggest that any particular 6 Mo grade has an advantage over the other grades in mechanical strength properties.

Although of high strength, the 6 Mo austenitics exhibit the excellent toughness and ductility characteristic of the 300 series austenitics. The design engineer upgrading from types 304/304L and 316/316L to the 6 Mo austenitic grades has the opportunity for construction economies by down-gaging. The 6 Mo austenitics are readily fabricated with standard equipment once allowances are made for the higher strength levels and the slightly higher springback.

If the 6 Mo austenitics need to be annealed or stress relieved, they ***must*** be given a full anneal and

TABLE 4
Design Stress (ksi), ASME Boiler and Pressure Vessel Code, Section VIII, Division 1 for Plate(1)

UNS Number	Grade	Temperature (F) 100	200	300	400	500	600	650	700	750	800
S31254	254 SMO	23.5	23.5	21.4	19.9	18.5	17.9	17.7	17.5	17.3	—
	254 SMO(2)	23.5	23.5	22.4	21.3	20.5	20.1	19.9	19.9	19.8	—
N08366	AL-6X	18.8	18.8	15.6	—	—	—	—	—	—	—
N08367	AL-6XN(2)	—	26.0	24.3	22.7	20.9	19.9	19.3	19.3	18.7	18.4
N08925	1925 hMo 25-6MO	—	21.7	20.9	19.6	18.3	17.3	16.9	16.9	16.9	16.9
N08026	20Mo-6	20.0	20.0	18.9	17.5	16.3	15.3	14.9	14.6	14.2	13.9
	20Mo-6(2)	20.0	20.0	19.6	19.2	18.5	18.1	17.8	17.5	17.3	17.0
S30451	Type 304N	20.0	19.1	16.7	15.0	13.9	13.2	13.0	12.7	12.5	12.3
	Type 304N(2)	20.0	20.0	19.0	18.3	17.8	17.4	17.3	17.1	16.9	16.6
S31603	Type 316L	16.7	14.1	12.7	11.7	10.9	10.4	10.2	10.0	9.8	9.6
	Type 316L(2)	16.7	16.7	16.0	15.6	14.8	14.0	13.8	13.5	13.2	13.0
N08904	Alloy 904L	17.8	16.7	15.1	13.8	12.7	12.0	11.7	11.4	—	—

(1)ASME Code Tables are published in English units only.
(2)The higher stress values (included in entire lines of data) were established at temperatures where the short-time tensile properties govern to permit the use of these alloys where slightly greater deformation is acceptable due to the relatively low yield strengths of these materials. These higher stress values exceed 67% but do not exceed 90% of the yield strength at temperature.

water quench. Some disagreement exists among the producers whether 2050 F (1120 C) or 2150 F (1175 C) is the minimum annealing temperature; the different positions all are based on sound technical reasoning.The fabricator should follow the producer's recommendations for annealing his grade with special attention to ensure that the workpiece has minimal temperature decrease from the annealing temperature to the instant of water quench. Heat treatments that permit the 6 Mo austenitics to spend time in the 1300 to 1900 F (705 to 1040 C) range risk extensive sigma phase formation with loss of corrosion resistance and possibly toughness.

There are some important differences between the 300 series stainless steels and the 6 Mo austenitics in welding. Because of their high alloy contents, the 6 Mo austenitics are particularly susceptible to molybdenum segregation during solidification of an autogenous weld, or a weld without filler metal. Although a few exceptions relate to high speed, automatic welding with low heat input and rapid quenching (for example, production of thin wall condenser tubing), autogenous welding without subsequent full annealing reduces the corrosion resistance of the 6 Mo austenitic grades. The fabricator should never create an autogenous weld on the 6 Mo austenitics *unless prepared to perform a subsequent full anneal and quench*. This prohibition applies to both primary welding and to any minor repair and patch welding.

Welding the 6 Mo austenitics is relatively simple: use filler metals that are sufficiently overalloyed with molybdenum that the welds are more resistant to corrosion than the base metal. The filler metal most frequently used has been alloy 625 with 9% molybdenum, but some fabricators prefer alloy C-276 or C-22. These filler metals are sufficiently overalloyed to compensate for the lower resistance of the as-welded structure. Welds made with these fillers can be used in the as-welded condition. In every case, it is essential that the welder follow conscientious practices of cleanliness before and after welding, and superior gas or slag shielding during welding. The heat inputs and weldment sizes are restricted to avoid hot cracking of these high-nickel filler metals.

Specifications and Availability

Tables 5 and 6 list the available product forms, applicable specifications, and common availability channels of the 6 Mo austenitics. Some producers may argue that various product forms are "available," but the end user usually thinks of availability in terms of timely delivery of required product forms and quantities, not just production capability. Also, availability can change rapidly as producers and distributors are increasingly responsive to user needs.

Since the 6 Mo grades appear both in stainless steel specifications and in nickel-based alloy specifications the user should be careful to select

TABLE 5

6 Mo Austenitics Meet a Variety of ASTM Specifications and ASME Codes

UNS Number	Grade	ASTM	ASME Section VIII, Divison 1	ASME Section III, Divison 1
S31254	254 SMO	A167, A182, A240, A249, A267, A269, A312, A358, A409, A473, A479, A193,(1) A194,(1) A403(1)	Table UHA-23	Code Case N-439, N-441
J93254	Cast 254 SMO CK-3MCuN	A351, A743, A744	Code Case 2036	Code Case N-440
N08366	AL-6X	B675, B676, B688, B690, B691	Table UNF-23.3	Code Case N-304
N08367	AL-6XN	B366, B462, B472, B564, B675 B676, B688, B690, B691	Table UNF-23.3	Code Case N-438
N08925	1925 hMo 25-6MO	B625, B649, B673, B764, B677	Table UNF-23.3(1)	Code Case N-453, N-454, N-455
N08026	20Mo-6	B463, B464, B468, B474	Table UNF-23.3	No

(1) Pending

the specific grade and applicable specifications, noting all options when seeking competitive responses. Having alternative suppliers of essentially equivalent grades allows the user to have assurance of continued supplies at competitive prices.

Applications

The 6 Mo austenitic stainless steels are finding wide application in process industry environments. They have replaced common austenitic stainless steels that have failed by pitting, crevice corrosion, and chloride stress corrosion cracking. Equipment fabricated of 6 Mo austenitics has included crystallizers, mixing vessels, pressure vessels, tanks, columns, evaporators, heat exchangers, piping, pumps, and valves. Seawater-cooled condensers, service water piping for nuclear power plants, and flue gas desulfurization (FGD) scrubbers' components (including ducting, absorbers, and internals) have been fabricated from 6 Mo austenitics.

This new class of corrosion-resistant austenitic stainless steels has provided the process industries with an economical, highly effective class of materials to enhance productivity, reduce risks of unscheduled downtime, reduce maintenance costs, and meet the need of mandated restrictions on effluents.

TABLE 6

6 Mo Austenitic Product Availability

Grade	Product Forms Available	Distributor Channels
254 SMO	Plate, sheet, strip, bar, billet, wire	A.M. Castle
	Pipe, fittings, tubing	Tubesales
	Condenser tubing	Trent Tube
AL-6X	Condenser tubing	Allegheny Ludlum
AL-6XN	Plate sheet, strip, bar, billet, wire, pipe, fittings, tubing	Rolled Alloys
	Pipe, fittings	Trent Tube
	Condenser tubing	Allegheny Ludlum
1925 hMo	Plate, sheet, strip, pipe, tubing, bar, billet	VDM Technologies
25-6MO	Plate	Inco Alloys International
20Mo-6	Plate, sheet	Rolled Alloys
	Bar, billet, strip, wire	Carpenter Service Centers
	Tubing, pipe	Trent Tube