New Castle Stainless Plate, LLC

High Performance 6% Mo Austenitic Stainless Steel

NC4529

UNS N08367/UNS N08926

General Properties

NC4529 is a 6% Mo austenitic stainless steel designed for maximum resistance to pitting and crevice corrosion. With high levels of chromium, molybdenum, and nitrogen, these grades are especially suited for high-chloride environments such as brackish water, seawater, pulp mill bleach plants, and other high-chloride process streams. NC4529 offers chloride resistance superior to that of Alloy 904L, Alloy 20, Alloy 825, and Alloy G and is compatible with the common austenitic stainless steels. It is often used as a replacement in critical components of larger constructions where Type 316L or 317L has failed by pitting, crevice attack, or chloride stress corrosion cracking. In new construction, 6% Mo stainless steels have been found in many cases to be a technically adequate and much less costly substitute for nickel-base alloys and titanium.

6% Mo stainless steels are substantially stronger than the common austenitic grades, and are also characterized by high ductility and impact strength and can be readily fabricated and welded.

Design Features

- High resistance to pitting, crevice corrosion, and chloride stress corrosion cracking
- 50% stronger than 300-series austenitic stainless steels
- Excellent impact toughness
- Excellent workability and weldability

Applications

- Seawater handling equipment
- Pulp mill bleach systems
- Tall oil distillation columns and equipment
- Chemical processing equipment
- Food processing equipment
- Desalination equipment
- Flue gas desulfurization systems
- Oil and Gas production equipment

Chemical Composition (wt%) *Table 1*

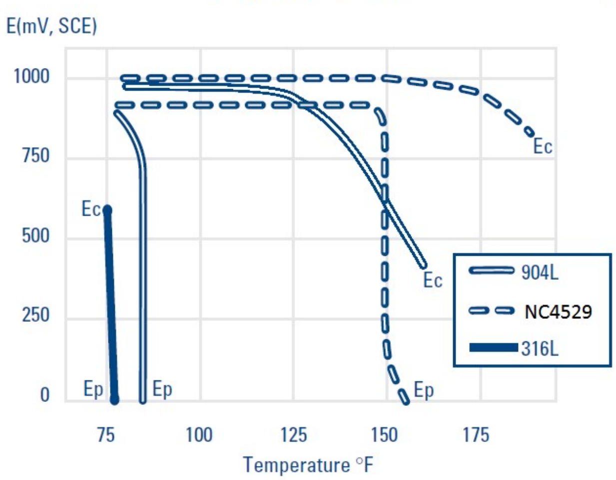
	C	Mn	Cr	Ni	Mo	N	Other
Typical	0.01		20.5	24.8	6.5	0.2	Cu:0.6
ASME SA-240	≤0.020	≤2.00	19.00-21.00	24.0-26.0	6.00-7.00	0.15-0.25	Cu:0.50-1.50
ASTM A240 (N08367)	≤0.030	≤2.00	20.0-22.0	23.5-25.5	6.0-7.0	0.18-0.25	
ASTM A240 (N08926)	≤0.020	≤2.00	19.0-21.0	24.0-26.0	6.0-7.0	0.15-0.25	Cu:0.5-1.5
EN 10028-7 (1.4529)	≤0.020	≤1.00	19.00-21.00	24.0-26.0	6.00-7.00	0.15-0.25	Cu:0.50-1.50

Resistance to Chloride Pitting Corrosion

Pitting is a highly localized form of corrosion. Once started, pitting can lead to perforation in a short time with little total weight loss. Pitting is usually caused by chlorides (or other halides), aggravated by more acidic conditions and higher temperatures. With high levels of chromium, molybdenum, and nitrogen, NC4529 is extremely resistant to pitting corrosion.

One method of measuring pitting resistance is to determine the electrical potential for a particular chemical environment that is required to initiate pitting, Ec. A related value is the repassivation potential, Ep, which measures the ability of the material to stop pitting once initiated. Figure 1 shows that NC4529 maintains a high pitting resistance in a chloride solution much stronger than seawater, and can repassivate in this solution at almost 150° F . Alloy 904L is less resistant because of its lower molybdenum and nitrogen contents.

Pitting (Ec) and Repassivation (Ep) Potentials in 3.56% NaCl.20 mV/min. Scan reversal at 5 mA/cm² (ASTM G 61) Figure 1



Crevice Corrosion

The presence of a crevice on a stainless steel surface, as might be caused by a gasket, greatly reduces resistance to chlorides. It is difficult to avoid crevices in construction and operation, although good design and conscientious maintenance help. As with pitting, high chromium, molybdenum, and nitrogen retard crevice corrosion.

There is a critical crevice temperature (CCT) for the initiation of crevice corrosion. The CCT is a function of crevice geometry and environment for each alloy composition. As shown in Figure 2, the CCT for NC4529 exceeds those of Type 316L, Alloy 904L, Alloy 825, and Alloy G.

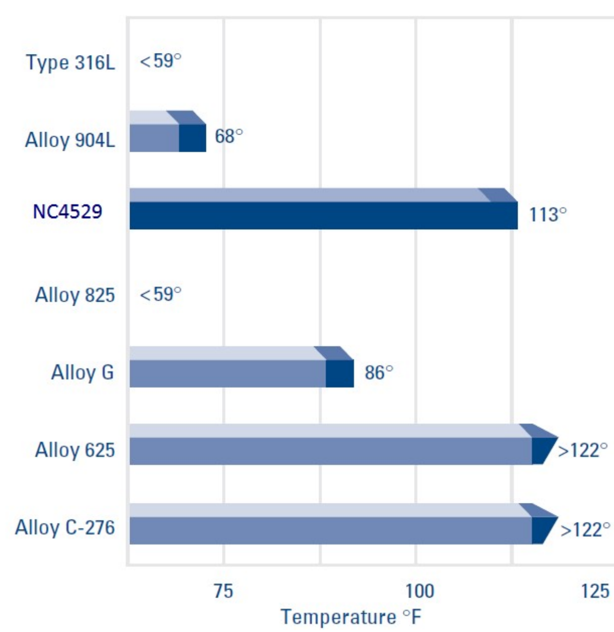
Actual seawater exposure confirms the laboratory observations. As shown in Table 2, NC4529 was unattacked after one year in low–flow rate seawater at 140°F, while Type 316L and Alloy 904L were severely attacked.

Crevice Corrosion in Seawater Table 2

Grade	Number of Specimens Attacked	Deepest Attack, Mils
NC4529	0 of 6	No Attack
Type 316L	6 of 6	8
Alloy 904L	6 of 6	6

Low Flow Rate (0.3 ft/sec) Seawater, 140°F, One Year, Plastic Washers

Critical Crevice Corrosion Temperature $FeCl_3$ Figure 2



Chloride Stress Corrosion Cracking

Stress corrosion cracking (SCC) of austenitic stainless steels can occur when the necessary conditions of temperature, tensile stress, and chlorides are present. Those conditions are not easily controlled, often being characteristic of the operating environment. The tensile stress

is seldom the operating design stress but rather residual stresses related to fabrication, welding, or thermal cycling. Type 304L and 316L are especially susceptible to SCC, but increasing nickel and molybdenum improves resistance to SCC. This improvement is demonstrated in Table 3. Although NC4529 can be cracked by boiling 42% magnesium chloride in standard laboratory tests, it does not crack in the wick test or boiling sodium chloride solution, tests that are more representative of practical situations. After decades of experience in high-chloride environments, no incidents of SCC have been reported for NC4529. As a practical engineering remedy to stress corrosion, 6% Mo stainless steels have successfully replaced 316L components that had failed by SCC.

Resistance to General Corrosion

In discussing the performance of stainless steels in strong acid environments, it is important to recognize that a very small concentration of halides can greatly accelerate general corrosion. As shown in Figure 3, NC4529 is highly resistant to pure sulfuric acid solutions, but Alloy 904L is somewhat more resistant at higher concentrations. However, as shown in Figure 4, the presence of only 200 ppm chloride makes NC4529 the more resistant grade for acid concentrations up to 90%.

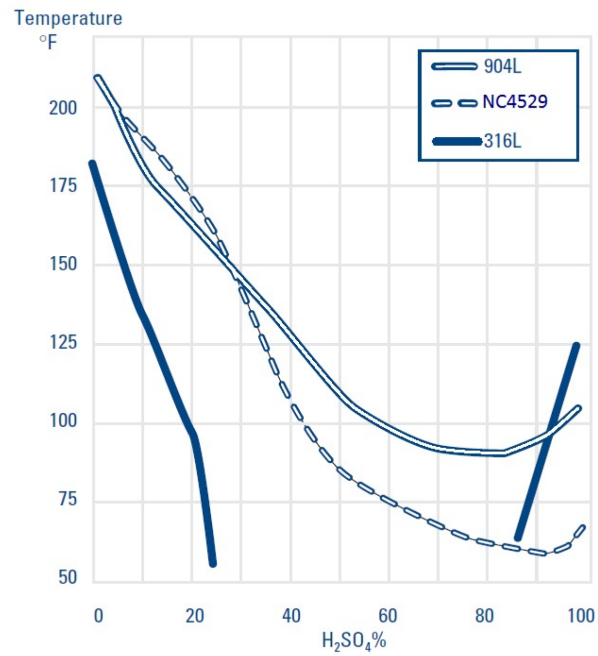
Chloride Stress Corrosion Cracking Resistance Table 3

Grade	Boiling 42% MgCl2	Wick Test	Boiling 25% NaCl
NC4529	F	P	P
Type 316L	F	F	F
Type 317L	F	F	F
Alloy 904L	F	P or F	P or F
Alloy 20	F	P	P
Alloy 625	P	P	P
Alloy C-276	P	P	P

(P = Pass, F = Fail)

Hydrochloric acid is especially aggressive with respect to stainless steels. Type 316L cannot be used for hydrochloric acid because of the risks of both localized and general corrosion. However, as shown in Figure 5, NC4529 may be used in dilute hydrochloric acid at moderate temperatures.

Isocorrosion Curves 0.1 mm/year for given steels in pure sulfuric acid Figure 3



Isocorrosion Curves 0.1 mm/year for given steels in sulfuric acid containing 200 ppm of chloride Figure 4

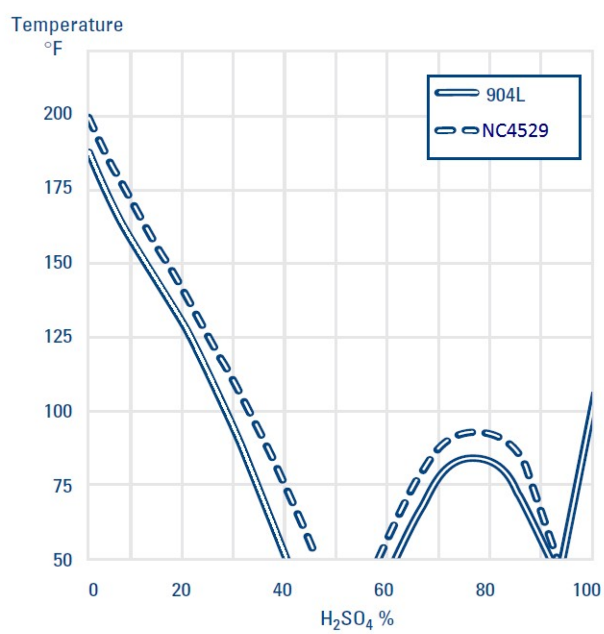
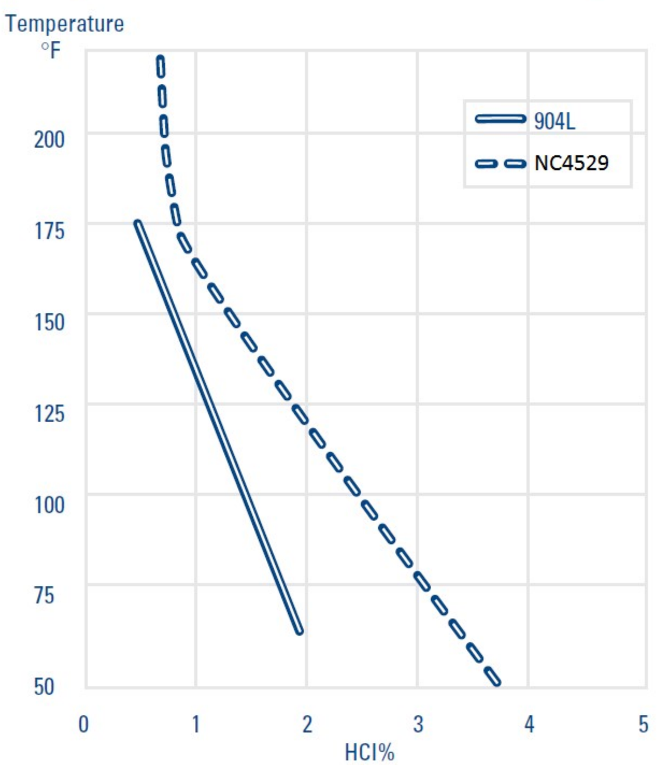


Table 4 reports corrosion performance in actual operating environments. Accurate characterization of such environments is not always possible because the material may see substantial variations of the temperature and chemical conditions during the operating and maintenance cycle. Wet process phosphoric acid is a complex mixture of corrosive chemicals including chlorides and fluorides. NC4529 was found to be substantially more resistant than Type 316L and Alloy 904L. There is a similar result for tall oil distillation, an application in which NC4529 has successfully replaced Alloy 904L. As is often the case, this replacement has allowed a significant increase in process efficiency because more aggressive operating parameters may be safely used. In a pure, strongly oxidizing acid solution, such as nitric acid, the molybdenum-free Type 304 is found to be superior to the molybdenum-containing grades. However, the presence of halides can reverse this relationship. NC4529 shows superior resistance to a strong pickling acid.

Table 5 compares the performance of NC4529 with other stainless steels in a variety of common corrosive environments. The table shows the lowest temperature at which the corrosion rate exceeds 5 mpy. All testing was done in accordance with the requirements of the Materials Testing Institute of the Chemical Process Industries (MTI).

Isocorrosion Diagrams, Corrosion rate 0.1 mm/year, in hydrochloric acid Figure 5



Performance in Selected ProcessStreams Corrosion Rate, mpy Table 4

Grade	Tall Oil Distillation 500°F	Wet Process Phosphoric Acid,* 140°F	Pickling Acid 20% HNo3 4% HF 77°F
NC4529	0.4	2	12
316**	35	>200	>200
317LM	11	-	-
904L	2.4	47	20

*Composition, %: 54 P_2O_5, 0.06Cl^-, 4H_2SO_4,
0.27 Fe_2O_3, 0.17 Al_2O_3,
0.10 SiO_2, 0.2 CaO, 0.70 MgO

Design and Fabrication Design

NC4529 is a strong, tough stainless steel, as shown in Table 6. The ASME Boiler and Pressure Vessel Code (Table 7) allows use of NC4529 up to 750°F, with excellent strength levels. In many constructions it is possible to use this strength for greater economy by reducing the thickness that would be required to perform the same function with Type 316L, Alloy 904L, or Alloy G. Table 8 gives the minimum tensile properties for NC4529 up to 750°F. 6% Mo stainless steels should not be used at temperatures above 1100°F because of the danger of precipitation of intermetallic phases and the consequent loss of corrosion resistance and ambient temperature toughness. However, 6% Mo stainless steels can be used indefinitely at the moderate temperatures typically encountered in chemical processing and heat exchanger service.

Cold Forming

6% Mo stainless steels are readily sheared and cold formed on equipment suited for austenitic stainless steels. They have a high initial yield strength and work harden rapidly. So greater force is required, as is a greater allowance for springback in comparison with Type 316L. Viewed in another way, the rapid work hardening can provide useful strength while still retaining excellent toughness.

Lowest Temperature (°F) at Which the Corrosion Rate Exceeds 5 mpy

Table 6

Corrosion Environment	654 SMO®	**NC4529**	904L	Type 316L (2.7 Mo)	Type 304	2507	2205 Code Plus Two®	2304
0.2% Hydrochloric Acid	>Boiling	**>Boiling**	>Boiling	>Boiling	>Boiling	>Boiling	>Boiling	>Boiling
1% Hydrochloric Acid	203	**158**	122	86	86p	>Boiling	185	131
10% Sulfuric Acid	158	**140**	140	122	—	167	140	149
60% Sulfuric Acid	104	**104**	185	<54	—	<57	<59	<<55
96% Sulfuric Acid	86	**68**	95	113	—	86	77	59
85% Phosphoric Acid	194	**230**	248	203	176	203	194	203
10% Nitric Acid	>Boiling	**>Boiling**	>Boiling	>Boiling	>Boiling	>Boiling	>Boiling	>Boiling
65% Nitric Acid	221	**212**	212	212	212	230	221	203
80% Acetic Acid	>Boiling	**>Boiling**	>Boiling	>Boiling	212p	>Boiling	>Boiling	>Boiling
50% Formic Acid	158	**212**	212p	104	≤50	194	194	59
50% Sodium Hydroxide	275	**239**	Boiling	194	185	230	194	203
83% Phosphoric Acid + 2% Hydrofluoric Acid	185	**194**	248	149	113	140	122	95
60% Nitric Acid + 2% Hydrochloric Acid	>140	**140**	>140	>140	>140	>140	>140	>140
50% Acetic Acid + 50% Acetic Anhydride	>Boiling	**>Boiling**	>Boiling	248	>Boiling	230	212	194
1% Hydrochloric Acid + 0.3% Ferric Chloride	>Boiling, p	**203ps**	140ps	77p	68p	203ps	113ps	68p
10% Sulfuric Acid + 2000ppm Cl^- + N_2	149	**104**	131	77	—	122	95	<55
10% Sulfuric Acid + 2000ppm Cl^- + SO_2	167	**140**	122	<<59p	—	104	<59	<<50
WPA1, High Cl^- Content	203	**176**	122	≤50	<<50	203	113	86
WPA2, High F^- Content	176	**140**	95	≤50	<<50	167	140	95

ps = pitting can occur
ps = pitting/crevice corrosion can occur

WPA	P_2O_5	Cl^-	F^-	H_2SO_4	Fe_2O_3	Al_2O_3	SiO_2	CaO	MgO
1	54	0.20	0.50	4.0	0.30	0.20	0.10	0.20	0.70
2	54	0.02	2.0	4.0	0.30	0.20	0.10	0.20	0.70

Mechanical Properties at Room Temperature

Table 6

Property/Product Form	Wrought Products	Castings
Tensile Strength, ksi	—	80 min
Sheet and Strip	100 min	NA
Plate	95 min	NA
0.2% Offset Yield Strength, ksi	45 min	38 min
Elongation in 2 in, %	35 min	35 min
Brinell Hardness	210 max	—
Charpy V-Notch Impact Strength, ft-lb	71 min	—

NA = Not Applicable

Maximum Allowable Stress Values, ASME Boiler and Pressure Vessel Code, Section VIII, Division 1 2007 Revision, 3.5 Safety Factor

Table 7

Grade	Stress, ksi						
	-20°to 100°F	400°F	500°F	600°F	650°F	700°F	750°F
NC4529	**26.9**	**24.3**	**23.5**	**23.0**	**22.8**	**22.7**	**22.6**
2205 (S31803)	25.7	23.9	23.3	23.1	—	—	—
Alloy G	23.3	23.3	23.3	22.7	22.4	22.2	22.0
Type 316L	16.7	15.7	14.8	14.0	13.7	13.5	13.2
Alloy 904L	20.3	13.8	12.7	11.9	11.6	11.4	—

Tensile Properties at Elevated Temperatures

Table 8

Temperature °F	68	122	212	392	572	752
0.2% Yield Strength, ksi	45	39	34	28	25	23
1.0% Yield Strength, ksi	—	44	39	33	30	28
Tensile Strength, ksi	95	92	89	81	76	74

Machining

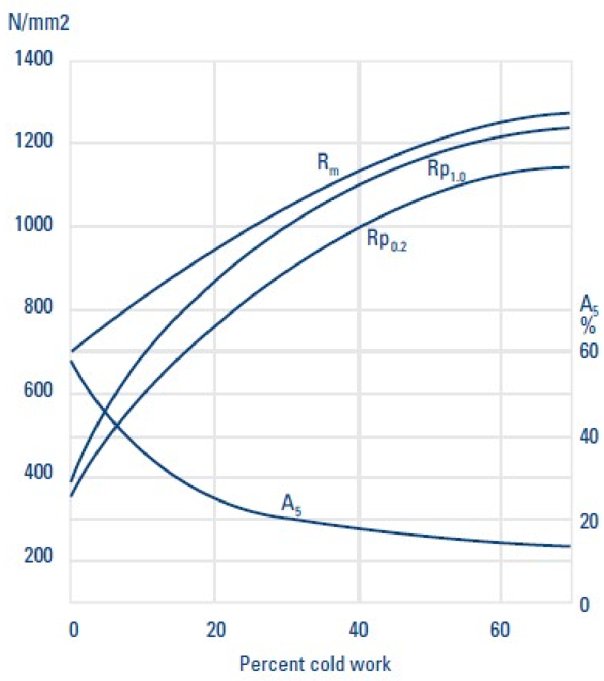
Similar to other austenitic stainless steels, 6% Mo stainless steels are tough and resist machining. However, the special care taken in production of these grades ensures a steel of excellent cleanliness and uniformity. With appropriate selection of tools and machining parameters, satisfactory results have been obtained, as in the drilling of large tubesheets.

Hot Forming, Annealing

Forming at room temperature is recommended whenever possible. When hot working is required, the workpiece should be heated uniformly and worked within the range 1800-2100°F. Higher temperatures will reduce workability and cause heavy scaling. After the hot working, the piece should be annealed at 2100°F minimum — long enough to ensure that the whole piece achieves temperature throughout — and then water quenched. The anneal and quench are essential to achieve maximum corrosion resistance.

Mechanical Properties after Cold Working

Figure 6



Welding

Stainless steel mill products have been worked and annealed to develop a uniformity of composition throughout the piece. However, remelting of the parent metal, as may occur during welding without filler metal, may cause microscopic segregation of elements such as chromium, nickel, and molybdenum. This phenomenon occurs in all highly alloyed austenitic stainless steels, but becomes increasingly pronounced with the more highly alloyed grades. These variations may reduce the corrosion resistance of the weld. As a principle, 6% Mo stainless steel should not be welded without filler unless the weld will be subsequently fully annealed.

When the weld is not to be subsequently annealed, an over-alloyed filler metal should be used, such as ERNiCrMo-3 (Alloy 625), P12, or P16. Molybdenum segregation will also occur within these highly alloyed filler metals, but the regions of lowest molybdenum will still be richer in molybdenum than the base metal. So the weld metal will still have corrosion resistance at least equivalent to that of the base metal.

Physical Properties

Table 9

Temperature °F		68	212	392	572	752
Modulus of Elasticity	psi x10^6	29	28	27	26	25
Coefficient of Thermal Expansion (68°F to T)	x10^{-6}/°F	–	8.9	8.9	9.2	9.5
Thermal Conductivity	Btu/h ft°F	7.5	8.1	8.7	9.8	10.4
Heat Capacity	Btu/lb°F	0.120	0.124	0.129	0.133	0.136
Electrical Resistivity	Ωin x 10^{-6}	33.5	35.4	37.4	40.6	43.3
Density	lb/in³	0.287	–	–	–	–
Magnetic Permeability		1.003	–	–	–	–

The following procedures have been found to be essential for optimizing the corrosion resistance and mechanical soundness of 6% Mo stainless steel weldments. More precise descriptions of set-up and welding procedures are provided in the brochure, "How to Weld Type 254 SMO® Stainless Steel."

1. The arc should be struck in the weld joint itself because an arc strike on the face of the base metal can reduce corrosion resistance at that point.

Characteristic Temperatures

Table 10

	Temperature °F
Solidification Range	2550-2415
Scaling Temperature in Air	1830
Sigma Phase Formation	1300-1800
Carbide Precipitation	840-1470
Hot Forming	1800-2100
Solution Annealing	2100 min, water quench
Stress Relief Annealing	2100 min, water quench

2. Heat input should be minimized, with arc energy input not exceeding 38 kJ/in. Heat input in kJ/in. is calculated as:

$$\frac{\text{Voltage x Amperage x 6}}{\text{Travel Speed (in/min) x 100}}$$

The weld metal should be deposited as a stringer bead without weaving.

3. In order to minimize the chance for cracking of the high nickel weld in multi-pass welding, the workpiece should be allowed to cool below 212°F between passes.

4. Crater cracks must be removed by grinding. Craters may be avoided by backstepping. The arc should be broken on the weld bead, and not on the base metal.

5. Filler wire should be fed continuously and as evenly as possible, to minimize variations in the composition of the weldment. Dilution from the base metal should be minimized. A minimum root gap of 0.02 to 0.06 inch is required to ensure sufficient filler metal addition. Root shielding is essential in both tacking and joining operations.

6. Preheating, except to the extent necessary to prevent condensation, is not desirable. Heat treatment is not normally required after welding. However, any weld without filler metal should be solution annealed at 2100° F minimum and water quenched for best corrosion resistance.

7. For optimum corrosion resistance, both root and face of the weld should be cleaned, preferably by pickling. Wire brushing should not be relied upon unless the brush is of a material with corrosion resistance equal to that of NC4529.

DCRP Welding

Table 11

Electrode size, inch	3/32	1/8	5/32
Amperes	40-70	60-95	90-135

Typical welding parameters for Gas Metal Arc Welding (GMAW) spray-arc welding, with 99.95% argon-shielding gas, 35–55 ft3/hr., are shown in Table 12:

Table 12

Wire Diameter, inch	Amperes	Volts
0.035	170-190	28
0.045	220-280	30
0.062	280-330	31

Cleaning and Passivation

6% Mo stainless steel mill product forms are delivered with a surface that is cleaned, most frequently by pickling, to remove oxide, embedded iron, or other foreign material. It is essential for maximum corrosion resistance that this cleanliness be maintained or restored after handling and fabrication. A major source of surface contamination is iron transferred from handling equipment, shears, dies, work tables, or other metal equipment. In service this iron can corrode and activate a pit. Other sources of contamination include slag entrapment in welds, weld spatter, heat tint, forming lubricants, dirt, and paint.

To maximize the corrosion resistance of stainless steel fabrications, acid passivation should be used to remove surface contaminants. For 6% Mo stainless steel, the suggested practice is to immerse the piece in a solution of 20-40% nitric acid in water for about 30 minutes at 120-140°F. Further guidelines for this procedure are given in ASTM A 380.

If the surface of the steel is oxidized, for example, the heat tint associated with welding, it may be necessary to use mechanical cleaning or pickling to restore maximum corrosion resistance. Some guidance is provided in the brochure, “How to Weld Type NC4529 Stainless Steel.”

Welding Consumables

Coated electrodes; wires for GTAW, GMAW, FCW, and SAW; welding fluxes; and pickling pastes, have been formulated to produce excellent results when welding 6% Mo stainless steel.

Technical Support

New Castle assists users and fabricators in the selection, qualification, installation, operation, and maintenance of 6% Mo stainless steel. Technical personnel can draw on years of field experience with these grades to help you make the technically and economically correct materials decision. New Castle is prepared to discuss individual applications and to provide data and experience as a basis for selection and application of 6% Mo stainless steels.

New Castle works closely with its distributors, fabricators, and end users to ensure timely availability of 6% Mo stainless steel in the sizes and quantities required by the user. For assistance with technical questions and to obtain top quality products, call New Castle at 1-800-349.0023.

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