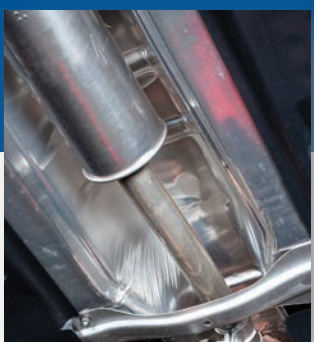
AUTOMOTIVE EXHAUST

SYSTEM MATERIALS COMPARATOR



Catalytic Converter

Flanges

Heatshields

Manifolds

Muffler

Cleveland-Cliffs manufactures stainless steels for exhaust system components to meet lightweighting and durability requirements. Combined with industry experience and material expertise, Cleveland-Cliffs is your automotive exhaust materials solutions provider. Potential applications include stamped and tubular manifolds, catalytic converters, mufflers, flanges, tubing and heat shields. The data presented in this brochure will help you compare the various material alternatives to choose the right solution for your application.

Mechanical Properties

TABLE 1 – ALLOY COMPOSITION (WT %) OF MATERIALS FOR EXHAUST SYSTEMS

Alloy	C	Mn	Si	Cr	Ni	Ti	Cb	Mo	Al
Type 409	0.010	0.25	0.50	11.20	0.25	0.20	—	—	—
Cleveland-Cliffs 409 Ni	0.010	0.75	0.35	11.0	0.85	0.20	—	—	—
Type 439	0.015	0.25	0.30	17.30	0.25	0.30	—	—	—
Cleveland-Cliffs 15 Cr-Cb® SS	0.010	1.00	1.30	14.50	0.30	0.25	0.35	—	—
Cleveland-Cliffs 18 Cr-Cb™ SS	0.015	.25	0.40	18.00	0.25	0.25	0.55	—	—
Cleveland-Cliffs 441	0.010	0.25	0.30	17.90	0.25	0.20	0.45	—	—
Cleveland-Cliffs 436L	0.010	0.30	0.30	17.25	0.25	0.30	—	1.30	—
Cleveland-Cliffs 18 SR® SS	0.015	0.25	0.60	17.30	0.25	0.25	—	—	1.7
THERMAK® 17 SS	0.020	1.20	1.00	16.00	0.50	0.50	0.50	—	—
Type 304L	0.025	1.75	0.30	18.10	8.50	—	—	0.20	—
Type 309S	0.050	1.80	0.30	22.25	12.50	—	—	—	—
Type 444	0.025	1.00	1.00	18.50	1.00	0.20	0.80	2.00	—

TABLE 2 – TYPICAL ROOM TEMPERATURE MECHANICAL PROPERTIES (FLAT SHEET)

Alloy	0.2% YS, ksi. (MPa)	UTS MPa (ksi.)	Elongation % in 2 in. (50.8 mm)	Rockwell Hardness, B
Aluminized Type 1	22 (152)	44 (303)	44	31
Type 409	33 (228)	60 (414)	35	66
Cleveland-Cliffs 409 Ni	57 (393)	69 (476)	35	82
Aluminized Type 409	40 (276)	63 (434)	32	68
Type 439	41 (283)	65 (448)	34	74
Aluminized Type 439	45 (310)	70 (483)	29	77
Cleveland-Cliffs 15 Cr-Cb SS	50 (345)	74 (510)	34	82
Cleveland-Cliffs 18 Cr-Cb SS	46 (317)	70 (483)	31	79
Cleveland-Cliffs 441	45 (310)	70 (483)	33	78
Cleveland-Cliffs 436L	46 (317)	70 (483)	33	79
Cleveland-Cliffs 18 SR SS	55 (379)	77 (531)	29	84
THERMAK 17 SS	63 (434)	81 (528)	29	89
Type 304L	40 (276)	90 (621)	57	81
Type 309S	43 (296)	91 (627)	48	82
Type 444	52 (360)	75 (515)	30	85

Mechanical Properties

TABLE 3 – PHYSICAL PROPERTIES AT ROOM TEMPERATURE

Alloy	Density, lbs./in.^{3} (gm/cm^3)	Electrical Resistivity, $\mu\Omega$•in. ($\mu\Omega$•cm)
Type 409	0.278 (7.70)	23.62 (60)
Type 439	0.273 (7.56)	24.80 (63)
Cleveland-Cliffs 18 Cr-Cb SS	0.277 (7.67)	23.29 (59)
Cleveland-Cliffs 441	0.276 (7.65)	23.29 (59)
Cleveland-Cliffs 436L	0.279 (7.73)	23.68 (60)
Cleveland-Cliffs 18 SR SS	0.270 (7.48)	38.58 (98)
THERMAK 17 SS	0.278 (7.69)	—
Type 304L	0.287 (7.96)	28.32 (72)
Type 309S	0.285 (7.90)	30.70 (78)

TABLE 4 – REPRESENTATIVE AS-WELDED* TUBE PROPERTIES

Alloy	0.2% YS, ksi. (MPa)	UTS, ksi. (MPa)	Elongation % in 2 in. (50.8 mm)	n-Value
Aluminized Type 1	36 (248)	51 (352)	40	0.18
Type 409	52 (359)	67 (462)	31	0.16
Cleveland-Cliffs 18 Cr-Cb SS	65 (448)	78 (538)	25	0.12
THERMAK 17 SS	76 (524)	86 (593)	23	—

**Tensiles cut parallel to tube length in base alloy and tubes measured 0.045 x 2 in. (1.14 x 50.8 mm) diameter.*

Formability

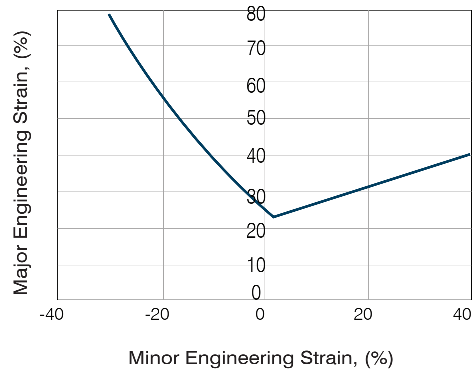
TABLE 5 –WORK HARDENING RATE AND PLASTIC STRAIN RATIO

Alloy	n-Value	r-Value	Relative Rating
Aluminized Type 1	0.22	1.8	B
Type 409	0.23	1.4	B
Aluminized Type 409	0.19	1.5	C+
Cleveland-Cliffs 409 Ni**	0.13	—	D
Type 439	0.21	1.6	B
Aluminized Type 439	0.18	1.4	C-
Cleveland-Cliffs 15 Cr-Cb SS	0.18	1.4	B
Cleveland-Cliffs 18 Cr-Cb SS	0.19	1.3	C
Cleveland-Cliffs 441	0.20	1.4	C+
Cleveland-Cliffs 436L	0.20	1.3	C+
Cleveland-Cliffs 18 SR SS	0.17	1.5	C-
THERMAK 17 SS	0.15	1.3	—
Type 304L	0.40	1.0	A*
Type 309S	0.29	1.0	A-*

**A = most formable.*
***Alloy developed for heavier gauge light plate (0.1875 – 0.375 in.) applications (flanges) due to superior toughness. Standard formability is limited.*

The formability of most stainless alloys depends on a balance between ductility measured by % elongation and work-hardening rate or n value (slope of the stress-strain curve). As n-Values increase, so does the ratio of UTS/YS. The r-Value is the average plastic strain ratio and can be thought of as a number proportional to an alloy's resistance to thinning during plastic deformation.

FIGURE 1 – FORMING LIMIT CURVE



The forming limit diagram is an experimentally developed graphical representation of the amount of biaxial strain or thinning a material can undergo during various forming operations (stretch, plane strain, draw) prior to the onset of localized thinning and subsequent fracture. A typical ferritic stainless forming limit diagram (Figure 1) is shown above. The table below (Table 6) shows the major strain and resultant thinning at three defined minor strain levels for seven standard exhaust system stainless alloys.

TABLE 6 –MAJOR AND MINOR STRAIN POINTS DEFINING THE FORMING LIMIT CURVE, TRANSVERSE TO SHEET ROLLING DIRECTION

Alloy	Percent Minor Strain					
	-20		0 (FLC_0)		+20	
	Major	Thinning	Major	Thinning	Major	Thinning
Type 409	58.5	21	26.5	21	34	38
Aluminized Type 409	58.5	21	26.5	21	32.5	37
Type 439	54	19	23	19	33	37.5
Cleveland-Cliffs 18 Cr-Cb SS	52	18	22	18	32.5	37
Type 304L	67	25	37	27	43	41.5
Type 309	54	19	36	26.6	41	41

Weldability

TABLE 7 – WELDABILITY

Alloy	Relative Ranking*	
	High Frequency	Arc Welding (with filler metal)
Type 409	A	A
Aluminized Type 409	B+	B
Type 439	A-	A
Aluminized Type 439	B-	B-
Cleveland-Cliffs 15 Cr-Cb SS	B-	B+
Cleveland-Cliffs 18 Cr-Cb SS	C+	B
Cleveland-Cliffs 441	C+	B
Cleveland-Cliffs 436L	B-	B+
Cleveland-Cliffs 18 SR SS	D	C
THERMAK 17 SS	B-	B+
Type 304	B	A
Type 309S	—	B

**Steels are ranked relative to the weldability (ease of joining and weld formability) of 409.*
A = most weldable.

The essentials of good stainless steel welding practice are:

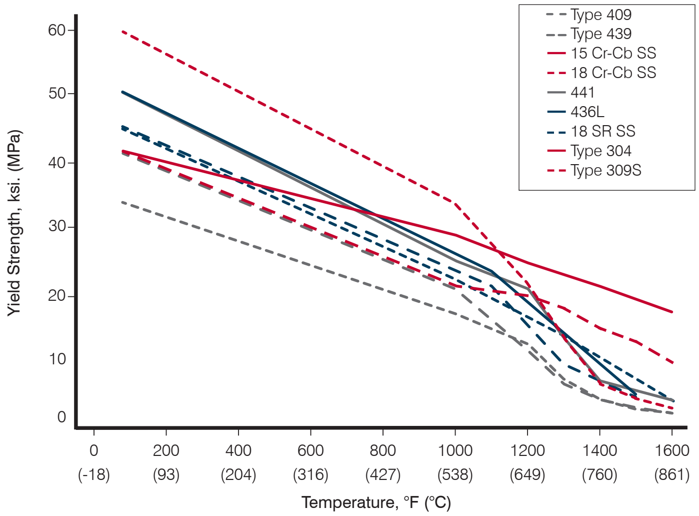
1. design of components which accommodates the material properties and loading conditions in service
2. clean starting material
3. well-matched base and filler metal chemistries
4. proper joint-fit-ups and geometries
5. a welding process in control

Popular exhaust alloy filler materials include the ferritic alloys Cleveland-Cliffs 409 Cb, Type 430 Ti and Cleveland-Cliffs 18 Cb.

The austenitic alloys Type 308L and Cleveland-Cliffs 309L are also used, particularly when joining ferritic and austenitic alloys.

Elevated Temperature Properties

FIGURE 2 – SHORT TIME ELEVATED TEMPERATURE YIELD AND TENSILE STRENGTHS ksi. (MPa)



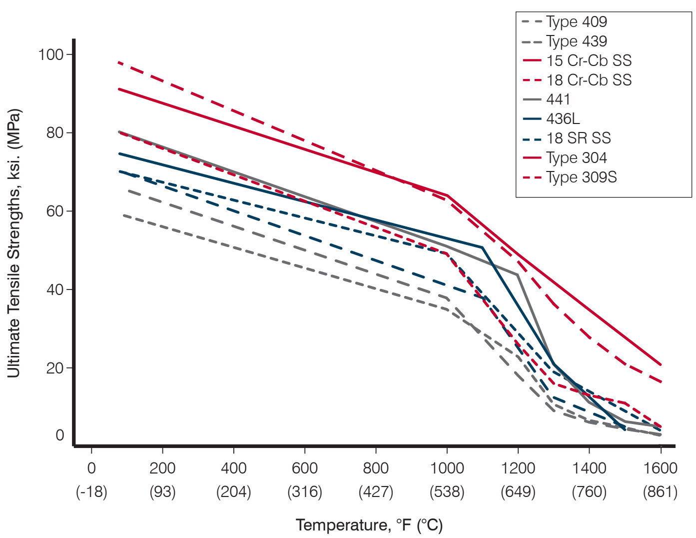


TABLE 8 – STRESS RUPTURE

Alloy	Temperature, 1300 °F (704 °C)		Temperature, 1300 °F (704 °C)	
	Stress, ksi. (MPa) 100 hrs.	Stress, ksi. (MPa) 1000 hrs.	Stress, ksi. (MPa) 100 hrs.	Stress, ksi. (MPa) 1000 hrs.
Type 409	4.1 (28.3)	3.2 (22.1)	1.5 (10.3)	0.9 (6.2)
Type 439	4.0 (27.6)	3.0 (20.7)	1.6 (11.0)	1.0 (6.9)
Cleveland-Cliffs 18 Cr-Cb SS	5.8 (40.0)	4.4 (30.3)	2.4 (16.5)	1.8 (12.4)
Cleveland-Cliffs 18 SR SS	3.8 (26.2)	2.6 (17.9)	1.7 (11.7)	0.9 (6.2)
Type 304	16.9 (117)	11.6 (80)	6.2 (42.7)	3.7 (25.5)
Type 309S	—	—	8.2 (56.5)	4.3 (29.6)

Physical Properties

TABLE 9 – 1500 °F (816 °C) FATIGUE STRENGTH

Alloy	Endurance Limit, ksi. (MPa) For 10^7 cycles
Type 409	1.0 (6.9)
Type 439	1.4 (9.7)
Cleveland-Cliffs 18 Cr-Cb SS	3.0 (20.7)
Cleveland-Cliffs 18 SR SS	2.0 (13.8)

Properties of Aluminized Type 409 and Aluminized Type 439 would be expected to be similar to those of the uncoated base alloys.

TABLE 10 – POISSON'S RATIO VS. TEMPERATURE

Temp., °F (°C)	Ferritic Stainless	Austenitic Stainless
70 (21)	0.28	0.28
300 (149)	0.29	0.28
500 (260)	0.29	0.30
700 (371)	0.30	0.32
900 (482)	0.30	0.28
1100 (593)	0.31	0.29
1300 (704)	0.32	0.28
1500 (816)	0.33	0.25

TABLE 11 – YOUNG'S MODULUS psi. X 10^6 (MPa X 10^3) VS. TEMPERATURE

Temp., °F (°C)	Stainless Grade			
	Type 409	Type 439	Cleveland-Cliffs 18 Cr-Cb SS	Type 309S
70 (21)	29.9 (206)	28.4 (210)	29.8 (205)	28.5 (196)
200 (93)	28.1 (194)	27.4 (205)	29.2 (201)	27.7 (191)
400 (204)	27.5 (190)	26.6 (199)	27.9 (192)	26.4 (182)
600 (316)	26.5 (183)	26.2 (190)	26.7 (1848)	25.1 (173)
800 (427)	25.4 (175)	24.5 (179)	25.1 (173)	23.8 (164)
1000 (538)	23.8 (164)	22.3 (171)	23.3 (161)	22.5 (155)
1200 (649)	22.3 (154)	20.1 (153)	19.7 (136)	21.0 (145)
1400 (760)	16.6 (115)	16.7 (123)	17.1 (118)	19.5 (134)

Physical Properties

FIGURE 3 – THERMAL CONDUCTIVITY VS. TEMPERATURE

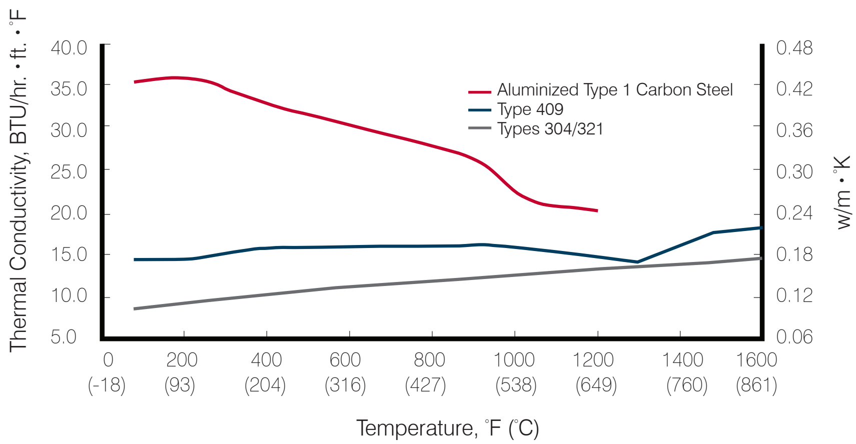


FIGURE 4 – COEFFICIENT OF THERMAL EXPANSION VS. TEMPERATURE

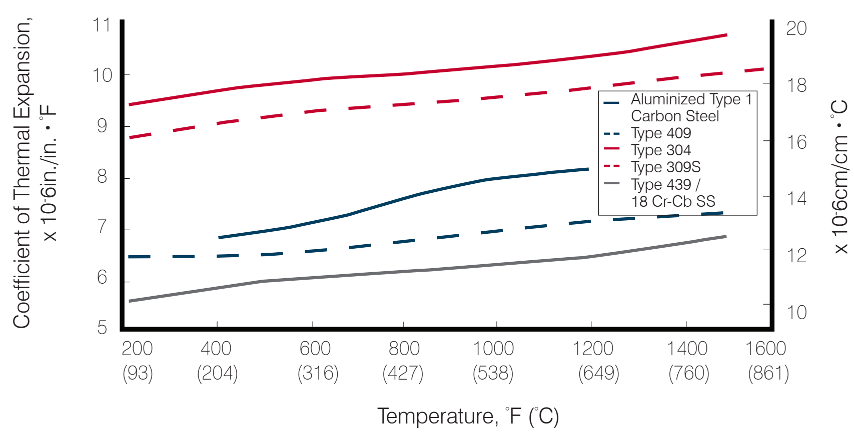
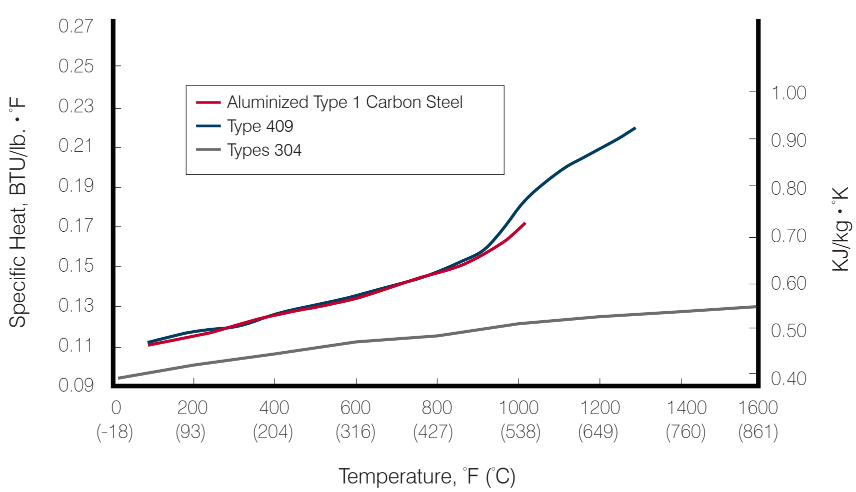


FIGURE 5 – SPECIFIC HEAT VS. TEMPERATURE



Elevated Temperature Corrosion Resistance

TABLE 12 – CYCLIC OXIDATION RESISTANCE

Each cycle consists of 25 min. heat/5 min. cool

1500 °F (816 °C) Weight Change, (mg/cm^2)						
Alloy	**50 cyc**	**100 cyc**	**150 cyc**	**200 cyc**	**350 cyc**	**520 cyc**
Type 409	1.66	2.09	2.42	2.51	2.64	2.71
Alumunized Type 409	0.34	0.43	0.50	0.53	0.64	0.74
Type 439	0.06	0.16	0.12	0.16	0.23	0.25
Alumunized Type 439	0.33	0.40	0.43	0.45	0.54	0.59
Cleveland-Cliffs 18 Cr-Cb SS	0.05	0.09	0.12	0.12	0.17	0.23
Cleveland-Cliffs 304L	3.92	-6.85	-8.59	-12.2	-19.4	-31.0

1650 °F (899 °C) Weight Change, (mg/cm^2)						
Alloy	**51 cyc**	**100 cyc**	**200 cyc**	**350 cyc**	**500 cyc**	**700 cyc**
Type 409	1.84	4.0	10.4	19.80	63.1	205
Alumunized Type 409	0.81	1.21	1.74	2.43	3.94	3.72
Type 439	0.29	0.36	0.50	0.79	1.94	9.35
Alumunized Type 439	0.51	0.62	0.73	0.78	0.98	1.16
Cleveland-Cliffs 18 Cr-Cb SS	0.26	0.42	0.59	0.76	1.30	5.24
Cleveland-Cliffs 304L	27.6	-57.0	-112	-193	*	*
Type 309S	0.17	0.31	0.37	0.-17	-14.1	-74.2

TABLE 13 – MAXIMUM SUSTAINABLE USAGE

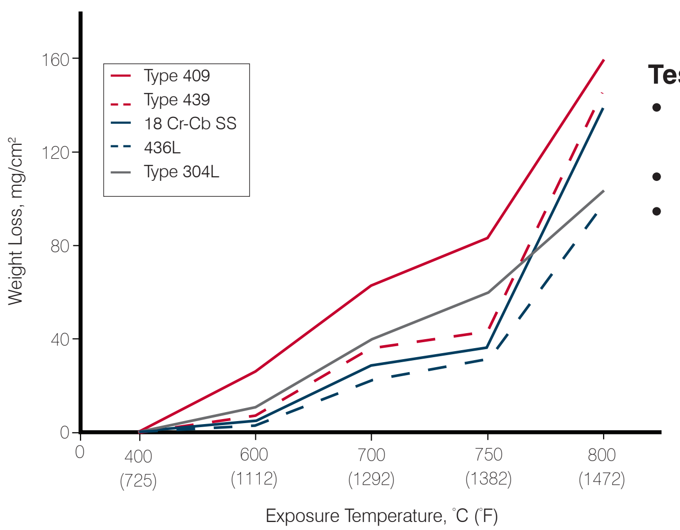
Alloy	Temperature, °F (°C)
Aluminized Type 1	1250 (677)
Type 409, Cleveland-Cliffs 304L	1500 (816)
Aluminized Type 409	1550 (843)
Type 439, Cleveland-Cliffs 436L	1625 (885)
Cleveland-Cliffs 18 Cr-Cb SS, Cleveand-Cliffs 15 Cr-Cb SS, Type 441, Aluminized Type 439	1650 (899)
18 SR SS	1900 (1038)
Type 309S	1700 (927)

Elevated Temperature Corrosion Resistance

HIGH TEMPERATURE SALT CORROSION RESISTANCE

The superior hot salt resistance of the aluminum coated stainless alloys is attributed to the high exposure temperatures converting the aluminum coating to Al_2O_3 with a thicker underlying Fe-Al intermetallic layer. After such a conversion, the Aluminized Type 409 surface becomes gray in appearance and would be subject to red rusting in wet chloride environments.

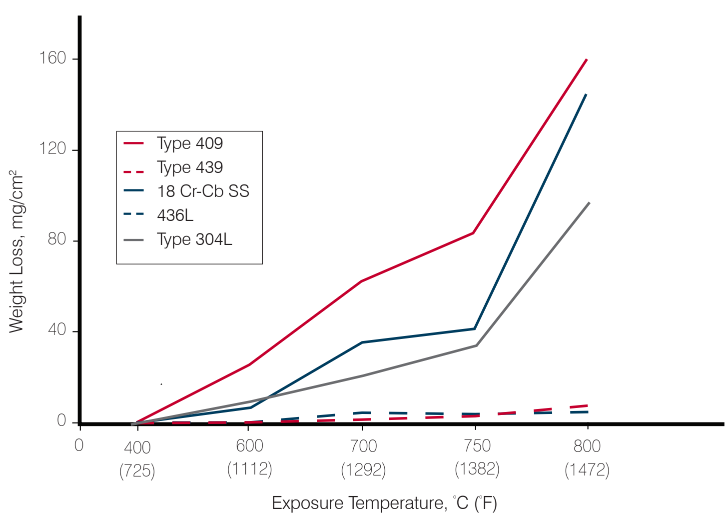
FIGURE 6 – STANDARD EXHAUST ALLOYS



Test Procedure

- Immerse 5 min. in cone NACL solution
- Heat 2 hrs.
- Air cool 5 min.

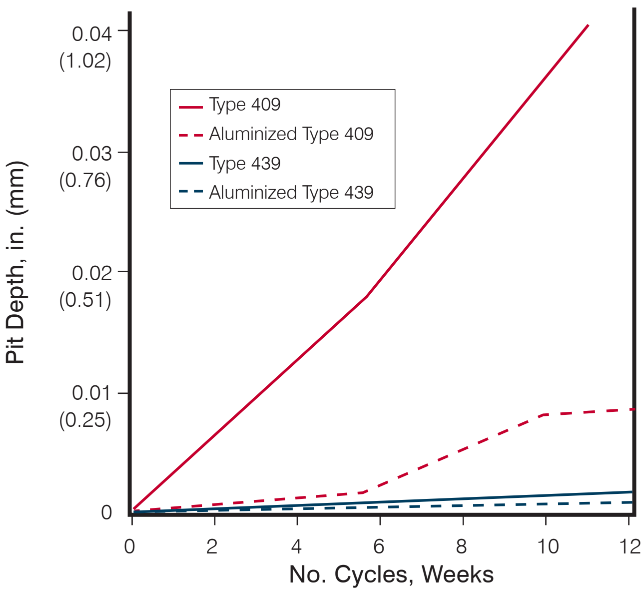
FIGURE 7 – ALUMINUM COATED EXHAUST ALLOYS



Wet Corrosion Resistance

FIGURE 8 – EXTERNAL EXHAUST SALT-HUMIDITY PITTING CORROSION

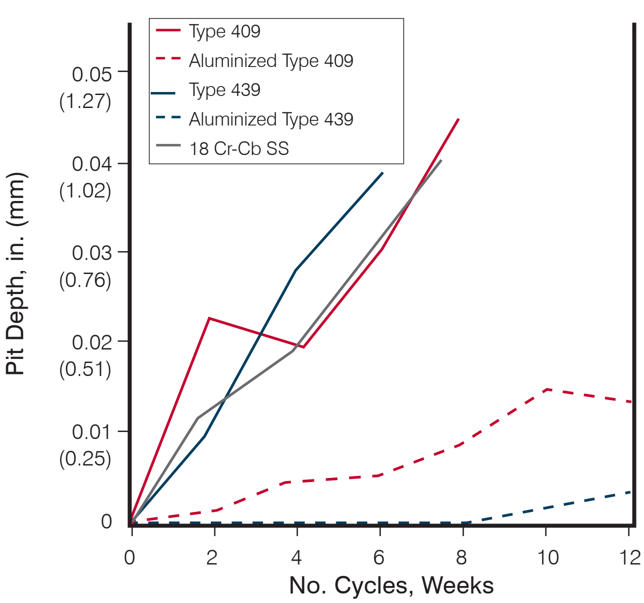
Muffler Simulation – 600 °F (316 °C) Heat Treat – Bold Exposure



At relatively low temperatures (e.g., 600 °F (316 °C), Type 409 forms a heat-tinted (oxidized) surface and pits readily after exposure to moist salt. The hot dip aluminum coating provides long-term galvanic protection against pitting corrosion.

Uncoated Type 439 is only slightly affected by pitting at 600 °F (316 °C) exposure. Unlike bare Type 439, Aluminized Type 439 protects against cosmetic red rusting.

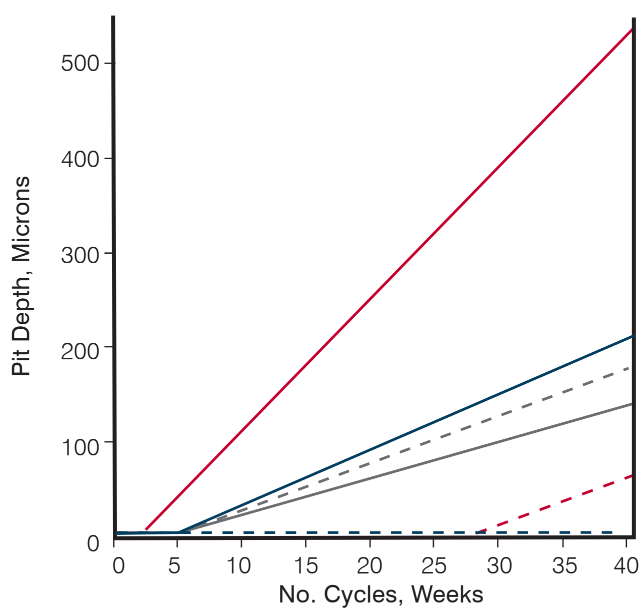
Converter Simulation – 1000 °F (538 °C) Heat Treat – Bold Exposure



A 1000 °F (538 °C) heat treat in the corrosion cycle test fully alloys the aluminum coating with the stainless steel substrate. The lower galvanic potential of the thick alloy coating still provides longer term protection against pit initiation. The effects of oxidation plus salt on the higher chromium uncoated grades cause earlier perforation compared to lower temperature testing. Bare Type 409 shows a shelf in pitting rate due to the formation of a scale jacket which eventually separates and exposes the base alloy.

Field corrosion data indicate that the 1000 °F (538 °C) test equivalence is approximately 1 week = 1 year in severe salt belt service.

Test cycle: Heat 1 hour (Monday only)
Daily Dip 15 min. – 5% NaCl
Air dry
Humidity – 85% RH, 140 °F (60 °C)



Wet Corrosion Resistance

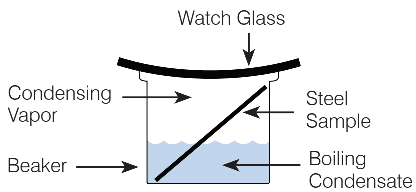
FIGURE 9 – BOILING BEAKER INTERNAL CONDENSATE CORROSION COMPARISONS

Test setup:
Partial immersion of 3 x 4 in. (7.6 x 10.2 cm) coupon in synthetic condensate

Test solution:
5000 ppm SO_4^{-3}
100 ppm Cl -
100 ppm NO_3-
100 ppm HCOOH
Initial pH 5.3 – 5.5
Final pH 3.3 – 3.5

Test cycle procedure:
Heat 1 hr. at 500 °F (260 °C)

Boil condensate 16 hr.
Expose 6 hr. in 85% humidity at 125 °F (52 °C)



COSMETIC CORROSION COMPARISONS

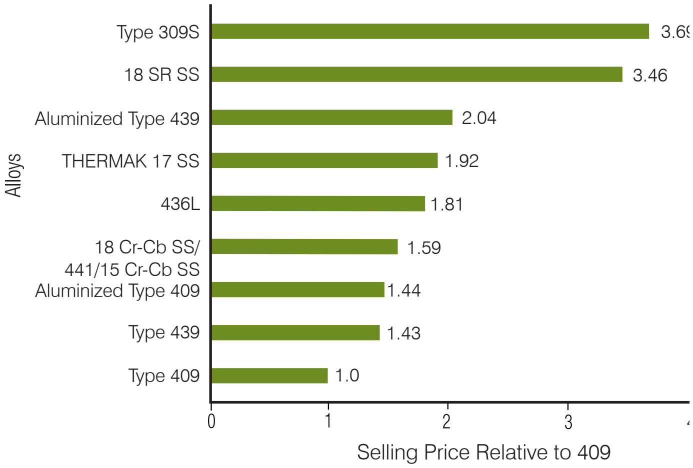
Bare 409 after 8 years in Newfoundland.

Bare 439 after 9 years in Windsor, Ontario, Canada

Aluminized 409 after 10 years in Windsor, Ontario, Canada. Black on the muffler top and tailpipe is paint.

AUTOMOTIVE EXHAUST SYSTEM MATERIALS COMPARATOR

FIGURE 10 – COST COMPARISONS OF STEELS FOR EXHAUST SYSTEMS



About Cleveland-Cliffs Inc.

Cleveland-Cliffs is the largest flat-rolled steel producer in North America. Founded in 1847 as a mine operator, Cliffs also is the largest manufacturer of iron ore pellets in North America. The Company is vertically integrated from mined raw materials and direct reduced iron to primary steelmaking and downstream finishing, stamping, tooling, and tubing. The Company serves a diverse range of markets due to its comprehensive offering of flat-rolled steel products and is the largest steel supplier to the automotive industry in North America. Headquartered in Cleveland, Ohio, Cleveland-Cliffs employs approximately 25,000 people across its mining, steel and downstream manufacturing operations in the United States and Canada.

CLIFFS

CLEVELAND-CLIFFS INC.
200 Public Square
Suite 3300
Cleveland, OH 44114-2315
844.STEEL99 | 844.783.3599
clevelandcliffs.com

May 2021