

Corrosion behavior of different alloys in industrial media

Stainless steels are normally inclined to nitridation attack when subjected to ammonia based conditions at high temperatures. Ammonia is a widely used nitriding gas for case hardening of steel material that is used at temperatures from 500 – 590oC or 925 – 1100oF. The furnace units and components that are repeatedly subjected to such service conditions broadly receive brittle damages due to nitridation attack.

Carbonitriding another way of case hardening, develops a surface layer of carbides and nitrides. The process is conducted at 700 – 900oC or 1300 – 1650oF in ammonia with inclusions of carbonaceous gases for example methane. Hence, the heat treat retort, fixtures, and other furnace systems are subjected to nitridation and carburization.

The production of ammonia is another source of nitridation attack. Ammonia is developed by combining nitrogen and hydrogen over a catalyst, normally at temperatures 500 – 550oC or 930oF – 1020oF and pressures about 200 – 400 atm.

Nitridation resistance

Nitridation attack is unlike to other modes of high temperature attack in which metals or alloys do not attain metal loss or wastage. Nitrogen from the environment is absorbed on the metal surface and then diffuses into the interior. When nitrogen crosses its solubility limit, nitrides precipitate out.

When temperature is small, about 500oC or 930oF, nitrogen diffusion is nominal.

Nitridation at such temperature limits normally causes the production of surface nitride. At the elevated temperatures about 1000oC or 1830oF, the diffusion of nitrogen is quick. In such condition, nitrogen causes the production of internal nitrides in the matrix and at grain boundaries. With a surface nitride or internal nitride, the metal may become brittle.

An ammonia cracker unit utilized to develop nitrogen and hydrogen, damaged after 1000 hours of service. The preheater tubes are constructed of SS 304 steel while the furnace tubes performing at 600oC or 1100oF were constructed of SS 310. These grades attained intense nitridation attack. To choose other alloys, nitriding analyses were conducted on the different alloy samples at 600oC or 1100oF in a condition comprising of 6 – 8% ammonia, 75.77 – 77.5% nitrogen and 16.25 – 16.5% hydrogen. The results are shown in the following table:

Alloy	Penetration depth of nitridation attack, mm, mills					
	50 hours	100 hours	300 hours	600 hours	1000 hours	1500 hours
Carbon steel	decarburized	decarburized	decarburized	decarburized	decarburized	decarburized
Titanium	0.0066 mm, 0.3 mills	0.0133 mm, 0.5 mills	0.233 mm, 9.2 mills	0.266 mm, 0.5 mills	Cracked	Cracked
304	-	0.013 mm, 0.5 mills	0.013 mm, 0.5 mills	0.03 mm, 1.2 mills	0.06 mm, 2.4 mills	4.2 mm, 165 mills
316	0.02 mm, 0.8 mills	0.02 mm, 0.8 mills	0.02 mm, 0.8 mills	0.03 mm, 1.2 mills	0.04 mm, 1.6 mills	0.04 mm, 1.6 mills
310	-	0.03 mm, 1.2 mills	0.13 mm, 5.1 mills	0.16 mm, 6.3 mills	0.33 mm, 13 mills	0.40 mm, 15.7 mills
321	0.013 mm, 0.5 mills	0.013 mm, 0.5 mills	0.013 mm, 0.5 mills	0.016 mm, 0.6 mills	0.06 mm, 2.4 mills	0.06 mm, 2.4 mills
Incoloy 800	0.02 mm, 0.8 mills	0.10 mm, 3.9 mills	0.20 mm, 7.9 mills	-	0.20 mm, 7.9 mills	0.20 mm, 7.9 mills

The alloys offered excellent performance are SS 316 and SS 321. Incoloy 800 and SS 304 attained corrosion higher than stainless steel 316. The outcomes also described that titanium received intense nitridation corrosion that caused from intense sample cracking. The temperature about 600oC or 1100oF may be extremely high for carbon steel in ammonia conditions as this grade attained decarburization only after 50 hours.

The nitridation resistance of different alloys was examined in an ammonia converter and preheater line. The outcomes are described in the following table:

Alloy	Corrosion rate, mm/y, mpy	
	Ammonia converter	Plant ammonia line
SS 304	0.015 mm/y, 0.59 mpy	2.53 mm/y, 99.5 mpy
SS 316	0.012 mm/y, 0.47 mpy	>13.21 mm/y, 520 mpy
SS 321	0.012 mm/y, 0.47 mpy	-
SS 309	0.006 mm/y, 0.23 mpy	2.41 mm/y, 95 mpy
SS 310	0.004 mm/y, 0.14 mpy	
SS 330	0.002 mm/y, 0.02 mpy	0.43 mm/y, 17.1 mpy
Inconel 600	-	
Nichrome 80	-	
Nickel	-	2.01 mm/y, 79 mpy

Corrosion rates were observed to be firmly based on ammonia content. Stainless steel 304 is attacked at the rate of 0.02 – 2.5 mm/yr with increase in concentration of ammonia 5 – 6% to 99% at 500oC or 930oF. In ammonia converter containing 5 – 6% ammonia at 490oC to 550oC or 910oF to 1020oF, the stainless steel grades tested are 304, 316, 309, 310, 321 and 330, they showed nominal nitridation attack at the rate of 0.03 mm/ye or less. For a plant ammonia line that was subjected to 99% NH₃, stainless steel grades 309 and 316 suffered from intense nitridation attack with corrosion rates about 2.54 mm pr yr or above. SS 304 offered better performance than 316.

Many components constructed from Steel grade 304 subjected to temperatures about 500oC or 930oF with ammonia concentrations about 20% attained nominal nitridation attack of rate 0.01 – 0.1 mm/yr. A grade 304 described nominally higher corrosion rate of 0.25 mm/yr or 10 mils/yr due to elevated temperature limits. **Inconel 600** offered better corrosion resistance as compare to stainless steel grades, showing nominal attack rates as described in the following table:

Component	Alloy	Temp, oC	Ammonia %	Operation time, years	Thickness of nitrides, micro-m, mills	Average nitriding, micro-m/yr, mills/yr
Lining	SS 304	525 oC	15 to 20 %	4 years	1000 µm, 39.4 mills	250 µm/yr, 9.8 mills
Plate, second bed	SS 304	475 oC	15 to 20 %	7 years	100 µm, 3.9 mills	14 µm/yr, 0.6 mills
Bolt	302	-	-	7 years	375 µm, 14.8 mills	54 µm/yr, 2.1 mills
Wire mesh, second bed	Inconel 600	520 oC	-	7 years	8 µm, 0.3 mills	1 µm/yr, 0.04 mills
Perforated plate, first bed	SS 304	500 oC	13 %	5 years	270 µm, 10.6 mills	54 µm/yr, 2.1 mills
Inner shell, 2 nd bed	SS 304	440 oC	8 to 10 %	5 years	45 µm, 1.8 mills	9 µm/yr, 0.4 mills
Perforated plate, 2 nd bed	SS 304	440 oC	8 to 10 %	5 years	60 µm, 2.4 mills	12 µm/yr, 0.5 mills
Center tube, 2 nd bed	SS 304	485 oC	16 %	5 years	440 µm, 17.3 mills	88 µm/yr, 3.5 mills
Nuts, bottom	SS 304	480 oC	16 %	5 years	260 µm, 10.2 mills	52 µm/yr, 2 mills
Bolt, bottom	403	480 oC	16 %	5 years	540 µm, 21.3	108 µm/yr, 4.3 mills
Wire mesh	Inconel 600	500 oC		4 years	6 µm, 0.2 mills	1.5 µm/yr, 0.06 mills
Thermowell	304	500 oC	3.5 %	8 years	200 µm, 7.9 mills	25 µm/yr, 1 mills

Corrosion performance of different alloys in ammonia converter

The test outcomes conducted in Casale converter at 540oC or 1000oF and 76 MPa or 11,000 psi for 1 to 3 years are shown in the following table:

Alloy	Nitridation depth, mm, mills	
	1 year	3 year
SS 304	1.08 mm, 42.7 mills	1.12 mm, 44 mills
SS 316	0.46 mm, 18.2 mills	0.48 mm, 18.7 mills
SS 321	0.46 mm, 18.3 mills	0.60 mm, 23.6 mills
SS 309	0.24 mm, 9.5 mills	0.24 mm, 9.6 mills
SS 310	0.22 mm, 8.8 mills	0.23 mm, 9.2 mills
Incoloy 800	0.14 mm, 5.4 mills	0.13 mm, 5.3 mills
Inconel 600	0.16 mm, 6.4 mills	0.16 mm, 6.4 mills
Nickel 200	No attack	No attack

From the results, it is evident that Nickel offers enhanced corrosion resistance against nitridation. The surprising fact was that Inconel 600 showed same nitridation depth after 3 years that occurred after one year.

Halogen gas corrosion

The attack of halogen gas includes reactions among metals and chlorides, fluorides and hydrogen halides for example hydrogen chloride, HCl and hydrogen fluoride, HF. Halogen and its compounds normally corrode in gaseous phase or molten salt compounds. The salts result in slagging and decomposition of oxide layer, the gaseous halogens penetrate deeply into the material without damaging the oxide layer. So preoxidation is of no use. In this section, primarily gas-phase halogenation is described.

Halogen gas attack resistance:

In chloride and HCl containing conditions, the attack of different alloy systems is firmly based on whether the media is of oxidizing or reducing nature. For chlorine based media with negligible oxygen, iron and steel are prone to chloride corrosion. Inclusion of chromium and nickel to iron enhances the corrosion resistance of alloy. Hence ferritic and austenitic stainless steels can prevent chlorination attack at the higher temperatures than cast iron and carbon steels. Nickel base alloys such as Inconel, Incoloy and Hastelloy offer considerably better resistance to chlorination than stainless steels. Following table describes the corrosion resistance of stainless steel in chlorine media.

Corrosion rate of stainless steels in chlorine

Alloy	Temperature		Flow rate, L/min	Linear rate constant, micro-m/min	Corrosion rate	
	oC	oF			Mm/y	Mills/yr
Ferritic stainless	300 oC	572 oF	15 L/min	$4 \times 10^{(-8)} \mu\text{m}/\text{min}$	0.2 mm/y	7.9 mpy
Ferritic stainless	360 oC	680 oF	15 L/min	$3.8 \times 10^{(-3)} \mu\text{m}/\text{min}$	2 mm/y	79 mpy
Ferritic stainless	440 oC	824 oF	15 L/min	$6.7 \times 10^{(-2)} \mu\text{m}/\text{min}$	40 mm/y	1.6 mpy
Ferritic stainless	540 oC	1004 oF	15 L/min	$1.35 \mu\text{m}/\text{min}$	700 mm/y	28 mpy
Austenitic stainless	418 oC	784 oF	15 L/min	$1.1 \times 10^{(-3)} \mu\text{m}/\text{min}$	0.6 mm/y	24 mpy
Austenitic stainless	450 oC	842 oF	15 L/min	$4.3 \times 10^{(-2)} \mu\text{m}/\text{min}$	20 mm/y	787 mpy
Austenitic stainless	480 oC	896 oF	15 L/min	$0.13 \mu\text{m}/\text{min}$	70 mm/y	2.8 mpy
Austenitic stainless	535 oC	995 oF	15 L/min	$0.47 \mu\text{m}/\text{min}$	200 mm/y	7.9 mpy
Austenitic stainless	640 oC	1184 oF	15 L/min	$46 \mu\text{m}/\text{min}$	20,000 mm/y	787 mpy
Austenitic stainless	315 oC	599 oF	28 L/min	$1.4 \times 10^{(-3)} \mu\text{m}/\text{min}$	0.8 mm/y	31 mpy
Austenitic stainless	340 oC	644 oF	28 L/min	$2.9 \times 10^{(-3)} \mu\text{m}/\text{min}$	1.5 mm/y	59 mpy
Austenitic stainless	400 oC	752 oF	28 L/min	$5.9 \times 10^{(-3)} \mu\text{m}/\text{min}$	3 mm/y	118 mpy
Austenitic stainless	450 oC	842 oF	28 L/min	$2.9 \times 10^{(-2)} \mu\text{m}/\text{min}$	15 mm/y	590 mpy
Austenitic stainless	480 oC	896 oF	28 L/min	$5.9 \times 10^{(-2)} \mu\text{m}/\text{min}$	30 mm/y	1.2 mpy

Austenitic stainless	290 oC	554 oF	28 L/min	1.5 x 10 ⁽⁻³⁾ μm/min	0.8 mm/y	31 mpy
Austenitic stainless	315 oC	599 oF	28 L/min	2.9 x 10 ⁽⁻³⁾ μm/min	1.5 mm/y	59 mpy
Austenitic stainless	340 oC	644 oF	28 L/min	5.9 x 10 ⁽⁻³⁾ μm/min	3 mm/y	118 mpy
Austenitic stainless	400 oC	752 oF	28 L/min	2.9 x 10 ⁽⁻²⁾ μm/min	15 mm/y	590 mpy
Austenitic stainless	450 oC	842 oF	28 L/min	5.9 x 10 ⁽⁻²⁾ μm/min	30 mm/y	1.2 mpy

In oxidizing conditions chlorine and oxygen, molybdenum and tungsten are detrimental to the resistance of alloy towards chlorination attack, presumably because of the production of highly volatile oxychlorides for example WO₂Cl₂ and MoO₂Cl₂. Hence nickel base alloys comprising of large levels of tungsten or molybdenum such as **Hastelloy C-276** attain higher corrosion rates than iron- nickel-chromium and nickel-chromium-iron alloys for example Stainless steel 310 and Inconel 600. The inclusion of aluminum enhances the chlorination resistance of nickel base alloys such as **Haynes 214**. Following table shows the corrosion rates of nickel base alloys and stainless steels in oxygen and chlorine based conditions.

Alloy	Metal loss		Average metal loss	
	Mm	mills	Mm	Mills
Haynes 214	0 mm	0 mills	0.012 mm	0.48 mills
R-41	0.004 mm	0.16 mills	0.028 mm	1.12 mills
Inconel 600	0.012 mm	0.48 mills	0.035 mm	1.36 mills
SS 316	0.012 mm	0.48 mills	0.041 mm	1.60 mills
Hastelloy S	0.053 mm	2.08 mills	0.063 mm	2.48 mills
Hastelloy X	0.020 mm	0.80 mills	0.071 mm	2.80 mills
Hastelloy C276	0.079 mm	3.12 mills	0.079 mm	3.12 mills

In the reducing media comprising of HCl, nickel and nickel base alloys offer higher resistance as compare to iron base alloys, for example stainless steels. In the following table, corrosion rates of different materials including stainless steels in arid HCl is shown.

Alloy	Approx temperature, oC, oF at which corrosion rate exceeds							
	0.8 mm/yr, 30 mpy		1.5 mm/yr, 60 mpy		3 mm/yr, 120 mpy		15 mm/yr, 600 mpy	
Nickel	455 oC	850 oF	510 oC	950 oF	565 oC	1050 oF	675 oC	1250 oF
Inconel 600	425 oC	800 oF	480 oC	900 oF	538 oC	1000 oF	675 oC	1250 oF
Hastelloy B	370 oC	700 oF	425 oC	800 oF	480 oC	900 oF	650 oC	1200 oF
Hastelloy C	370 oC	700 oF	425 oC	800 oF	480 oC	900 oF	620 oC	1150 oF
Hastelloy D	288 oC	550 oF	370 oC	700 oF	455 oC	850 oF	650 oC	1200 oF
18-8Mo	370 oC	700 oF	370 oC	700 oF	480 oC	900 oF	593 oC	1100 oF
25-12 Cb	345 oC	650 oF	400 oC	750 oF	455 oC	850 oF	565 oC	1050 oF
18-8	345 oC	650 oF	400 oC	750 oF	455 oC	850 oF	593 oC	1100 oF
Carbon steel	260 oC	500 oF	315 oC	600 oF	400 oC	750 oF	565 oC	1050 oF
Ni-resist	260 oC	500 oF	315 oC	600 oF	370 oC	700 oF	538 oC	1000 oF
Monel 400	230 oC	450 oF	260 oC	500 oF	345 oC	650 oF	480 oC	900 oF
Cast iron	205 oC	400 oF	260 oC	500 oF	315 oC	600 oF	455 oC	850 oF
Copper	93 oC	200 oF	148 oC	300 oF	205 oC	400 oF	315 oC	600 oF

Stainless steels are prone to corrosion in fluorine gas at temperature below to 300oC or 570oF or even below as shown in the following table.

Alloy	Test time, hours	Corrosion rate, mm/yr, mills/yr					
		200oC or 400oF		370oC or 700oF		540oC or 1000oF	
Monel 400	5	0.013 mm/yr	0.5 mpy	0.048 mm/yr	1.9 mpy	0.76 mm/yr	29.8 mpy
	24	0.013 mm/yr	0.5 mpy	0.043 mm/yr	1.7 mpy	0.29 mm/yr	11.3 mpy

	120	0.003 mm/yr	0.1 mpy	0.031 mm/yr	1.2 mpy	0.18 mm/yr	7.2 mpy
Inconel 200	5	0.084 mm/yr	3.3 mpy	0.043 mm/yr	1.7 mpy	0.62 mm/yr	24.5 mpy
	24	0.013 mm/yr	0.5 mpy	0.031 mm/yr	1.2 mpy	0.41 mm/yr	16.1 mpy
	120	0.003 mm/yr	0.1 mpy	0.010 mm/yr	0.4 mpy	0.35 mm/yr	13.8 mpy
304	5	0.155 mm/yr	6.1 mpy	40 mm/yr	1565 mpy	-	-
304L	24	0.191 mm/yr	7.5 mpy	153 mm/yr	6018 mpy	-	-
	120	0.65 mm/yr	25.4 mpy	-	-	-	-
70	5	0.102 mm/yr	4 mpy	108 mm/yr	4248 mpy	-	-
Monel R	5	0.152 mm/yr	6 mpy	0.32 mm/yr	12.7 mpy	103 mm/yr	4038 mpy
Inconel 600	5	0.015 mm/yr	0.6 mpy	2 mm/yr	78 mpy	88 mm/yr	3451 mpy

Commercially pure nickel offers excellent resistance to fluorine attack at high temperatures, featured to the production of adherent nickel fluoride layer. Various nickel base alloys offer poor performance than pure nickel.

Stainless steels also attain poor resistance to fluorination corrosion in HF conditions. As described in the following table, pure nickel and nickel base alloys Monel 400 and Inconel 600 are significantly better resistant to HF corrosion as compare to stainless steels.

Alloy	Attack rate, mm/yr, mills/yr					
	500oC or 930oF		550oC or 1020oF		600oC or 1110oF	
Nickel	0.9 mm/yr	36 mpy	-	-	0.9 mm/yr	36 mpy
Monel 400	1.2 mm/yr	48 mpy	1.2 mm/yr	48 mpy	1.8 mm/yr	72 mpy
Inconel 600	1.5 mm/yr	60 mpy	-	-	1.5 mm/yr	60 mpy
Copper	1.5 mm/yr	60 mpy	-	-	1.2 mm/yr	48 mpy
Aluminum	4.9 mm/yr	192 mpy	-	-	14.6 mm/yr	576 mpy
Magnesium	12.8 mm/yr	504 mpy	-	-	-	-
Carbon steel	15.5 mm/yr	612 mpy	14.6 mm/yr	576 mpy	7.6 mm/yr	300 mpy
SS 304	-	-	-	-	13.4 mm/yr	528 mpy
SS 347	183 mm/yr	7200 mpy	457 mm/yr	18000 mpy	177 mm/yr	6960 mpy
309Cb	5.8 mm/yr	228 mpy	43 mm/yr	1680 mpy	168 mm/yr	6600 mpy
SS 310	12.2 mm/yr	480 mpy	100 mm/yr	3960 mpy	305 mm/yr	12000 mpy
SS 430	1.5 mm/yr	60 mpy	9.1 mm/yr	360 mpy	11.6 mm/yr	456 mpy

Ash or salt deposit attack

Attack by fuel ash or salt deposit is a serious issue in several units such as incinerators, boilers, heat exchangers, gas turbines, calciners and recuperators. Excluding gaseous fuels, combustion of fossil fuels develops solid, liquid and gaseous compounds that are attacking to structural parts such as superheater tubes and heat transfer surfaces. Besides of accumulations of solid and liquid residues in gas supplies can change the heat distribution properties of the system with significantly aggressive effects on the equipment's efficiency and tube wall temperatures.

Remainders from combustion process named ash, comprise of 6 – 20% of bituminous coals however they may run as high up to 30%. The composition of coal ash changes significantly however it is significantly composed of silicon, aluminum, iron and calcium compounds with nominal magnitudes of magnesium, titanium, sodium and potassium compounds.

Wood, bagasse and other vegetable waste utilized as fuel in few industrial units contain nominal magnitudes of ash than present in coal. In several cases, although compositions of these vegetable ashes is comparable to that of coal ash.

The fuel oils contain ash contents that nominally exceed 0.2%. However so corrosion and fouling of oil-fired boilers can be specifically problematic because of the nature of the oil ash deposits. The prime pollutants in fuel oil are vanadium, sodium and sulfur-elements constitute numerous compounds several of which are tremendously attacking.

Irrespective of the fuel, the quick fireside corrosion conditions are similar in specific respects. A liquid phase is created in the ash deposit adjacent to the tube surface. As liquid phase creates, the security oxide scale on the tube surface is dissolved and quick wastage follows. The coal-fired boilers, the liquid phase is a combination of sodium and potassium iron trisulfate: $(Na_3Fe(SO_4)_3$ and $K_3Fe(SO_4)_3$. Combinations of these substances melt at temperatures as low as 555oC or 1030oF. In oil-fueled boilers, the liquid phase that creates a mixture of V_2O_5 with either sodium oxide (Na_2O) or sodium sulfate (Na_2SO_4). Combinations of these compounds have melting points down to 540oC or 1000of. The production of liquid salts is responsible for accelerated corrosion attack by oil-ash attack.

Coal-ash attack: While the burning of coal, minerals in the burning coal are subjected to the elevated temperatures and to the firmly reducing effects of produced gases for example carbon monoxide and hydrogen. Aluminum (Al), Iron (fe), potassium (K), sodium (Na) and sulfur compounds are slightly degraded, emitting volatile alkali compounds and sulfur oxides. The residual part of the mineral matter combines to create glassy particles called as fly ash.

Attack of coal ash begins with the accumulation of fly ash on surfaces that serve predominantly at temperatures from 540oC to 705oC, basically surfaces of superheater and reheater tubes. These accumulations may loose or they may be sintered or slag type masses that are more adherent.

Over a long duration, volatile alkali and sulfur compounds condense on the fly ash and react with it to produce complex alkali sulfates like $KAl(SO_4)_2$ and $Na_3Fe(SO_4)_3$ at the boundary, between the metal and the deposit. The reactions that produce alkali sulfates are trusted to be based on the catalytic oxidation of sulfur dioxide to sulfur trioxide in the external layers of the fly ash accumulation. The specific chemical reactions that create alkali sulfates are trusted to be based in part on the catalytic oxidation of sulfur. The sulfides cannot occur in the strongly oxidizing conditions so at least on the tube surface, the conditions are of reducing nature.

In the coal ash corrosion, the attack rate attains a bell shaped curve with respect to temperature for austenitic stainless steels. The corrosion rate increases with temperature to a largest value then reduces with further increase in temperature. The highest corrosion rates about 675 – 730oC or 1250oF to 1350oF. The increased corrosion related with this bell shaped curve is related to the production of molten alkali metal iron-trisulfate $[(Na,K)_3Fe(SO_4)_3]$. Change in the sodium to potassium ratio significantly affects the melting point of the complex sulfate in an ash deposit stating a significant change in the melting points of the combination of sodium iron trisulfate and potassium iron trisulfate.

Oil-Ash corrosion resistance

Boilers fired with Bunker C oils comprise of high concentration of vanadium. The test racks were subjected in the superheater section. Different types of alloys, varying from low steels to iron and nickel base alloys, receive intense corrosion attack. The outcomes of one test rack are described in the following table:

Outcomes of a field test subjected in the superheater section at 815oC or 1500oF in a boiler subjected with concentrated vanadium Bunker C fuel.

Alloy	Corrosion rate, mm/yr or mpy
Stainless steel 321	9 to 13 or 346 to 505
Stainless steel 310	4.7 or 187
Incoloy 800	9 to 12 or 364 to 458
Inconel 600	5 or 196

The samples of stainless steel series 300, Incoloy and Inconel alloys were included. The analyzed alloys attained severe corrosion rates. It is found that concentration of vanadium in fuel oil increases the corrosion rate accordingly.

Superheaters and reheaters performing at lower temperatures than tube supports are also prone to attack by oil-ash. Bolt tested different superheater and reheater materials in an experimental boiler firing with heavy oil comprising of 2.2% sulfur, 200 ppm V and 50ppm Na. An analysis was done on **stainless steel 310 tubes, Incoloy 800H tubes** and other grades. It was found that these tubes offered suitable performance.

Fireside attack in waste incinerators

Incineration has become a feasible method for disposing different kinds of wastes such as municipal, hospital, chemical and hazardous wastes. An increasing count of incineration units have been installed and put into service. Although system problems caused from fireside attack have been normally occurred in the complex nature of the wastes and corrosive contaminants that are in a larger count and greater concentrations as compare to regular fuels like coal and oil.

Sulfur is constantly available in the conditions produced by incineration of wastes. Sulfidation has commonly been noticed to occur in fireside attack in the different waste incinerators. High nickel alloys including **Hastelloy X, Hastelloy C-276** have been attacked by sulfidation in municipal waste incinerators when subjected to a temperature limit of 750 – 980oC or 1400 – 1800oF. The erosion shields produced from stainless steels rapidly receive sulfidation attack in municipal waste incinerators.

Wide studies in the municipal incinerators have stated that in the temperature limit of 150 – 315oC or 300 – 600oF, many alloys offer suitable service in preventing high temperature attack. The suitable alloys are **Incoloy 825, stainless steel 310, SS 316I, Inconel 600 and Inconel 601**. When subjected to wet accumulations, simulating boiler downtime conditions, the entire austenitic stainless steel grades are attacked by chloride stress corrosion cracking. Here Inconel 600 and 601 are attacked by pitting.

Unless the boilers are to be kept at a temperature above HCl dew point while the downtime, **Incoloy 825** is preferred for use.

Attack in molten salts and liquid metals

Molten salts or named as fused salts can cause corrosion by the solution of constituents of the container material, specific attack, pitting, electrochemical reactions, metal loss due to thermal gradients, reaction of constituents of molten salt with container material, impurities reaction in the molten salt with the container materials and interaction of impurities in the molten salt with an alloy.

The comparable attacking rate of different alloys in molten chlorides, nitrates or nitrites, sodium hydroxide, fluorides and carbonates is considered. Reducing oxidizing contaminants for example oxygen and water vapor in the melt can also considerably decrease the attack of molten salt. Thermal gradient in the melt, in case of circulating systems, may cause dissolution of an alloying element at the hot leg and accumulation of the element at the cold junction, causing the significant tube plugging issues.

Attack in liquid metals: The liquid metal that is of utmost significance to stainless steel is sodium (Na). Stainless steels are a crucial part of the fast breeder reactors. Therefore many studies have been conducted. Increased attack of stainless steels in liquid sodium occurs with oxygen contamination with a significant effect taking place at 0.02% oxygen by weight. Following table shows the corrosion rates of stainless steels in the liquid sodium media.

Materials	Temperature		Test time	Test equipment	Mass change rate, mg/cm ² /sec
	oC	oF	Hours		
1010 steel	593 oC	1100 oF	1000 hrs	Flowing	-0.49 mg/cm ² /sec
	593 oC	1100 oF	1000 hrs	static	-0.37 mg/cm ² /sec
2.25Cr-1Mo	552 oC	1026 oF	943 hrs	Flowing	-0.12 mg/cm ² /sec

	556 oC	1033 oF	902 hrs	static	-0.12 mg/cm ² /sec
	593 oC	1100 oF	1000 hrs	Flowing	-0.14 mg/cm ² /sec
	593 oC	1100 oF	1000 hrs	static	-0.09 mg/cm ² /sec
9Cr-1Mo	552 oC	1026 oF	943 hrs	Flowing	+0.22 mg/cm ² /sec
	556 oC	1033 oF	1913 hrs	static	-0.06 mg/cm ² /sec
	593 oC	1100 oF	500 hrs	Flowing	+0.23 mg/cm ² /sec
	593 oC	1100 oF	500 hrs	static	-0.08 mg/cm ² /sec
410	593 oC	1026 oF	943 hrs	Flowing	+0.35 mg/cm ² /sec
	593 oC	1033 oF	902 hrs	static	-0.05 mg/cm ² /sec
420	593 oC	1100 oF	500 hrs	Flowing	+0.70 mg/cm ² /sec
	593 oC	1100 oF	1000 hrs	static	+0.29 mg/cm ² /sec
304	593 oC	1100 oF	1000 hrs	Flowing	+0.38 mg/cm ² /sec
	593 oC	1100 oF	1000 hrs	static	+0.35 mg/cm ² /sec
310	593 oC	1100 oF	500 hrs	Flowing	+0.33 mg/cm ² /sec
	593 oC	1100 oF	500 hrs	static	+0.31 mg/cm ² /sec
316	593 oC	1100 oF	1000 hrs	Flowing	+0.17 mg/cm ² /sec
	593 oC	1100 oF	1000 hrs	static	+0.15 mg/cm ² /sec
347	593 oC	1100 oF	500 hrs	Flowing	+1.46 mg/cm ² /sec
	593 oC	1100 oF	500 hrs	static	+0.22 mg/cm ² /sec
410	1000 oC	1830 oF	400 hrs	static	+29.8 mg/cm ² /sec
430	1000 oC	1830 oF	400 hrs	static	+46.8 mg/cm ² /sec
446	1000 oC	1830 oF	400 hrs	static	+28.2 mg/cm ² /sec
304	1000 oC	1830 oF	400 hrs	static	+25.5 mg/cm ² /sec
316	1000 oC	1830 oF	400 hrs	static	+29.6 mg/cm ² /sec
310	1000 oC	1830 oF	400 hrs	static	+28.2 mg/cm ² /sec
347	1000 oC	1830 oF	400 hrs	static	+44.2 mg/cm ² /sec
Inconel 600	1000 oC	1830 oF	400 hrs	static	+18.7 mg/cm ² /sec

Subjecting to molten lead in the dynamic conditions usually causes mass loss in the stainless steel alloy systems. Specifically intense corrosion can take place in the powerful oxidizing conditions. The stainless steels are normally corroded by molten aluminum, zinc, antimony, bismuth, cadmium and tin.

Influence of carburization on stainless steels

Diffusion of carbon in stainless steel results in the production of carbides that may occur in the form of M₇C₃, M₂₃C₇ or M₃C₂. In the same steel prior carburization, carbides were small and limited to the grain boundaries. In the carburized steel, chromium has moved to carbides, depleting the matrix. Chromium depletion occurs, relative % of nickel and iron has increased.

For wrought stainless steels by performing pack carburization tests the outcomes are described in the following table.

Alloy	Chemical composition	Silicon concentration %	Increase in carbon content %
Incoloy 800	34Ni-21Cr	0.34 %	0.04 %
SS 330	35Ni-15Cr	0.47 %	0.23 %
SS 330	35Ni	1 %	0.08 %
SS 310	20Ni-25Cr	0.38 %	0.02 %
SS 314	20Ni-25Cr +Si	2.25 %	0.03 %
SS 309	12Ni-25Cr	0.25 %	0.12 %
SS 347	8Ni-18Cr +Nb	0.74 %	0.57 %
SS 321	8Ni-18Cr+Ti	0.49 %	0.59 %
SS 304	8Ni-18Cr	0.39 %	1.40 %
SS 302B	8Ni-18Cr +Si	2.54 %	0.22 %
SS 446	28Cr	0.34 %	0.07 %

SS 430	16Cr	0.36 %	1.03 %
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Silicon is found to be a beneficial alloying agent as shown by Stainless steel grade 330. The enhanced carburization of silicon alloyed stainless steel is featured to the production of SiO₂ scale that is more impervious to carbon entrance than Cr₂O₃ scale. Chromium offers significant performance in Fe-Cr alloys. Nominal inclusions of titanium or niobium seemed to be advantageous for SS 304, SS 321 and SS 347. Improved nickel content in iron-chromium-nickel alloys also offers increased resistance to carburization, as nickel decreases the diffusivity of carbon.