High Temperature Erosion Testing in a Gasifier Environment

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Abstract

The development of materials with the ability to operate in adverse conditions while resisting the effects of erosion and corrosion is essential to the future success of high efficiency power plants. Many next generation coal power plants are envisioned as combined cycle, with gasifiers used to produce both steam and syngas. The gasifier sections of these plants require materials of construction that are resistant to the effects of erosion from silica found in the gas streams and corrosion caused by a reducing atmosphere that may contain sulfur and chloride compounds. The Albany Research Center has developed a test apparatus designed to test the erosion-resistance of candidate materials under a range of environmental conditions, including those found in gasifiers. This Hostile Atmosphere Erosion Wear test apparatus (HAET) has been used to evaluate a group of high alloy candidate materials such as iron aluminide and Haynes HR 160, and compare them to a conventional 310 stainless steel. Erosion tests were conducted using 270μm silica abrasive, a typical impact velocities of 20 m/sec at temperatures up to 700°C in an atmosphere simulating gasifier conditions. The effects of erosion under these conditions on the surface scales that form are described. The total loss rate, loss rates due to erosion and corrosion for the test materials are compared.

Introduction

Gasification is the process of turning solid coal into a combustion gas that can be used elsewhere: for burning in a turbine, for use in a fuel cell, or as a feedstock in a chemical plant. The materials lining the center of the gasifier are refractories, because no other material will stand up to this high temperature-gas environment. Further downstream the environmental conditions change and the gases can then be handled, cleaned, and prepared for their eventual uses by equipment that is mostly metallic in construction.

In general, the higher the temperature that can be maintained during power production – at least until the energy conversion step - the more efficient the process. Gasifier systems are no different. Engineers are continuously trying to improve power system efficiency by increasing operating temperatures. Unfortunately metals that can withstand high temperatures than are currently used, are difficult to find.

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In gasifiers, the reducing atmosphere limits the formation of surface oxides that form an erosion-resistant protective layer. Many of today's materials have limitations. T11, T21, and T91 steels, which are often used in non-aggressive conditions, are commonly used in the manufacturing of conventional boilers. Unfortunately, their useful life is severely limited in the reducing conditions found in gasifiers[1]. 310 stainless steel, and other high alloy boiler code materials, also experience accelerated corrosion and corrosion/erosion rates in high temperature gasifier conditions. Nickel-based materials readily react with the sulfur in the coal leading to a high corrosion rate.

High levels of erosive wear arise because of abrasive particles in the high-velocity gas stream. Wear losses are a problem for power producers due to increased downtime, expense of replacement parts, decreased efficiency, the need to find replacement power, etc. Recognizing the seriousness of this problem for manufacturers, the Albany Research Center began testing a variety of materials that might prove more profitable for use in gasification plants than current materials.

To investigate materials resistant to conditions in power plants it is necessary to simulate the combined actions of erosion and corrosion in the laboratory. The main variables that influence erosion are the (i) erodent: size, shape, velocity, angle of impact, and composition of the eroding particles, (ii) the properties of the surface being eroded, and (iii) the temperature of the system[2, 3, 4, 5]. The main variables that influence corrosion are (i) the gas chemistry, (ii) the temperature of the system, and (iii) the properties of the surface being corroded[6, 7, 8, 9]. One of the key measures of materials wear is wastage rate. For syngas coolers, material wastage rates for the heat exchanger tubes must be less than about 0.1 mmpy (4 mils/year) to obtain a service life of 25 years[7, 8]. To approach this rate a target wastage rate of 0.1 to 1.0 mmpy was established for this study. There are other applications, like thermocouple wells used, in gasifiers where parts are simpler, relatively easy to replace, and operators are willing to tolerate much shorter lifetimes.

A number of the variables in this study were matched to the conditions within the range experienced or envisioned in coal gasifiers. These variables include the temperature, particle velocity and gas chemistry. The temperature range experienced by fireside of the coal gasifier's heat exchangers is typically between 350°C and 420°C[6, 8]. At other locations closer to the gasifier temperatures can be much higher. The velocity of the eroding particles is between 10 m/s and 40 m/s[3, 4], and the gas chemistry (volume percent) is in the range of 15 to 64 CO, 2 to 15 CO_2, 10 to 30 H_2, 0 to 4 CH_4, 0 to 20 H_2O, 0.03 to 1.2 H_2S, 0.02 to 0.12 HCl, and 1 to 57 N_2[8, 9, 10, 11]. In our tests silica sand was chosen as the erodent. Silica is one of the major mineral components in ash and is the principal cause of most of the erosion[3, 4, 8]. The silica sand feed was adjusted to produce the target wastage rate (estimated to be in the range of 0.05 to 0.5 g/minute). The impingement angle of the abrasive was chosen to be 90° to the surface. Previous work has shown this to be the most severe angle, because the material being eroded tends to be the brittle scale on the surface and not the base metal. The test time was a balance between minimum time to produce useful weight losses, the time required to get past an initial period of heavy scale growth, and a reasonable test completion time.

Experimental Procedure

HAET apparatus

The HAET test apparatus, fig 1, was designed to simulate the abrasive material, hostile environment, and processing machinery/systems in the power industry, thus helping the industry identify materials that will minimize costly, dangerous, and frustrating wear problems.
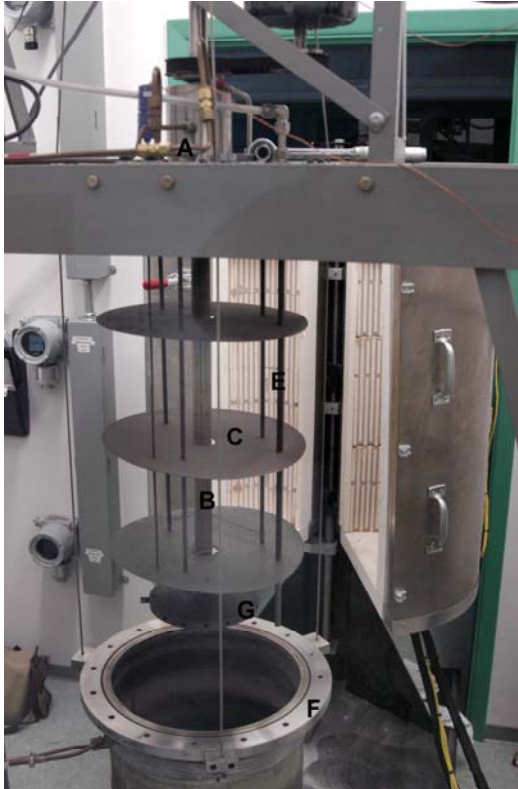
Components of HAET apparatus:
A   Lid
B   Drive shaft
C   Heat shields
D   Abrasive feed tube
E   Gas inlet/outlet tubes
F   Retort
G   Sample mounting disk
H   Samples

Figure 1. Picture showing an overall view of the HAET apparatus.

The lid (A) holds the drive shaft (B), heat shields (C), abrasive feed tube (D), and gas inlet/ outlet tubes (E). Prior to operation, the retort (F) was brought up to the lid of the apparatus, creating an enclosed test environment. The long drive shaft (B), which is driven by a variable speed motor and supported by both a bearing and a gas tight feed through, is inserted vertically through the lid. The drive shaft holds and rotates the central assembly's sample mounting disk (G). The drive shaft provides the velocity component of the abrasion test.

An auger screw feeder was used to feed the abrasive. The abrasive was fed from the screw feeder into a feed tube that runs from the gas tight box through the drop tube and into the furnace/retort area. A long abrasive feed tube allows gravity to accelerate the abrasive (a ~270 micrometer SiO_2 abrasive) so that the abrasive wear impact area covers the surface of the samples as they whorl through the abrasive stream.

The gases, see table 1, used in the tests (including all of the hostile gases) were fed into the lid and released at the top of the enclosure. For these tests either nitrogen, or a simulated gasifier gas with 30 pct CO, 8 pct CO$_2$, 2 pct CH$_4$, 20 pct H$_2$, 0.8 pct H$_2$S, 0.02 pct HCl and 40 pct N$_2$ were used. They were mixed and heated as they flow down the retort. The gases were exhausted from the system by a tube that extends past the heat shields to a location just above the central core's sample mounting disk. A total flow rate of one liter per minute was used during a test.

Gas	Test gas composition, Rper min
CO	0.30
CO$_2$	0.08
CH$_4$	0.02
H$_2$	0.20
H$_2$S	0.008
HCl	0.0002
N$_2$	0.40

Table 1, Test gases and flow rates for simulated gasifier conditions.

The test samples (H) were attached to a 17-cm diameter sample mounting disk (G) which was at the lower end of the drive shaft (B). The distance from the lid (A) to the sample mounting disk is about 63 cm. Test samples (12 x 10 mm) were capacitive discharge welded to 6.4 mm diameter 304 SS stubs. These stubs, with the samples attached, were inserted in the periphery of the sample mounting disks and locked into place with wires that were fed through holes in both the disks and the stubs, as shown in figure 2. The disk/sample assembly looks somewhat like a ceiling fan made with small sample "blades". For a sample erodent impact velocity of 20 m/sec eight samples at a time attached to the mounting disk.
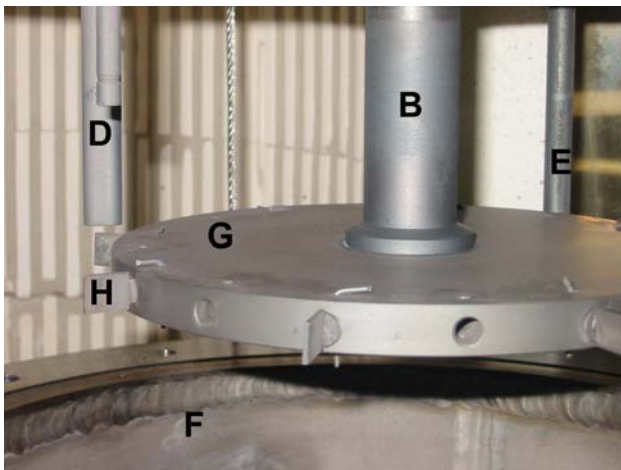

Figure 2. Parts associated with HAET apparatus. Note in this case the test specimens are mounted in alternating locations in mounting disk for testing at 20m/sec erosion velocity.

After the samples were welded to the 304 SS stubs, they were ground smooth and flat using abrasive papers. They were then cleaned and weighed to the nearest 0.01mg.

For these tests two samples of each material were inserted into the sample mounting disk as erosion-corrosion samples. Additional samples were hung from the bottom heat shield in an area devoid of abrasive (and therefore erosion) to separate out and isolate the effect of corrosive atmosphere. In addition to the regular corrosion samples, mounting stubs were hung in order to separate corrosion effect on them.

After the system was sealed nitrogen was used to purge the system of air. After several hours of purging the sample drive shaft motor was turned on. Next the furnace was turned on and brought up to the chosen temperature (from room temperature up to 700° C). After a hold time of one hour the selected gas chemistry was added and the abrasive feed was started simultaneously.

HAET tests ran for 120 hr. At that point the furnace, environmental gases, and abrasive feed were turned off. Nitrogen was used to purge the system as the system cooled. Once the system was cooled, it was opened and the samples were removed.

The samples were visually examined to evaluate the condition of the scale. A sample from each erosion corrosion condition was examined using scanning electron microscopy (SEM). After visual and SEM examination the samples were cleaned, first with a soft bristle brush and soapy water, then ultrasonically cleaned and dried. The samples were weighted and again examined visually. The corrosion, erosion corrosion, and total loss rates were determined using gravimetric calculations.

Materials

A variety of metal materials were chosen for evaluation in the HAET apparatus. The 310 stainless steel is a widely used conventional high Cr stainless steel. It was used as a baseline material for these tests. An iron aluminide was also included in these tests. These Fe_3Al materials have been shown[12] to have very good corrosion resistance in both oxidation and sulfidation environments. The Haynes alloys HR-120 and HR-160 are both high alloy solid solution strengthened materials developed to have good sulfidation resistance. Where the HR-120 has around 33 wt pct Fe, the HR-160 has in its place about 30 wt pct Co. The AR Nitronic 30 is a N_2 strengthened high Cr and Mn, low-Ni stainless steel. This alloy has demonstrated good aqueous corrosion resistance in many applications. The T91, a 9 Cr 1 Mo, is a boiler tube material used very successfully in conventional pc power plants. Its use in gasifier systems is limited to lower temperature applications. The Waspaloy is a Ni-based superalloy with high temperature strength and good oxidation resistance.

	Fe	Al	C	Co	Cr	Mn	Mo	Ni	Si	Ti	W
310 Stainless Steel	bal.		<0.25		24-26	<2		19-22	<1.5		
Fe$_3$Al	bal.										
Haynes HR-120	bal.	0.1	0.05	3	25	0.7	2.5	37	0.6		2.5
Haynes HR-160	3.5		0.05	30	28	0.5	1	37	2.75	0.5	1
Nitronic 30	bal.				17	9		3	<1		
T91, 9Cr 1Mo Steel	bal.	0.04	0.1		9	0.4	1		0.35		
Waspaloy	<2.0	1.4	0.07	13.5	19.5		4.3	57		3	

Table 2. Primary composition of alloys tested in HAET apparatus.

Test conditions

Table 3 outlines the test conditions used for these series of tests in the HAET apparatus. The nitrogen was only used for the room temperature tests, since using the gasifier atmosphere at room temperature would not have resulted in a measurable amount of corrosion.

Test temperatures:	Room temp, 500, and 700ºC
Test environment:	Nitrogen and Gasifier atmosphere see table 1.
Test time:	120 hr tests
Erodent impact velocity:	20 m/sec.
Erodent:	1kg of ~270um SiO$_2$.
Erodent impact angle:	90 deg to test surface

Table 3. Conditions used for tests in HAET apparatus.

Results

After removal from the HAET apparatus the specimens were examined visually and by scanning electron microscopy (SEM), cleaned, weighed, and gravimetric calculations preformed.

Visual examination

Room Temperature Tests

All of the materials tested at room temperature with an erosion velocity of 20 m/sec performed well. The visual inspection of each sample noted no more than a roughing of the upper 3/5th of the surface that was exposed to the erosion. Figure 3 shows a typical sample after testing at room temperature. The lack of corrosion and much erosion was further verified when the samples were weighed and very low levels of weight loss were measured.

Figure 3. . A Waspaloy sample after room temperature testing that shows the typical roughing of the surface during testing.

500ºC Tests

When the temperature was increased to 500ºC the effects of corrosion along with the erosion were evident. At 500ºC the 310SS and the HR-120 showed a very thin scale. On the 310SS the erosion seems to clean the scale off the surface in the eroded/corroded region. Away from this eroded/corroded region a thin layer of scale covered the surface. The Fe$_3$Al material did not show any attached scale, but the eroded/corroded region showed rust colored discoloration after being removed. Below the eroded/corroded region was a bright zone, the bottom, back, and corrosion samples showed a similar dark glassy coating covering the surface. The HR-120 steel was generally free of scale on the front of the erosion-corrosion sample, but scale did develop on the backs of these samples as well as the corrosion sample. The HR-160 showed just a thin discoloration of the metallic surface. In the eroded/corroded region this corrosion based discoloration, and so the corrosion layer, was reduced and the eroded/corroded region looked brighter.

700ºC Tests

Generally a scale formed on the sample surface at the highest 700ºC temperatures. The character of this scale depended on the test material, test temperature, and whether the scale was being struck by the silica erodent particles. The high Ni alloys are subject to formation of a low melting Ni-Ni$_3$S$_2$ eutectic that can form at temperatures as low as 635ºC. This low melting eutectic may be responsible for promoting the formation of the thick scales on high Ni alloys. Because of the way the scales formed on the different samples, the gravimetric data did not provide for absolute analysis. In this study 310 SS was used as a comparison standard and will be described first.

310 SS

The 310 SS material at 700ºC formed a fine bright angular scale where only exposed to the processes of corrosion. The scale was weakly bonded and parts of this scale readily

flaked off in the handling/cleaning process. Below the scale appeared to be bare metal. The eroded/corroded samples of 310 SS showed a thicker, smoother scale in the middle of the zone where the abrasive struck the surface. This eroded/corroded scale appeared to be tougher since none of it was seen to flake off. The compositions of these scales were analyzed during the SEM examination.

Fe$_3$Al

The Fe$_3$Al intermetallic material showed exceptional performance at 700ºC. The corroded surface was slightly discolored and without any appearance of a sulfide scale, just a bare metal surface. The eroded/corroded samples generally showed a darker color in the erosion zone. Surrounding the main erosion zone was a light-colored transition band. At the bottom of the zone where the silica was striking the surface there was an adhered scale. This scale was thin and disappeared below where the silica struck the surface. The very top edge showed a small amount of rounding from erosion.

Haynes HR-120

The Haynes HR-120 formed a thin scale on the corrosion specimen. This scale, in general, was adherent and only small spots flaked off during handling/cleaning. The eroded/corroded samples showed several zones on the surface. The main erosion zone showed areas of thin scale and bare metal where the scale was removed. Below this, at the bottom of the area where the silica was striking the surface, there was a band of very thick scale. Where this scale had broken off there appeared to be bare metal. Below this fairly wide, thick scale was another zone where a thin layer of scale had formed, looking much like the scale that formed in the erosion impact zone.

Haynes HR-160

The Haynes HR-160 corrosion specimen formed a smooth dark protective thin layer on its surface. The eroded/corroded samples also showed different zones on the surface. In the main erosion zone a two-layer scale structure formed, one thin and one thick. At the top edge of the erosion zone these thicker scales were removed and a dark layer remained, of similar color to the corrosion specimen. At the bottom of the erosion zone the thick scale ended and a thin layer of scale was found.

Nitronic 30

The Nitronic 30 visually appeared to do well at 700ºC. The corrosion specimen showed a thin layer of scale that was partially removed during handling/cleaning. The eroded/corroded samples showed two zones. A thinner scale was evident in the zone of erosion with the silica, and a thicker scale layer formed below, away from the erosion impact.

T91, 9Cr 1Mo Steel

While 9 Cr 1 Mo steel performed essentially the same as other materials at room temperature, this was visually the worst performing material tested at 700ºC. Both the corrosion and the erosion/corrosion specimens showed virtually no differences. In both cases there was a thick outer scale that sloughed off easily during handling. Figure 4 shows a 9 Cr 1 Mo steel sample after testing. The upper thick layer of scale has broken free showing a lower more adherent layer below. On the eroded/corroded sample there was some discoloration of the outer layer where the erosion took place, along with some smoothing of this outer rough scale. Below the outer scale was a thick dark inner scale. This scale was very smooth, still showing polishing features of its preparation. Finally below this layer was the metal with a thin layer of corrosion on the surface. The metal was mostly consumed during the test.

Figure 4. The 9 Cr 1 Mo sample after testing at 700ºC. The thick fragile upper scale is partially removed exposing the next layer of scale.

Waspaloy

The Waspaloy after the 700ºC test showed a corroded surface with a fairly thick rough scale that had a fine surface structure. The eroded/corroded surface showed a similar scale away from the erosion zone. At the erosion zone, figure 5, the surface appeared smoother due to the erosion impact. It was shiner and gold in color. Cracks were also seen radiating from the erosion zone, caused by the stresses as this compacted scale layer cooled off.

Figure 5. Waspaloy sample eroded at 700ºC in a gasifier environment. Specimen shows cracking emanating from the erosion/corrosion zone.

SEM examination

700ºC Tests

A scanning electron microscope was used to examine samples from a gasifier test run at 700ºC and 20 m/s. Both the eroded/corroded and corroded surfaces of the samples were examined. Generally, a blocky angular scale formed on the surface of the specimens. On areas subjected to the SiO_2 erodent, the energy of the erosion particle impact was not sufficient to wear through the corrosion-induced scale. However, erosion did cause the scale to become much smoother and denser. This impacted scale often showed small smooth areas with sharp edges resulting from the impacts with the silica erodent. Using energy dispersive x-ray spectroscopy (EDS) it was found that a variety of different scale formed on the surface of the samples. Among the most common scales formed were (Fe, Ni)S and (Fe, Ni)$_2$S.

310 SS

The eroded/corroded region of the 310 stainless steel showed a moderately thin scale that was smoothed from the impact of the silica erodent. At the top of the eroded/corroded region the thicker scale was removed. In this area a higher Cr content was seen. The eroded/corroded region was basically a (Fe, Cr, Ni)S compound with imbedded silica. Below the eroded/corroded region the surface got rougher from coarse metal sulfide crystals.

Fe$_3$Al

The eroded/corroded surface showed a generally beaten surface with fragments of silica embedded in it. EDS analysis of the surface generally verified this observation with about 15 pct silica, while Al percentage was enriched from the 1 to 3 ratio found in the base alloy, and 5 pct S was the last element found in any large amounts. Since the EDS used

does not detect oxygen, it is surmised that S is associated with Fe, while the excess Al is an alumina compound. EDS showed that a light-colored scale area, as shown in fig 6, below the eroded/corroded zone consisted of FeS compound. Below this, the remaining surface was generally Al, presumed to be alumina, and some Si, presumed to be silica from the abrasive. It is thought that the alumina should be the general protective surface but the impact with the silica breaks the fairly brittle alumina and removes it.
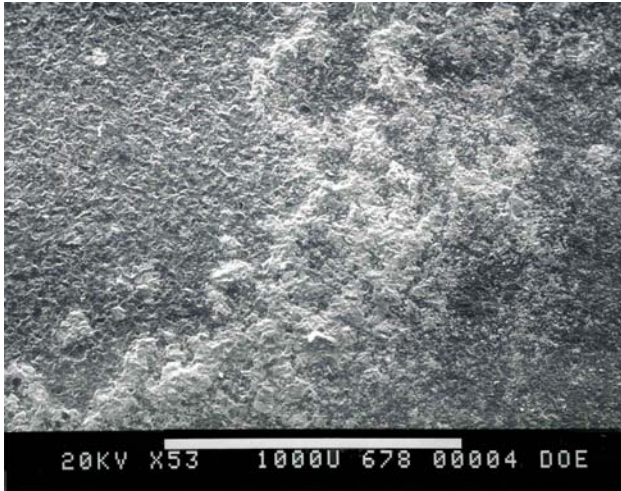

Figure 6. Fe$_3$Al specimen, showing eroded/corroded zone in upper left and transition to just corroded area.

Haynes HR-120

The HR-120 sample showed various corroded/scale layers. EDS analysis in the base of the eroded/corroded region shows a similar composition to the bulk except that the Cr is depleted. In the eroded/corroded region where a scale has formed the composition shows the scale is generally (Fe, Ni)$_2$S, with fairly low silica. The scale found at the bottom of the eroded/corroded region is similar to that found in the eroded/corroded region except higher amounts of Si are found. Finally at the bottom of the sample the scale consists of top layer of (Fe, Ni)$_2$S and a lower layer of (Fe, Ni)S. In both cases the Cr level is higher than is seen in the eroded/corroded region.

Haynes HR-160

The HR-160 sample, fig 7, showed various corroded/scale layers. Using EDS analysis on the different scale layers it was found that in the eroded/corroded region the thick scale layers were largely a (Fe, Ni)S compound. As the layers got thicker the ratio of Ni increased. Only in areas of thin scale was much Cr found. The metal in these thin scale areas was predominately Cr, with half as much Fe, a quarter as much Ni, and lower amounts of Co. The metal ratios continued to show a (Cr, Fe, Ni, Co)S compound was being formed. Along with the metals and S forming the surface scale, silica was mixed with the scale. Moving away from the eroded/corroded region the scale layer thinned out and the silica content decreased.
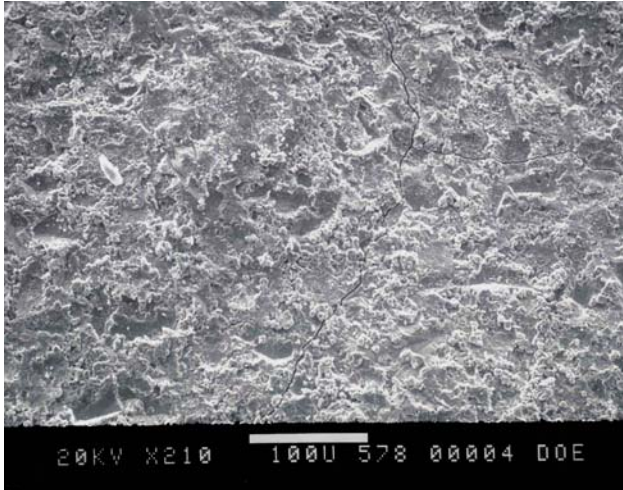
Figure 7. SEM image of HR-160 showing compacted surface scale from erosion/corrosion process.

Nitronic 30

The Nitronic 30 sample showed a thin layer of scale in the eroded/corroded region. This scale was very rich in silica, with up to 30 atomic pct Si. The metal was primarily Fe, with some Cr and Ni. The atomic ratios suggest that this scale was a combination of (Fe, Cr, Ni)S and (Fe, Cr, Ni)$_2$S. Moving away from the eroded/corroded region the scale got thicker. Analysis of this thicker scale was much the same as in the eroded/corroded region except the silica was reduced, to around 13 atomic pct Si. At the bottom of the specimen this layer of scale was completely removed and showed a low concentration of Si.

T91, 9Cr 1Mo Steel

A thick layer of coarse metal sulfide crystals covered the entire surface of the 9Cr 1Mo steel sample. In the eroded/corroded region the edges of the metal sulfide crystals were rounded from the impact with the silica erodent. The entire surface showed a higher Si content from the silica being collected on it. This outer layer was mostly a Fe$_2$S composition. This layer was easily removed and another thick dark scale layer was underneath. This second scale layer showed additional metals, with the Fe being about 40 pct of the total, Cr about 13 pct, and Mo about 12 pct. Again the composition formed was a (Fe, Cr, Mo)$_2$S. This layer was cracked in it, probably from stresses formed on cooling. Below this second thick layer of scale was a thin third layer of scale covering what was left of the original metal.

Waspaloy

The Waspaloy showed at least three different scale layers. In the eroded/corroded region the process of erosion thinned the thick outer scale. This outer scale was of similar composition across the surface, being a high Ni, Fe, Mo, Co, Cr sulfide. This outer scale was fairly fragile and easily removed. Below this outer thick layer was a thin scale layer

of varying composition. In this region there were areas that showed Mo, up to 14 pct, along with the Ni, Mo, Fe, and Cr. Below this layer was at least one further that showed fair amounts of Ti (up to 9 pct) and Cr (up to 40 pct) with some Ni and Fe. Fig 8 shows an area in the erosion/corrosion zone where the outer scale has been removed. The second layer of scale shows damage from the impact of the erodent. The impact-scale can be compared to the non-impact scale by looking down the corner of the specimen.
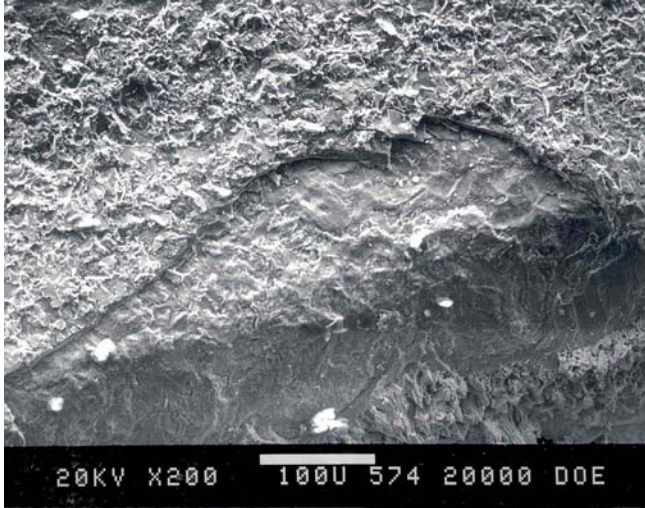

Figure 8. Image of edge of the eroded/corroded zone from the Waspaloy specimen. Picture shows a small area where the outer scale has been removed showing the two inner scale layers.

Gravimetric calculations

The corrosive loss was calculated by measuring the weight change of the corrosion sample (ΔW_c) and then subtracting the weight change of the stub (ΔS_c). The loss rate, in mmpy, was the weight change multiplied by the 8760 hours in a year and then divided by sample area times the density of the sample times the test time. Negative weight losses were common due to development of metal scale on the surface of the test specimens.

$$L_c = \frac{(\Delta W_c - \Delta S_c)*8760}{A*d*t}$$

Where L_C is loss due to corrosion
   ΔW_c is the sample weight change due to corrosion.
   ΔS_c is the stub weight change due to corrosion.
   A is the total area of the sample.
   d is the materials density.
   t is the test time, in this case 120 hr.

Conditions		Alloy, Corrosion loss in mmpy						
Temp, °C	Atmosphere	310 SS	Fe₃Al	Haynes 120	Haynes 160	Nitronic 30	9Cr 1Mo	Waspaloy
Room	Nitrogen	0	0	0	0	0	0	0
500	Gasifier	-0.2	-0.2	0.3	-0.7			
700	Gasifier	-1.9	-2.2	-1.7	-1.5	10.2	-0.1	-1

Note: "-" values are weight gain due to scale formation.

Table 3. Corrosion loss for materials tested at various temperatures, in mmpy.

Results of loss due to corrosion are shown in table 3. As would be expected the corrosion samples were unchanged in room temperature tests. In the simulated gasifier environment at 700°C the Nitronic 30 showed the highest weight loss. This is somewhat misleading, since the 9 Cr 1 Mo alloy had the most base material convert to a metal sulfide and is the material least able to resist attack at these conditions. Most of the materials showed a corrosion scale at both 500 and 700°C. The Fe₃Al performed the best against corrosion in this simulated gasifier environment and showed a mostly clean metallic surface after testing.

The erosive loss was calculated using a similar formula. The total weight loss of each erosion-corrosion sample was measured then the measured weight change due to corrosion and the measured weight change due to corrosion experienced by the stub were subtracted. The weight change due to erosive loss was multiplied by the 8760 hours in a year and then divided by the erosion area times the density of the sample times by the test time required to obtain the erosion loss rate.

$$L_e = \frac{(\Delta W_e - \Delta W_{ic} - \Delta S_c)*8760}{A'*d*t}$$

Where ΔW_e is the sample weight change due to erosion/corrosion.

A' is the area of the sample that was eroded.

Conditions		Alloy, Erosion/Corrosion loss in mmpy						
Temp, °C	Atmosphere	310 SS	Fe₃Al	Haynes 120	Haynes 160	Nitronic 30	9Cr 1Mo	Waspaloy
Room	Nitrogen	0.2	0.3	0.2	0.2	0.2	0.2	0.2
500	Gasifier	1.6	2.2	3.9	3.9			
700	Gasifier	-1	0.8	5.5	-5.5	9.2	-2.9	8.9

Note: "-" values are weight gain due to scale formation.

Table 4. Erosion loss for materials tested at various temperatures, in mmpy.

Results of loss due to erosion-corrosion are shown in table 4. All of the materials performed similarly at room temperature. As the temperature was increased to 500°C the samples show an increase in wear loss due to erosion. A number of factors can account for this loss; first the materials are softer at elevated temperature. Second, the materials are starting to build up a scale coating on the outside. As temperature is increased to 700°C the scale grows so fast that the erosion effect of removal is overwhelmed by the

growth of the scale. A higher erosion velocity would remove the scale faster as demonstrated by previous research[13].

Adding the corrosion loss value and the erosion loss value results in the erosion-corrosion rate. Again, all of these materials performed well at room temperature.

Conditions		Alloy, Total loss in mmpy						
Temp, °C	Atmosphere	310 SS	Fe$_3$Al	Haynes 120	Haynes 160	Nitronic 30	9Cr 1Mo	Waspaloy
Room	Nitrogen	0.2	0.3	0.2	0.2	0.2	0.2	0.2
500	Gasifier	1.4	2.1	4.2	3.3			
700	Gasifier	-2.9	-1.4	3.8	-7.1	19.4	-3	7.9

Note: "-" values are weight gain due to scale formation.

Table 5. Total measured loss rates for materials tested at various temperatures.

These data for the combined data are shown in table 5. All of the materials, save the Fe$_3$Al, show such erratic scale formation at 700°C that the combined gravimetric data is of limited use. Electrochemical methods are being explored to remove the surface scale to allow more meaningful gravimetric results. Even at 500°C all of these materials indicated loss rate is high enough to give concern about their use in these conditions.

Conclusion

A variety of environmental conditions affect the functionality of various alloys that might be used in high efficiency power plants. High operating temperatures are an ongoing problem. Impurities such as sulfur and HCl, introduced in the coal, can cause stable metals to turn into structurally unsound metal sulfides in high temperature environments. Silica and other hard non-combustion minerals can lead to wear and erosion damage in gasifier power plants.

Testing the erosion-resistance of candidate materials under a range of environmental conditions, including those found in power plant gasifiers, lead to some interesting conclusions and could help power plant designers pick the most appropriate metals for use in their power development processes. First, the character of surface scales subjected to erosion/corrosion is significantly different from those that form though just corrosion. A result shows that while the surface protective Al film is significantly changed by erosion, Fe$_3$Al showed very good resistance to the effects of the erosion in the hostile atmosphere. It is the only alloy that shows promise of being usable in conditions as severe as were tested here. While difficult to fabricate, it may prove valuable as a coating material. Nickel based and high nickel alloys are just as subject to erosion/corrosion attack in a sulfur containing atmosphere as they are to a strictly corrosion attack. Properly alloyed high nickel alloys like HR-120 and HR-160 can perform well, but in environmental conditions like these, their use would need to be limited to temperatures well below 700°C. Low nickel stainless steels, like the Nitronic 30, show some promise in resisting erosion/corrosion in moderate, ~500°C, temperature gasifier conditions.

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