Corrosive wear determines materials for coal handling

Once corrosion/wear mechanisms are understood, it is easier to specify the best materials for the construction of coal handling systems

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There are many industries in which equipment is subject to the effects of sliding wear under wet or corrosive conditions. Electric power generating plants, for example, have many components that must resist corrosion and abrasion during operation. Feedwater, steam, condensate and fuels can cause corrosion and wear in equipment such as piping, condensers, heat exchangers, valves, and tanks. These components and other accessories are frequently fabricated from corrosion/erosion-resistant materials.

Coal handling equipment is an excellent example because it often operates under moist or even wet conditions. Both utilities and coal preparation plants can have serious flow problems if the correct structural or wear resistant material is not selected. Chutes, surge bin feeders, vibrating screens, screw conveyors, and cyclones are just a few examples of components that must withstand the combined effects of corrosion and wear.

Steel is the most widely used material for plant construction because of its availability, fabricability, and low cost. Unfortunately, when moist coal or other materials contact steel surfaces, the combined effects of corrosion and the subsequent sliding of solids greatly accelerate metal wastage.

Cathodic reaction

However, severe corrosive conditions such as low pH, high temperature, and the presence of chlorides do not necessarily cause the problem. The true source of this problem is caused by the cathodic reaction—the reduction of oxygen in the water. The reaction that controls the rate of corrosion is the diffusion of oxygen upon a metal surface where a film of hydrous iron oxide is the main diffusion barrier. Anything that eliminates or slows down this reaction will greatly add to equipment life.

Environmental influences

There are two primary elements of the chemical reaction—the metal and the environment. In most cases, the process dictates the environment within narrow limits. Usually, little can be done to decrease the corrosive influence of the process reliably and economically. However, some corrosion control has been achieved through the use of inhibitors such as sodium nitrite, sodium chromate, and sodium metasilicate.

Sodium nitrite was selected as an inhibitor to study its effect on AISI 4340 (an upgraded steel relative to generic AR/abrasion resistant steels), Hadfield Mn steel, and four stainless alloys. Chemical analyses and heat treatments for all tested alloys are recorded in Table 1. The four stainless steels have a variety of metallurgical structures, hardness ratings, and work hardening capacities. For example, Type 409 is a soft ferritic grade, and S17400 is a corrosion resistant precipitation hardening stainless. In contrast, Type 304 and Nitronic 30 (tentatively designated S20400 by ASTM) are austenitic stainless steels with different work hardening capacities.

A synthetic Ni-Cu mine water was used to isolate the separate effects of corrosion, abrasion and the combined corrosive wear of the system. The corrosion component was determined by immersion testing with

Table 1. Chemical analysis, condition and hardness of tested alloys

Alloy	Chemical analysis, weight % C	Mn	Cr	Ni	Others	Condition	Hardness, HR
AISI 4340	0.34	0.69	0.63	1.92	.27 Mo	1500F-20 min.-O.Q +400F-2 hr-A.C.	C 48
[illegible]	0.25	1.00	1.60	3.60	.35 Mo	1650F-15 min.-A.C.	C 45
Hadfield Mn	0.79	13.20	0.16	0.07	.99 Mo	1850F-15 min.-W.Q.	B 93
[illegible]	0.01	0.25	10.89	0.16	0.39 Ti	1850F-1 hr-W.Q.	B 85
Type 410	0.11	0.33	12.34	0.21	—	1800F-15 min.-W.Q +I000F-2 hr-A.C.	C 33
[illegible]	0.04	0.60	15.72	4.45	3.3 Cu, .27 Cb	1900F-15 min.-W.Q. +900F-1 hr-A.C.	C 44
S20400	0.04	7.39	16.73	2.31	.19 N, .75 Cu	1950F-15 min.-W.Q.	B 90
[illegible]	0.07	1.66	18.45	8.90	—	1925F-15 min.-W.Q.	B 75
Type 316	0.06	1.77	17.46	12.93	2.2 Mo, .38 Cu	1950F-30 min.-W.Q. Cold rolled 50%	B 73 C 35
[illegible]	0.46	0.31	—	—	—	Unknown	B 84
Type 410*	0.13	0.44	11.9	0.26	.18 Mo, .10 Cu	Annealed	B 81
[illegible]	0.09	0.91	17.4	7.29	.22 Mo, .46 Cu	Cold rolled	C 36
Type 304*	0.05	0.82	17.8	8.10	.44 Mo, .63 Cu	Annealed	B 90
[illegible]	0.04	1.60	17.6	11.29	2.21 Mo, .25 Cu	Annealed	B 85
S20400* S20400*	0.04	7.10	16.2	2.10	— .71 Cu	Annealed Cold rolled	B 94 C 33
[illegible]	3.60	0.66	2.7	3.80	0.11 Mo, .14 Cu	Cast	C 58
F45003*	3.00	0.71	6.5	5.30	0.13 Mo, .18 Cu	Cast	C 43
[illegible]	3.00	0.58	25.7	0.35	0.14 Mo, —	Cast	C 55

* Tested in coal preparation plant.

Table 2. Effect of inhibitors on corrosive wear

Test conditions: laboratory ball mill, synthetic Ni-Cu mine water, .64 m/s, room temperature, 5-16 hr periods, 2 L of liquid, 0.2 L pea gravel - 6.4 mm + 3.2 mm size, duplicate sheet specimens.

	Cumulative volume loss, mm³				
Alloy	A - Corrosive wear pH 9.1-9.6	B - Corrosion only pH 9.1-9.6	C - Abrasion(1) * only	Synergy A-(B+C)	% Synergy Synergy/A
AISI 4340	37.13	16.49	4.83	15.81	42.6
Hadfield Mn	52.71	18.72	6.63	27.36	51.9
Type 409	12.45	0	10.67	1.78	14.3
S17400	8.18	0	7.13	1.05	12.8
S20400	5.90	0	4.91	0.99	16.8
Type 304	9.32	0	7.88	1.44	15.4

(1) Tap water inhibited with sodium nitrite (pH 10.5-11.0)

greatly increased effect of corrosion in the presence of solid particles in slurry handling pipelines fabricated from steel. The synergistic effect was attributed to the removal of surface rust and salt films by the moving solids. That action permitted much easier access of dissolved oxygen to the corroding surface. Another investigation for the South African mining industry came to the same conclusion.

Another environmental effect that influences metal wastage is the load between the abrasive and the metal. Logically, volume loss due to abrasion increases proportionately as load increases, but volume loss due to corrosion remains constant. Consequently, percent volume loss due to corrosion decreases as load is increased. In other words, mechanical wear (abrasion) is dominant in highly loaded systems, and corrosive wear is less significant. Hard, abrasion-resistant steels are cost effective where crushing or gouging is severe—as found in excavating equipment for example. However, austenitic stainless steels are preferred for most wet sliding areas in coal preparation plants and pulp and paper mills.

Even very hard, abrasion resistant cast irons will not perform well under corrosive wear conditions such as those found in coal preparation plants. Coupons attached to slurry mixing paddles in a heavy medium vessel were studied after 2500

Table 3. Corrosive wear of steel, stainless steels and cast irons in a coal preparation plant.

Test conditions: heavy medium vessel, specimens attached to rotating paddles, 70% solids in coal/water/magnetite slurry, 3 to 3/8 inch coal, 300 tons/hr, 2500 hours.

Alloy	Hardness, HR	Metal loss Mils/year	Metal loss µm/year
S20400	B 94	0.3	8
S20400	C 33	0.3	8
Type 304	B 90	0.4	10
Type 316	B 85	0.4	10
Type 410	B 81	0.5	13
Type 301	C 36	0.6	15
F45009	C 55	1.6	41
F45003	C 43	13.1	333
F45001	C 58	51.5	1308
AISI 1044	B 84	68.4	1737

Table 4. Effect of mild corrodent on corrosive wear.

Test conditions: hub machine, .42 m/s tip speed, 200 hr, room temperature, 1.5 L AFS 50/70 sand, 1.5 L slag, 1.5 L pea gravel, 1.5 L distilled water, pH 8.8-9.2, duplicate sheet specimens.

Alloy	Hardness, HR	Volume loss mm³
S20400	B 90	11.18
Type 304	B 75	17.71
Type 410	C 33	18.58
Type 409	B 85	34.48
MIL S 81378	C 45	44.86
AISI 4340	C 48	50.34

no abrasives present. The solution was agitated by a magnetic stirrer and the weight loss taken at 16-hour intervals. The abrasion-only tests were run with the solution inhibited with sodium nitrite, while the corrosive wear process took place at a pH of 9.1-9.6 in a laboratory ball mill.

The results in Table 2 show that the two alloy steels have good abrasion resistance (pH 10.5-11.0). AISI 4340 was the best steel tested. However, when the corrosive component was added, they fell far short of the stainless steels. The sum of the corrosion-only and abrasion tests is less than the total of the corrosive wear tests because there is a synergistic effect when corrosion and abrasion act simultaneously.

The synergistic effect is much less pronounced on the stainless alloys compared to the two alloy steels. Although S17400 is about as corrosion resistant as Type 304 and is much harder, it was not as wear resistant as S20400. S20400 has a very high work hardening rate, which allows the surface layers to be strained by the abrasives to hardnesses approaching HRC 50. This hardness is about equivalent to that achieved by AR 500 steels.

Electrochemical studies have demonstrated the

Summary of corrosion mechanisms

- Chemical inhibitors may greatly reduce the corrosion component of carbon steel wastage under wet sliding conditions.
- There is a synergistic effect when corrosion and abrasion operate simultaneously. Alloy steels are much more adversely affected compared to stainless steels.
- Hard steels and cast irons do not perform well under corrosive wear conditions compared to stainless steels.
- Even mild corrodents like distilled water can cause rapid metal wastage of steel.
- Abrasion resistant steels and cast irons are better choices for crushing and gouging conditions.
- Increasing the hardness of austenitic stainless steels by cold working does not enhance their corrosive wear resistance.
- Stainless steels have much better slideability than alloy steels under wet conditions because of polishing and the lack of pitting attack.
- S20400 stainless steel exhibited the best corrosive wear resistance of all alloys investigated.

Table 5. Effect of cold work hardness on corrosive wear of Type 316 stainless steel.

Test conditions: laboratory ball mill, synthetic sea water, .64 m/s, room temperature, 16-hr periods, pH = 8.3, 2 L liquid, .2 L pea gravel - 6.4 mm + 3.2 mm, duplicate sheet specimens.

	Cumulative volume loss, mm³	
Period No.	Type 316 annealed HRB 73	Type 316 cold rolled 50% HRC 35
1	1.95	1.98
2	2.45	2.51
3	3.70	3.79
4	5.39	5.55
5	6.40	6.61

Table 6. Effect of corrosive wear on surface roughness.

Test conditions: laboratory ball mill, .64 m/s, room temperature, 5-16 hr periods, pH 8.7, 2 L of coal mine effluent, .2 L pea gravel — 6.4 mm + 3.2 mm, duplicate sheet specimens.

Alloy	Hardness, HR	Surface roughness, μ in. min. AA Before test	After test
MIL S 81378	C 45	22	217
AISI 4340	C 48	37	172
Type 409	B 85	31	27
S17400	C 44	30	18
S20400	B 90	32	22
Type 304	B 75	37	22
Type 316	B 73	32	20

Table 7. Corrosive wear of alloy and stainless steels in a coal mine effluent.

Test conditions: laboratory ball mill, .64 m/s, room temperature, 5-16 hr periods, pH 8.7, 2 L of coal mine effluent, .2 L pea gravel - 6.4 mm + 3.2 mm, duplicate sheet specimens.

Alloy	Hardness, HR	Cumulative volume loss, mm³ Period 1	Period 3	Period 5
MIL S 81378	C 45	3.59	11.45	20.17
AISI 4340	C 48	4.25	12.76	21.75
Type 409	B 85	1.80	5.46	8.98
S17400	C 44	1.51	4.55	7.39
S20400	B 90	1.31	4.27	7.13
Type 304	B 75	1.58	4.98	8.38
Type 316	B 73	2.08	7.39	12.56

hours in a coal/water/magnetite slurry. The results in Table 3 show that the much harder cast irons were inferior to all the stainless steels by a wide margin. Even the 25.7% Cr cast iron did not have sufficient corrosion protection due to the high volume fraction of chromium carbides. When the chromium is tied up as carbides, it cannot form a passive surface film.

Once corrosion is recognized as a major contributor to metal wastage, proper material selection can be the most reliable and cost effective way to control the problem. Coal plant operators have long used stainless (mostly Type 304) for improved slideability and corrosive wear resistance. Don't forget moisture in the coal is enough to cause degradation of carbon steel.

Effect of moisture

Laboratory tests were conducted in a slurry using distilled water as the liquid. As the data in Table 4 reveal, even this very mild solution caused high metal wastage to the two alloy steels compared to the stainless steels. This demonstrates the controlling influences of the oxygen diffusion process as noted earlier. S20400 proved the best of the stainless steels as it had in the synthetic Ni-Cu mine water tests.

Effect of hardness

Bulk hardness can be a very misleading guide for the selection of materials that have solids sliding against them under wet conditions. As noted in the coal mixing areas in coal preparation plants (Table 3), low hardness alloys may outlast harder ones under these conditions. Could these low hardness alloys (austenitic stainless steels) be made even better by increasing their initial hardness by cold rolling?

Work at the Tennessee Valley Authority (TVA) indicated that S20400 was not improved by cold rolling to a higher hardness (Table 3). This agreed with laboratory tests comparing Type 316 annealed and cold rolled 50% (HRB 73 and HRC 35, respectively) stainless steel. The results (in Table 5) were similar to the S20400 results—*no improvement with higher hardness.*

Although heat treatment of steel generally does improve wear resistance, cold working austenitic alloys does not have the same effect. During the sliding abrasion process, the surface layers are deformed plastically beyond anything prior cold work could induce. Straining the material prior to operation is not necessary; doing so just accelerates reaching the maximum attainable strain. That leads to debris formation, and thus can be slightly detrimental. However, there may be other reasons to slightly cold work austenitic stainless steels—to produce a smoother surface for better slideability.

Stainless steel enjoys a good reputation for providing enhanced slideability of bulk solids in many areas of coal preparation plants. Laboratory tests were conducted to study the effect that coal mine effluent had on the wear and surface degradation of alloy and stainless steels.

The surface roughness readings taken before and after testing are recorded in Table 6. All the stainless steels became smoother from the polishing action of the abrasives, while the alloy steels became rougher due to pitting and general corrosion. Rusting and pitting retain fine debris which greatly increases friction at the surface of the metal. Clogging and rat-holing are two results that diminish productivity.

The corrosive wear results in Table 7 again show the viability of stainless steels over harder AR steels. The influence of corrosion resistance and work hardening is shown by comparing Type 316 with Type 304 and S20400. The greater corrosion resistance of 316 is secondary to the higher work hardening capacities of 304 and S20400. Similar results were found at an Illinois coal preparation plant where 304 had metal wastage much lower than 1018 steel and two Cu-Ni alloys in process water lines. **END**

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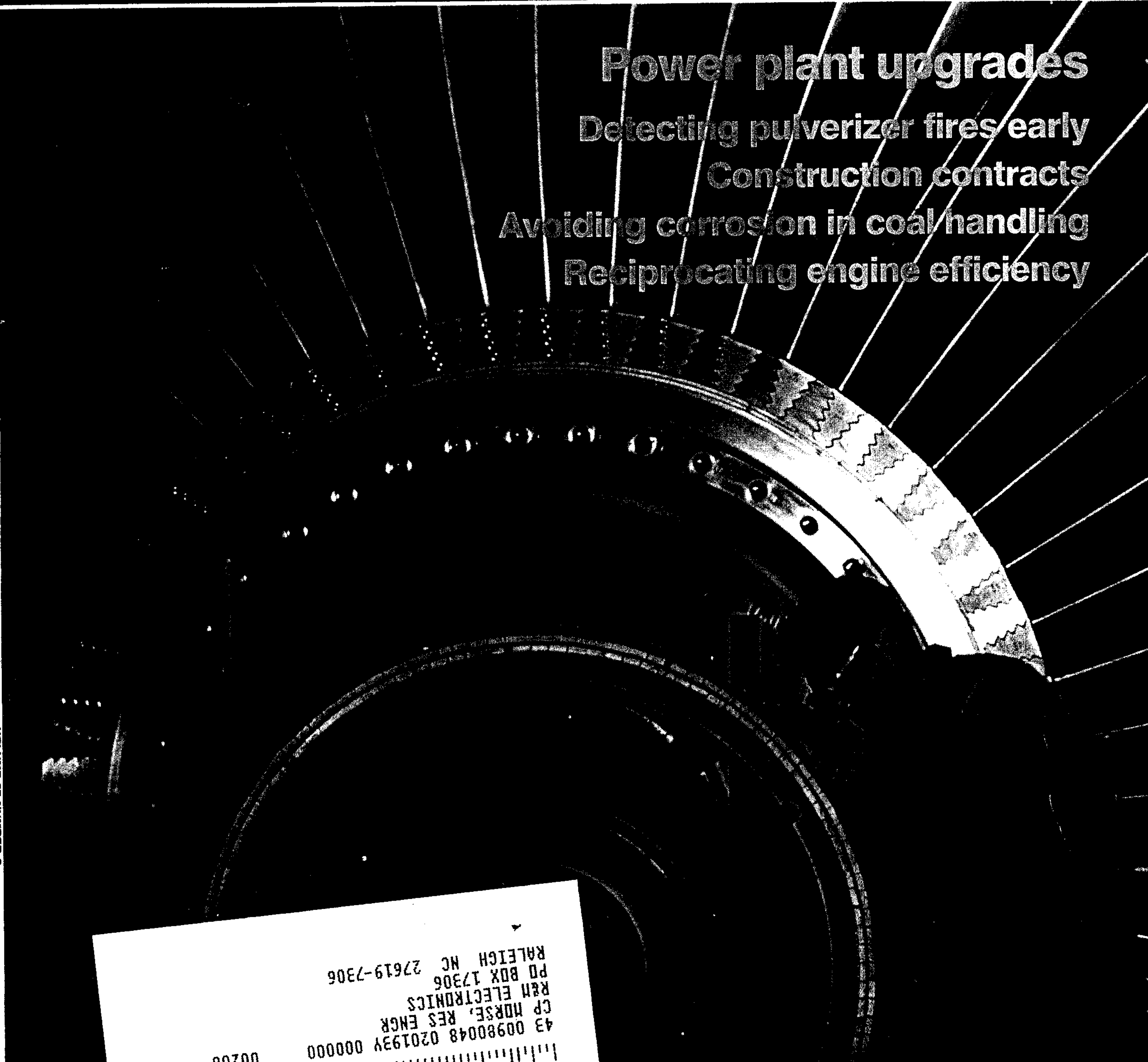
POWER ENGINEERING

A PENNWELL PUBLICATION

FEBRUARY 1993



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