The resistance of refiner plate alloys to bar rounding

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Bar rounding takes place by a form of slurry abrasion, resulting from sand and grit entrained in the pulp. What is the influence of refiner plate metallurgy on this type of wear?

Refiner plate wear affects pulp strength, pulp quality, refining stability, and machine runnability (*1–4*). Nevertheless, little work has been reported on either the identification of refiner wear mechanisms or on wear resistance of plate alloys.

The results of a metallurgical examination of used refiner plates showed that several wear patterns can be found, either singly or in combination (*5, 6*). These include bar rounding, clashing, and cavitation. Bar rounding is closely related to the passage of the pulp stock over the refiner plate bars. However, because uncontaminated paper fibers cause little wear when sliding or rubbing against steel (*7*), it is probable that sand or grit entrained in the stock plays a major role in the bar rounding process.

Owing to the nature of the pulp stock, the mechanism of bar rounding will be similar to that of slurry abrasion, in which the abrading particles are carried against the working surface by a liquid. Surfaces worn by slurry (abrasion, or slurry erosion) are characterized by short abrasion furrows and by platelets or lips of plastically deformed material (*8*). Similar features can be seen on worn bar surfaces. **Figure 1** shows a typical example of this behavior on the leading edge of a stainless steel refiner plate bar.

For our studies, a test rig has been designed and built at the Institute that permits abrasion to occur under corrosive conditions typical of refiner environments. In our study here, we have paid attention to the role of bulk alloy carbon content and carbide volume fraction, which are known to influence low-stress abrasion resistance in ferrous materials (*9*).

Experimental procedures

Design and operation of the rig

Figure 2 shows the general layout of the slurry abrasion rig, which is based on an original design by Madsen (*8*). The test solution is held in a large reservoir (A) before being mixed with silica fed from a hopper (B). The slurry is then pumped into the test chamber (C), where it is used on a once-through basis. A sand–liquid separation tank (D) is located below the rig. Filtered solution is recirculated to the reservoir on a continuous basis.

The principle of the test is to induce abrasive wear by moving the sand–liquid slurry past specimens by an impeller. We chose this rig because the abrading particles strike the specimen surface at a relatively low angle. Fibers move up and over the bars in a refiner (*10, 11*); the abrasion of refiner plates arising from grit brought in with the stock probably takes place at similarly low angles.

In operation, 16 cylindrical specimens were held in individual tapered blocks clamped between two stainless steel plates. The blocks were shaped to form a 16-sided, water-tight test chamber when arranged side-by-side. Each specimen was mounted with its test surface flush with its block. The impeller was placed inside the test chamber and rotated at a peripheral velocity of 11.5 m/s by a drill press. The shortest distance between each specimen and an impeller tip was about 2 mm. For these tests, the sand was AFS50-70, semi-rounded testing sand (SiO_2), supplied by the Ottawa Silica Co. The sand–liquid slurry was pumped on a once-through basis into the test chamber at a concentration of 1.5% by weight. A circular entry port on the top of the chamber was used to ensure an even distribution.

Specimen preparation and wear testing

Eight typical commercial refiner plate alloys were chosen. These alloys were cast by a number of manufacturers, as designated in **Table I**. However, each manufacturer provides a range of alloys, not all of which have been evaluated here.

Cylindrical specimens were trepanned by electro-spark machining from refiner plates cast in each alloy and were then turned down to final dimensions. Wear testing was performed on one end face of each specimen. These end faces were prepared by surface grinding, to a final surface finish of about 1.1 μm. Loss of material was measured

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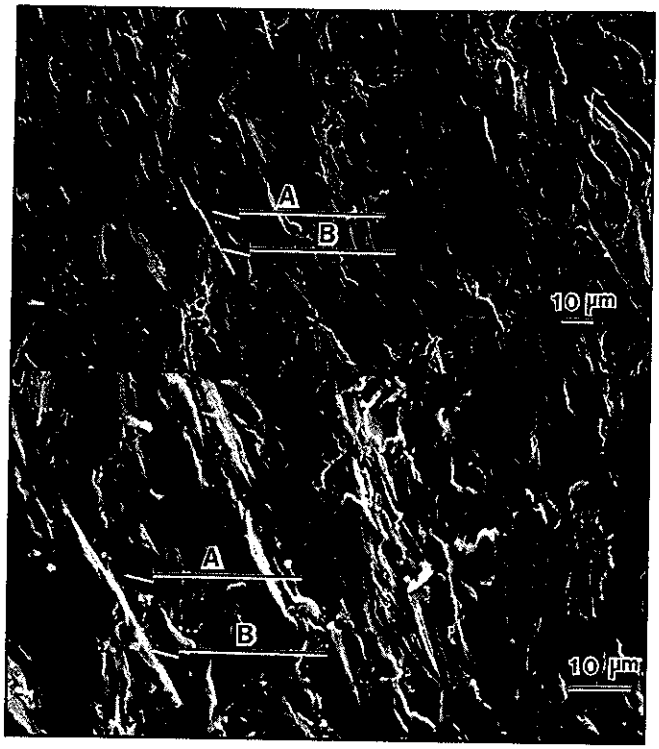
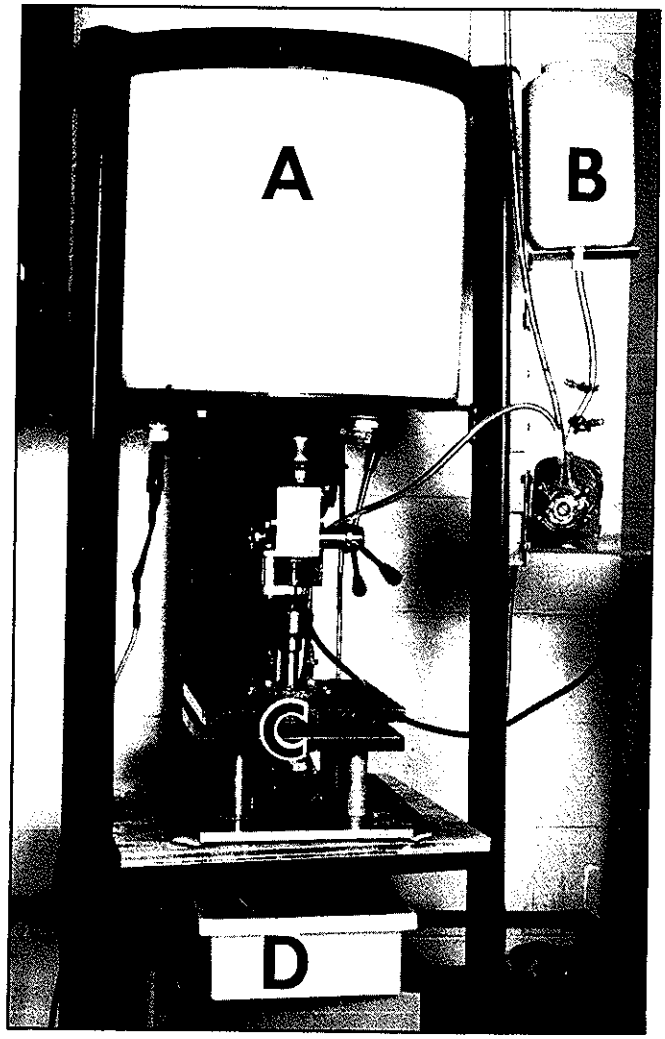
1. Slurry abrasion marks on the working surfaces of a refiner bar. Arrows A point to abrasion furrows, and Arrows B point to associated platelets of deformed material. The direction of abrasion is from bottom to top.



2. A general view of the slurry abrasion rig, showing the reservoir (A), the feed hopper (B), the test chamber (C), and the slurry separation tank (D)



gravimetrically and converted to a volumetric basis using an average density of 7.8 g/cm³. Each test lasted for 20 h, with specimens being removed, cleaned, and weighed every 4 h. Weight losses were measured to ±0.1 mg. Single specimens of each alloy were exposed in each test. The remaining sample holders were occupied by AISI 1020 carbon steel specimens, prepared like the refiner alloy specimens. The carbon steel samples were used to monitor the precision of the rig on a routine basis.

After testing, slurry-abraded surfaces were examined by low-power optical microscopy and scanning electron microscopy. A representative carbide volume fraction was determined for each alloy by computerized image analysis, using an Omnicon. 3500 system. We measured 100 fields per specimen, at a field size of 15.6μm; the carbide volume fractions reported are an average. Chemical analyses of the eight plate alloys, hardnesses, and average carbide volume fractions are given in Table I. Hardnesses were measured on the Rockwell C scale; the higher the number, the higher the hardness.

Results

In every test, eight or nine specimens of 1020 carbon steel were used to measure the precision of the rig. The coefficient of variation for these specimens generally lay in the range of 5-8%. This result compares with the 7% maximum recommended for dry abrasion testing in ASTM Standard G65 (*12*). We considered it an acceptable basis for testing the refiner plate alloys.

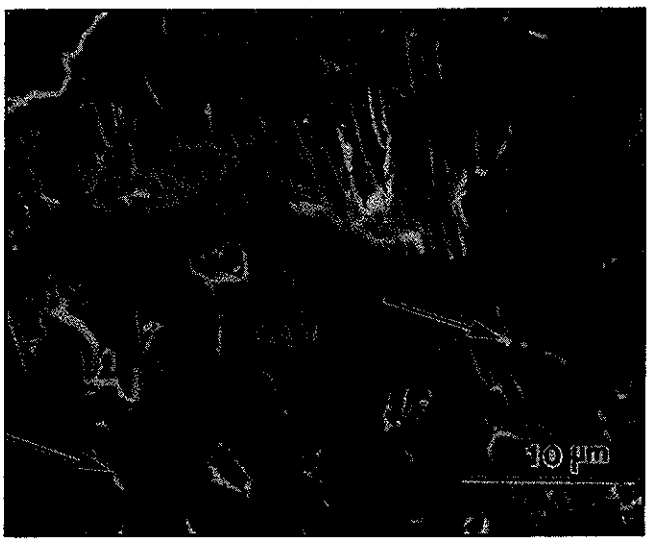
Testing was carried out in buffered distilled water of pH 7.5, buffered synthetic white water of pH 7.0, and synthetic white water of pH 4.5. All the results obtained in these solutions have been summarized in **Table II.** In all cases, the exposed surfaces after testing showed numerous short abrasion furrows, often associated with the formation of platelets or lips of deformed material. **Figure 3** shows that these features are similar to those observed on the leading edges of bars from used refiner plates. After each test, the primary carbides were usually left in relief on the surface. An exception was stainless steel Alloy 7, whose carbides were undermined and lost.

Initial testing was done in distilled water buffered to pH 7.5 with sodium borate. This environment is essentially noncorrosive and was chosen so that the behavior of the alloys could be studied when abrasion was the principle means of metal loss. Results are given in **Fig. 4**, in the form of cumulative volume loss as a function of time. As a group, the cast irons had greater wear resistance than the stainless steels. Of the various compositional and microstructural parameters that characterize these materials, volume loss was found to correlate best with bulk alloy carbon content and primary carbide volume fraction. No relationship was observed for hardness,

I. Chemical analyses, carbide volume fractions, and hardnesses of the test alloys

Alloy type	I.D. no.	Manufacturer	Element, % by weight								Carbide volume fraction, %	Hardness, Rc
			C	Cr	Ni	Si	Mo	Mn	P	S		
Cast iron	1	A	3.33	2.35	4.01	1.19	0.31	0.61	0.03	0.141	40	61
Cast iron	2	B	2.95	27.69	1.13	0.60	0.12	0.54	0.032	0.028	28	52
Cast iron	3	B	2.73	23.16	0.35	0.54	2.01	0.71	0.016	0.024	29	53
Cast iron	4	C	2.53	23.35	0.50	0.55	0.14	0.52	0.027	0.046	20	49
Cast stainless steel	5	D	1.63	16.26	1.49	1.07	0.87	0.59	0.013	0.017	11	55
Cast stainless steel	6	E	1.00	18.15	1.47	0.68	0.65	0.50	0.011	0.015	3	53
Cast stainless steel	7	C	0.84	18.00	1.35	0.85	0.51	0.59	0.025	0.015	3	54
Cast stainless steel	8	E	0.35	16.66	2.10	1.24	0.37	0.66	0.027	0.030	0.01	46

3. Abrasive damage on test specimens, where the direction of abrasion is from top to bottom of the photograph



II. Total alloy volume losses for the three test environments

Alloy	Buffered distilled water, pH 7.5, mm³	Synthetic whitewater, pH 4.5, mm³	Buffered synthetic whitewater, pH 7.0, mm³
1	0.5	4.2	2.8
2	0.5	1.6	0.9
3	0.6	2.2	1.6
4	. . .*	1.7	. . .*
5	0.9	2.0	1.6
6	0.9	1.4	1.3
7	1.3	3.0	2.6
8	2.2	3.3	3.1

*Alloy not available at time of test.

although hardness is often used as an indicator of wear resistance.

Figure 5 shows the total volume loss as a function of alloy carbon content. For comparison, average results for the reference specimens of 1020 carbon steel have also been included. Generally, wear resistance increased continuously with carbon content. A similar relationship was observed for carbide volume fraction.

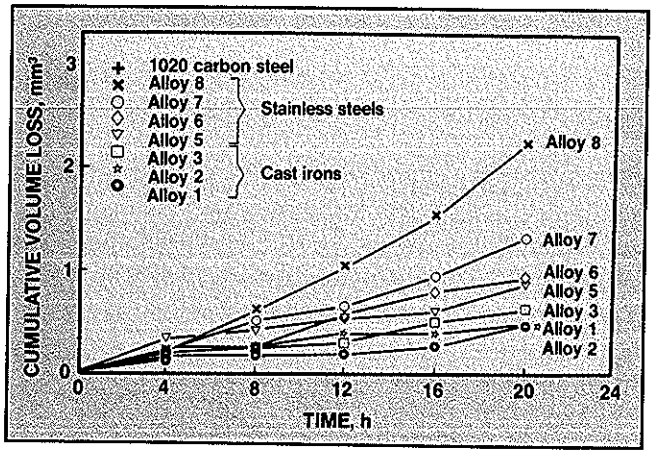
A change in alloy ranking was obtained when the abrasion took place in a corrosive environment. **Figure 6** shows the average cumulative volume losses from two tests in synthetic white water at pH 4.5. Overall, the martensitic stainless Alloy 6, the high-chromium, white, cast-iron Alloy 2, and the high-chromium, white, cast-iron Alloy 4 gave the best results. In contrast to the results in buffered distilled water, the low-alloy, cast iron (Alloy 1) had the highest overall wear loss at pH 4.5.

Figure 7 shows total volume wear loss at pH 4.5 as a function of carbon content. In contrast to the situation with buffered distilled water, comparable wear behavior was obtained from different types of alloy, because of the influence of corrosion. For alloys containing up to about 1% carbon, wear loss decreased sharply as carbon content increased. Between about 1% and 3% carbon, the change in wear resistance was much less, with alloys in this range having comparable wear behavior. In particular, the 1%-carbon stainless (Alloy 6) performed well, with a volume loss similar to that of the 3%-carbon cast iron (Alloy 2) and the 2.5%-carbon cast iron (Alloy 4). Similar behavior was observed for carbide volume fraction.

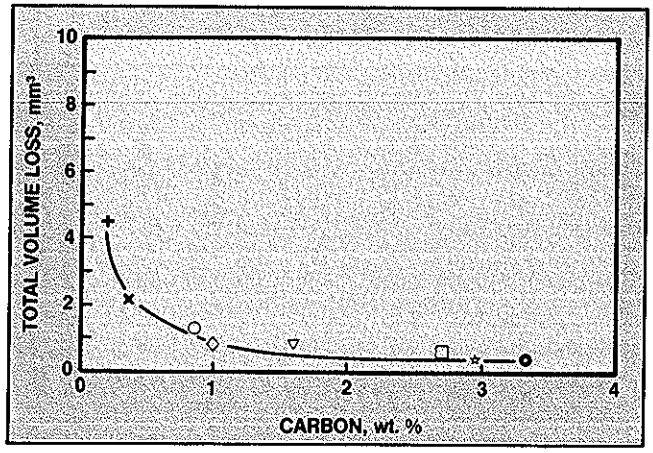
Corrosion was visible on all specimens after testing. Its effect was particularly important on the low-alloy cast iron, resulting in an increase in volume wear loss at carbon contents greater than 3%.

The data in Fig. 7 could be influenced by the microstructural condition of each alloy. In particular, the as-received cast-iron Alloys 2 and 3 contained significant amounts of retained austenite. Transformation to martensite by soaking test specimens at 980°C for 4 h followed by air cooling to room temperature increased their hardnesses by 10 points and 4 points, Rockwell C, respectively. The resulting wear losses were decreased by about 65%. A similar heat treatment of the stainless steel Alloy 7 also decreased its total volume wear loss, again

4. Cumulative volume losses in distilled water buffered to pH 7.5 with sodium borate



5. Total volume loss as a function of alloy carbon content, in distilled water buffered to pH 7.5 with sodium borate



by conversion of retained austenite.

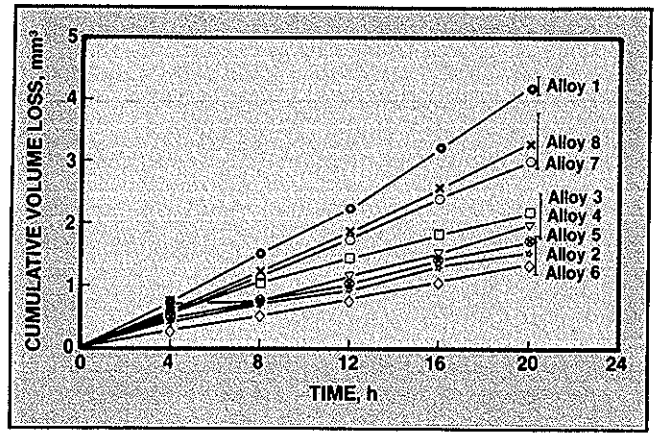
To study alloy behavior in less-corrosive white waters, an additional test was performed in which the pH was buffered to 7.0 by addition of sodium carbonate. Results are shown in **Fig. 8** as a function of carbon content. The alloy ranking was similar to that at pH 4.5, although the volume losses were generally lower in the neutral environment. The low-alloy cast iron showed the greatest improvement, with a performance comparable to the stainless steel Alloys 7 and 8.

As noted previously, stainless steel Alloy 7 was susceptible to premature removal of its primary carbides. Consequently, this alloy had greater wear than would be expected from either its composition or its primary carbide volume fraction. This behavior, which occurred in all the test environments, could be caused either by localized chromium depletion at the carbide-matrix interface (similar to sensitization in austenitic stainless steels) or by carbide-matrix galvanic corrosion. To determine which of these two mechanisms was the most likely cause, a series of abrasion tests was carried out using samples of Alloy 7 that had been re-quenched and tempered.

Samples were re-austenitized at 1100°C for 3.5 h, were quenched with water, and held in liquid nitrogen for 30 min to minimize residual austenite. Individual samples were then tempered at different temperatures and air-cooled prior to abrasion testing. Tempering reactions are time and temperature dependent and may include both continued matrix diffusion and precipitation of secondary carbides (*13*).

Results are given in **Table III** and are consistent with a chromium depletion, or sensitization, mechanism being responsible for premature carbide loss. For example, no removal of carbides took place when the alloy was either quenched with water (where there was no precipitation of secondary carbides) or tempered at 200°C. [This temperature was too low for appreciable chromium diffusion to existing primary carbides or for precipitation of chromium-rich secondary carbides (*14*).] In contrast, some removal of primary carbides was observed when the alloy was tempered at 500°C, as a result of the increased chromium diffusion at this temperature and the precipitation of chromium-rich secondary carbides (*15*). Similar effects of sensitization have been discussed for 13% chromium steels (*16*) and for a 10%-chromium cast iron (*17*).

6. Cumulative volume losses for the eight alloys in synthetic white water at pH 4.5. The error bars indicate the range of values recorded for each group of alloys



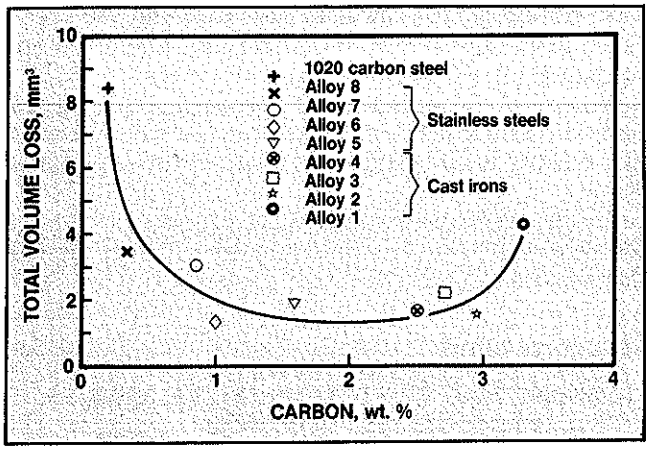
The data in Table III suggest that Alloy 7 as-received must have been heavily sensitized, because it had lost all of its primary carbides. Furthermore, for similar bulk hardnesses, its volume loss was approximately double that of the laboratory-sensitized specimen.

Discussion

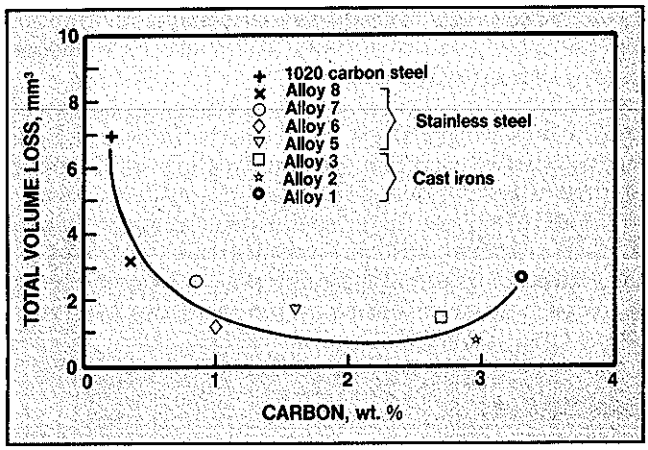
Alloy performance, as determined by the slurry abrasion rig, is in reasonable agreement with data available from refiner operations. Surface textures developed during testing were comparable to those seen on the leading edges of refiner bars (*6*). In particular, small lips or platelets of deformed metal were formed by the action of the sand particles, and the loss of primary carbides in Alloy 7 was also seen on a used plate cast in this material.

In wear resistance, the low-alloy cast iron had the highest total volume loss when abraded in white water at pH 4.5. The high-chromium, white, cast-iron Alloys 2 and 4 and the stainless steel Alloy 6 had the smallest volume losses. Other grades of stainless steel were intermediate in their behavior. An extensive survey of thermomechanical pulp (TMP) installations (*18*) showed that, for both

7. Total volume loss as a function of alloy carbon content, in synthetic white water at pH 4.5



8. Total volume loss as a function of alloy carbon content, in synthetic white water buffered to pH 7.0 with sodium carbonate



III. The effect of quench and temper heat treatments on the wear resistance of stainless steel Alloy 7

Condition	*Hardness, Rc*	*Volume loss, mm³*	*Comments*
As-received	54.5	2.2	Carbides missing
Water-quenched	57.0	1.0	Carbides intact
Water-quenched, tempered 2 h at 200° C	55.5	1.1	Carbides intact
Water-quenched, tempered 40 min at 500° C	55.5	1.0	Some carbides missing

Test environment was pH 4.5 synthetic whitewater, with a sand concentration of 1% by volume.

primary and secondary refiners, plate life increased in the following order: low-alloy cast iron; stainless steel; high-chromium, white, cast-iron. Wide variations in plate performance, however, were reported from individual mills.

More complete alloy performance ratings have recently been published by Clayton (*19*) and Sunds Defibrator (*20*), although the information is qualitative, with no details of environmental conditions. Both publications stated that the best resistance to wear was obtained with (a) high-chromium, white, cast irons similar in composition to our Alloys 2 and 4 and (b) stainless steels with carbon levels of about 1% or more, which are similar to Alloy 6. Low-alloy cast iron and stainless steel similar to Alloy 8 were given the worst rating.

Several features we observed have also been reported by others. Bulk carbon content (*21*) and carbide volume fraction (*22*), for example, provide a useful indication of wear resistance, if the hardness of the abradant is less than that of the carbides. This criterion is met in our study because silica sand typically have a hardness of about 840 Knoop, compared to about 1020–1700 Knoop for iron chromium carbides (*23*). Under these conditions, the carbides help protect the softer matrix from abrasive action. On the other hand, bulk hardness does not necessarily give a good correlation with abrasion resistance, because it may not reflect actual surface hardnesses generated during abrasion (*9*).

Our study shows that when abrasion occurs in an aqueous environment, the correlation between wear loss and either carbon content or carbide volume fraction is best for essentially noncorrosive solutions, such as buffered distilled water. When tested in even marginally corrosive conditions, such as white water buffered to pH 7.0 with sodium carbonate, the corrosion resistance of some of the stainless steels (such as Alloys 5 and 6) makes their performance much better than would be predicted from compositional or microstructural considerations alone. The influence of corrosion is even more marked in white water at pH 4.5. Carbon content or carbide volume fraction cannot, therefore, be used as a reliable guide to the abrasive wear performance of these refiner alloys in service.

Corrosion of the alloys is related more to the nature of the carbide-matrix interface than to the behavior of the matrix. This relationship is particularly evident with the sensitized Alloy 7, but surface examination of the other cast irons and stainless steels after testing also showed attack occurring preferentially at the interfacial areas. Individual carbides are apparently undermined by

corrosion and are then removed by the abrasive action of the sand particles, leaving fresh material exposed for further attack. This mechanism is especially important in the case of the primary carbides, which directly influence an alloy's abrasion resistance (*9*).

Our study has indicated that the abrasion resistance of at least some of the alloys tested can be increased from the as-received condition by heat treating to eliminate residual austenite, thus producing a completely martensitic matrix. While this may be beneficial in terms of wear, however, residual austenite can increase toughness in hard, abrasion-resistant materials (*24*), and further work would be necessary to determine how these two properties can be optimized for use in refiner plates.

Conclusions

A test rig for laboratory wear has been constructed that reproduces the slurry abrasion wear mechanism on the bar edges of refiner plates. Based on results for a typical selection of commercial refiner plate alloys, the test rig consistently ranked the materials in an order that correlated with field experience.

For all the alloys tested, abrasive wear in white water was dependent upon both corrosion and abrasion resistance. In these environments, the low-alloy cast iron had the lowest wear resistance. The martensitic, stainless steel Alloy 6, and the high-chromium, cast-iron Alloys 2 and 4 had the highest wear resistance.

In buffered distilled water, wear of the alloys was determined purely by their abrasion resistance. Under these conditions, the stainless steel Alloy 8 had the lowest wear resistance. The low-alloy cast iron and the high-chromium, cast-iron Alloy 2 had the highest wear resistance.

Because of the influence of corrosion, bulk carbon content or primary carbide volume fraction cannot be used as a reliable guide to slurry abrasion resistance in white water.

Finally, premature removal of the primary carbides in stainless steel Alloy 7 is caused by sensitization around the carbides.

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