Erosion in Disturbed Liquid/Particle Pipe Flow: Effects of Flow Geometry and Particle Surface Roughness*

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ABSTRACT

Erosion rates were measured along the length of a tubular flow cell of type 304 (UNS S30400) stainless steel (SS) carrying dilute slurries of silica sand (0.43 mm diam) and smooth glass beads of a similar size. The segmented test cell contained a sudden constriction, a sudden expansion, and a groove to produce disturbed flow conditions. Erosion rates were reduced by changes in the cell wall geometry that resulted from erosion at positions of high local metal loss and from erosion further downstream because of the reduction in turbulence and particle dispersion. Smoothing of the sand particles in the test system halved the erosion rates; however, reduced erosion rates obtained with the sand were 2 orders of magnitude higher than those produced with the glass beads. This difference was attributed to surface microroughness of the particles.

KEY WORDS: disturbed flow, erosion rate, flow, particle roughness, pipe, slurry, stainless steel

INTRODUCTION

It is well known that slurry erosion rates are time-dependent. The most severe erosion problems are localized, occurring under disturbed flow conditions (e.g., at weld beads, elbows, and fittings). As reported by Lotz and Heitz, high local erosion rates can lead to substantial changes in wall geometry, which in turn modifies the structure of the flow and leads to different rates of erosion.[1]

The effect of changing wall geometry has been observed in industrial equipment and must be taken into account in experimental studies to determine erosion rates and in predictive models being developed to calculate erosion rates.[2,3]

Another important time-dependent effect, especially in test systems, has been modification of the erosiveness of suspended particles. In previous sand slurry erosion tests, size distribution measurements and microscopic examination revealed no significant changes in particle size or surface roughness that could account for changes in erosiveness.[4,5] The latter tests were carried out in a recirculating flow loop. Masden found that recycling a sand slurry in a slurry pot tester led to reduced erosion rates that could not be attributed to a reduction in particle size.[6] Following high-magnification (5,000x) surface examination, Masden concluded that "micropolishing" of the particles was responsible. The smoothing of the rough surfaces was on a scale of less than 2 μm.

Time-dependent particle erosiveness probably is more important in experimental systems than in industrial flow systems since industrial flow systems usually involve once-through flows. Once-through laboratory tests are difficult to run because of the amount of test fluids and/or solids required and because of the difficulty in reproducing the complex hydrodynamic conditions encountered in pipelines and other equipment using a slurry pot tester. Both

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recirculating loop equipment[7-9] and once-through test systems (i.e., the once-through slurry pot tester described by Masden[6,10]) have uses.

The present study was part of a program for the development of predictive models for erosion corrosion under disturbed flow conditions in pipelines. The objective was to determine the relationship between the structure of the flow and erosion corrosion.

Erosion in the absence of corrosion was studied in a complex flow geometry that included a sudden expansion, a sudden constriction, and a groove in a stainless steel (SS) pipe carrying dilute sand slurries. Experiments were designed to investigate effects of time-dependent wall geometry and time-dependent particle roughness on erosion rates. The effect of particle roughness was investigated in experiments with glass beads instead of sand.

EXPERIMENTAL

The test cell of tubular type 304 SS (UNS S30400)[(1)] was positioned in a vertical leg of a slurry flow loop, with an entry length of 50 diam (Figure 1). The flow loop was composed of a rubber-lined centrifugal pump, a magnetic flow meter, a double-pipe heat exchanger, and steel wire-reinforced tubing. The loop was been described previously in detail.[7] The test cell contained a sudden constriction, a groove, and a sudden expansion and was segmented to enable local erosion rates to be determined by mass loss measurement. Short 3-mm segments were used at the inlet to the sudden constriction and at the downstream edge of the groove, where high and very localized erosion rates were expected. The SS flow cell segments were machined from seamless cold-drawn tubing. Experimental parameters are listed in Table 1.

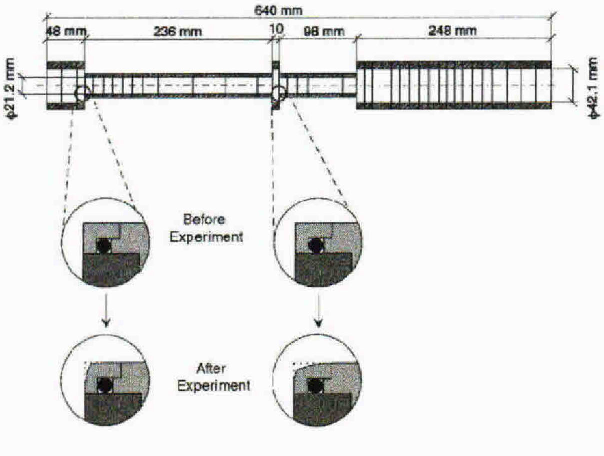


FIGURE 1. *Segmented erosion test section.*

RESULTS AND DISCUSSION

Erosion Rate Profile

The effect of the test cell geometry is shown in Figure 2. As expected, highest erosion rates occurred with the sudden constriction at 50 mm and at the downstream edge of the groove at 300 mm because of the large mean flow curvature in those regions. In straight portions of the pipe, erosion rates were much higher in the constricted section (21.2 mm-diam) of the pipe, where the fluid velocity was 13.3 m/s, than after the sudden expansion section (42.1 mm-diam), where velocity was 3.3 m/s.

(1) UNS numbers are listed in *Metals and Alloys in the Unified Numbering System*, published by the Society of Automotive Engineers (SAE) and cosponsored by ASTM.

TABLE 1

Experimental Parameters in Type 304 SS Test Cell

Cell material	Stainless steel	AISI Type 304
Pipe diameter (Inside)	Large pipe Small Pipe	42.1 mm 21.2 mm
Slurry flow velocity	Large pipe Small pipe	3.3 m/s; Re = 170,000 13.3 m/s; Re = 340,000
Carrier fluid	Distilled water, deaerated by N_2	Temperature = 30°C
Particle average diameter	Silica sand Large glass beads Small glass beads	d_m = 0.43 mm d_m = 0.4 mm d_m = 0.01 mm
Particle concentration		2 vol%; 5 vol%; 10 vol%
Exposure time		2 h – 72 h

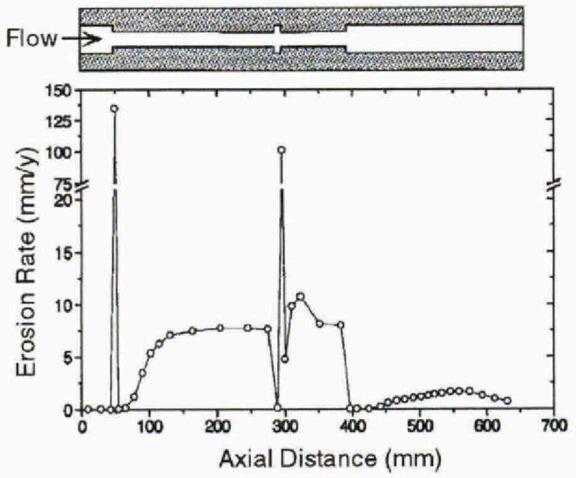
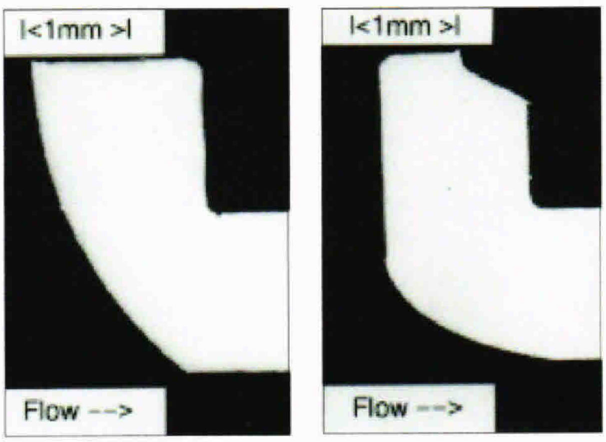


FIGURE 2. *Typical erosion rate profile at sand concentration 2 vol% after a 24-h run.*



(a) (b)

FIGURE 3. *Eroded edge of the small inserts used to determine the localized mass loss at: (a) sudden constriction and (b) downstream edge of the groove. Sand concentration was 2 vol% at a duration of 72 h.*

The erosion rate in the section after the sudden expansion exhibited a maximum at 560 mm. This was downstream of the estimated fluid reattachment point at 460 mm.[3] Previous calculations showed the expected maximum erosion rate to occur near 560 mm, where the particle impact angle and frequency would be optimal for cutting erosion.

The erosion rate dropped to low values at several positions: in the "dead water" in the straight portion of the pipe before the sudden constriction; immediately downstream of the leading edge of the constriction where a small separation bubble (recirculation zone[11]) caused particles to divert from the wall; and in the corner following the sudden expansion in the "dead water" region. Results shown in Figure 2 agreed with those obtained for a similar flow geometry by Lotz and Postlethwaite.[7] Results were reproducible within 10% in repeated experiments.

Effect of Changing Wall Geometry

Test cell geometry changed with time as a result of erosion, especially at the leading edge of the sudden constriction and at the downstream edge of the groove, where substantial rounding occurred. Erosion profiles corresponding to the two positions of maximum wear are shown in Figure 3.

The two profiles differed because the two locations differed, with more of the leading edge of the sudden constriction exposed to the impinging particles. It was difficult to assign erosion rates to such profiles. Changes in geometry resulted in lower erosion rates where rounding of edges occurred and well downstream. Rounding of the edges created lower turbulence levels and particle dispersion, resulting in lower erosion rates further downstream.

This effect was studied in an experiment that was interrupted four times to determine the mass loss. New sand was introduced each time to minimize the effect of smoothing of the sand particles. The erosion rates in Figure 4 were averages for each 2-h period.

Variation of the erosion rates as the flow system geometry changes with the erosion process will require the development of unsteady state predictive erosion models. The models will have to accommodate determination of the flow structure and erosion rates in the presence of the rounded surfaces produced by the erosion. These models will require substantial development beyond models proposed previously.[3]

Effect of Particle Concentration

Slurry erosion rates increase with increasing particle concentration.[6,8,9,12,13] The effect decreases with increasing particle concentration due to particle-particle interaction.[6,12,13] Heitz found erosion rates varied linearly with the particle concentration from 0 mass% to 5 mass% for fully developed pipe flow[8] and from 0 mass% to 0.5 mass% at the reattachment point of a sudden expansion.[9]

Results of three continuous 24-h experiments with 2 vol%, 5 vol%, and 10 vol% sand (5.1 mass%, 12.2 mass%, 22.7 mass%, respectively) are shown in Figure 5. Erosion rates did not vary linearly with particle concentration. Erosion rates increased by a factor of about 2.5 within the concentration range of 2 vol% to 5 vol% and by only 20% within the range 5 vol% to 10 vol%, both in the constriction and at the maximum downstream of the reattachment in the expansion. The nonlinearity was attributed to particle-particle interference.

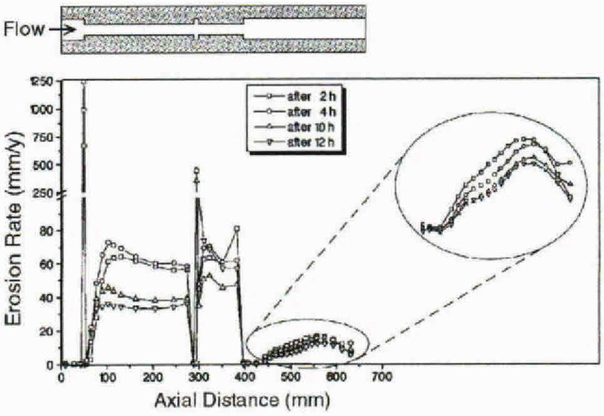


FIGURE 4. *Effect of time-dependent test cell geometry at sand concentration 5 vol%.*

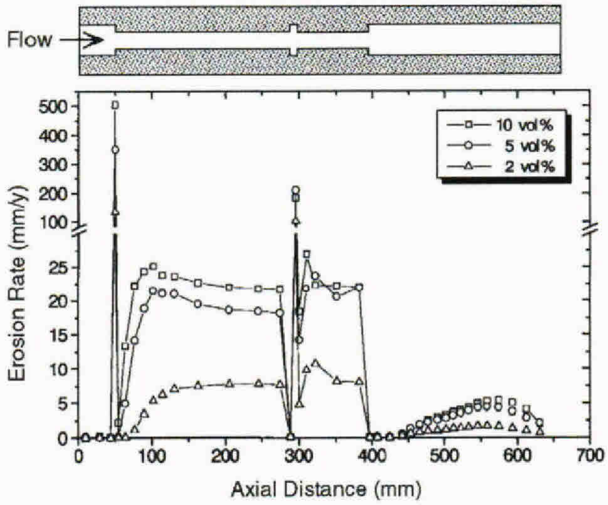


FIGURE 5. *Effect of sand concentration on the erosion rates after a 24-h run.*

Effect of Particle Smoothing

Exposure time had a significant effect on erosiveness of the sand particles (Figure 6). Results of a continuous 24-h experiment were compared to results from an intermittent 24-h run in which the experiment was stopped seven times and used sand was replaced with new sand. The lower erosion rates in the continuous experiment were related to a decrease in the particle microroughness of the sand with time.

Effect of Particle Microroughness

To explain the changes in particle erosiveness, scanning electron microscopy (SEM) was used to examine the sand particles before and after the experiments (Figures 7 and 8). In previous sand slurry flow loop studies, it was reported that there was little change in the size distribution and no obvious smoothing effects caused by recirculation in the flow loop.[4,5] Low magnifications used in previous studies failed to detect changes in sand microroughness during the exposure in the loop, however. These changes were observed by comparison of Figures 7 and 8. The difference became obvious only at higher magnification (2,000x). The SEM images illustrated how the particles' rough edges were sheared during exposure.

To remove any doubts about the effect of particle microroughness, experiments was carried out using glass beads with approximately the same mean diameter (400 µm) as the sand. SEM images of the glass beads at the same magnification as the sand particles illustrated the smoother, almost featureless surfaces of the glass beads (Figure 9). After the experiments with the glass beads, no discernible surface change was observed. The very low erosion rates obtained with the glass beads required 72-h runs

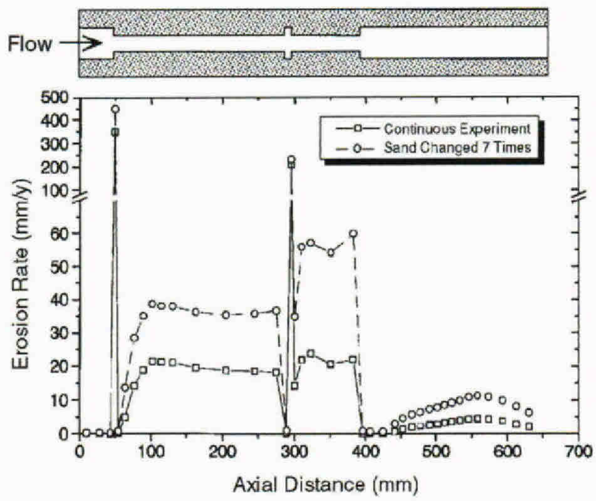


FIGURE 6. *Effect of smoothing the surface of the sand particles on the erosion rates.*

to achieve reasonably accurate mass loss measurements. Qualitatively similar erosion profiles were obtained with the glass beads as with the sand. Erosion rates with the glass beads were 2 orders of magnitude lower that those obtained under similar conditions with the sand (Figure 10) because of the smooth surface of the glass beads.

Hardness of the impinging particles also could have been considered to contribute to this large difference. The glass beads had approximately half the hardness of the silica sand particles (Vickers hardness numbers [HVN] 500 and 1,000, respectively). However,

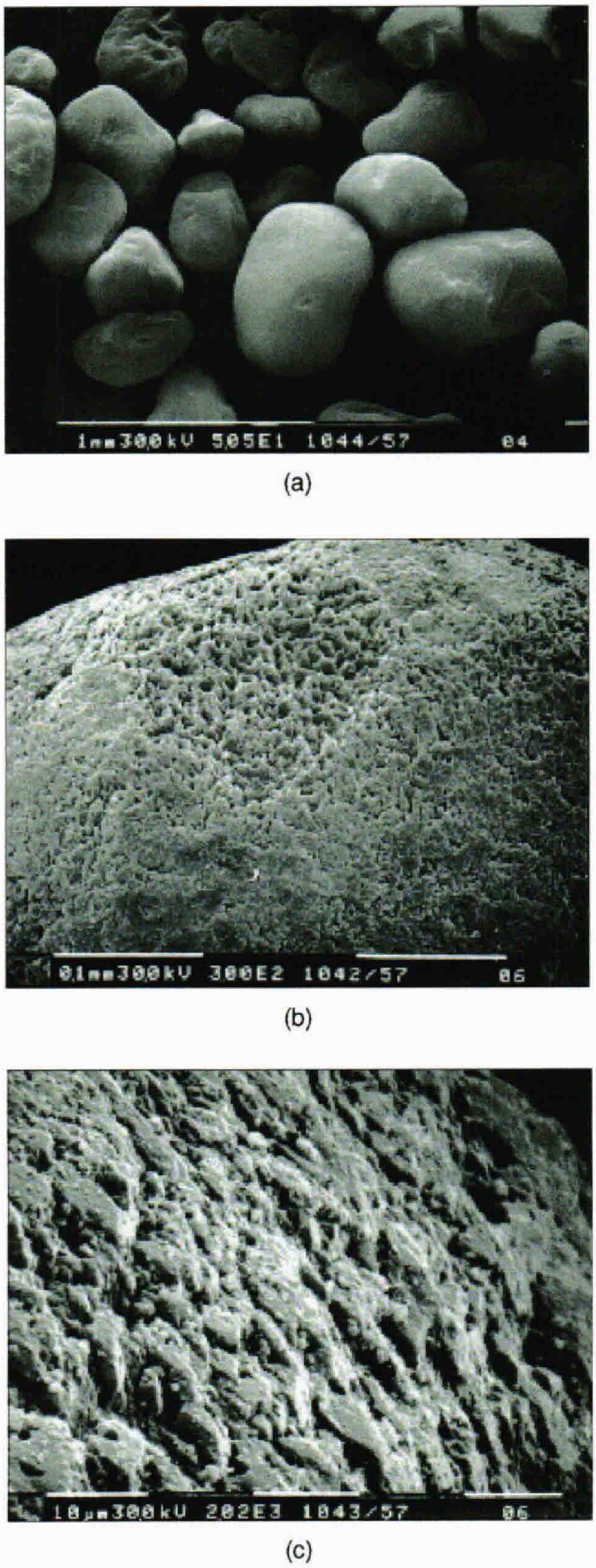


FIGURE 7. *Surface of the sand particles before use in the test system: (a) 50x, (b) 300x, and (c) 2,000x.*

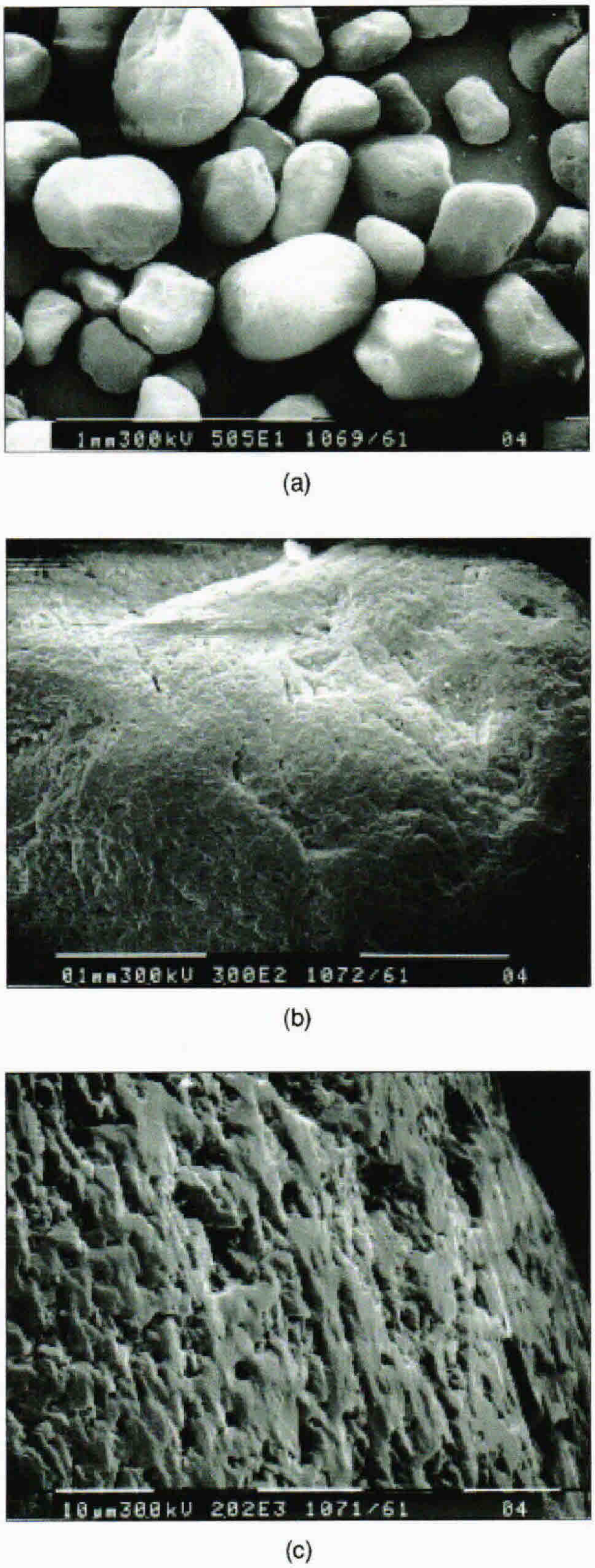
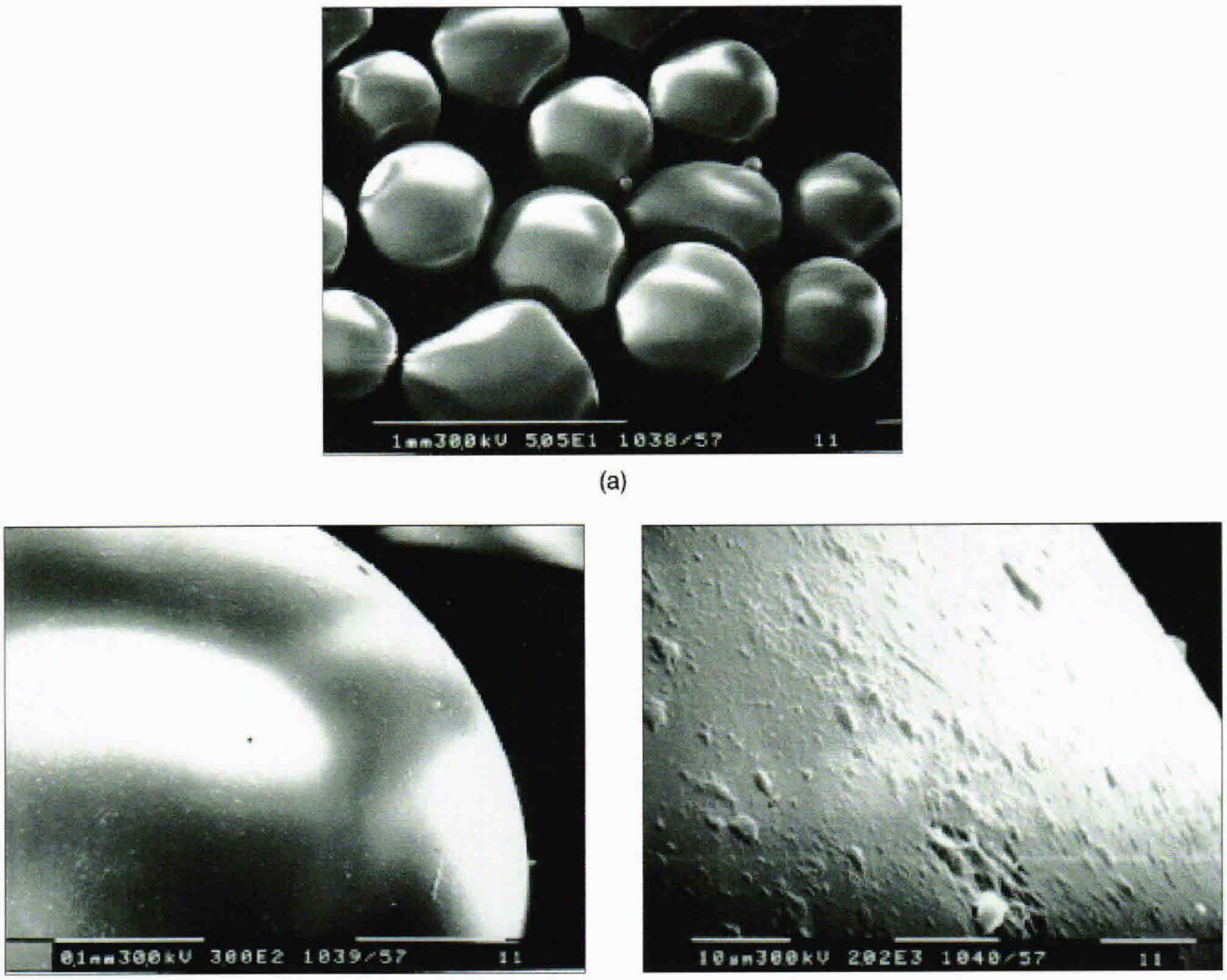


FIGURE 8. *Surface of the sand particles after use in the test system: (a) 50x, (b) 300x, and (c) 2,000x.*



(a)

(b) (c)

FIGURE 9. *Surface of the glass beads before use in the test system: (a) 50x, (b) 300x, and (c) 2,000x.*

when the particles have been much harder than that of the metal (in this case, approximately HVN 108) the particle hardness has had little effect on the erosion rate.[12] The diifference of 2 orders of magnitude between the glass- and the sand- induced erosion rates could not be explained on this basis.

Scars (1 μm width scale) covered the surface of the metal after the erosion with sand (Figure 11[a]). This size corresponded to the microroughness scale of the particles. After erosion by the glass beads, the metal surface was covered with platelets forged by particle impacts (Figure 11[b]). The length scale of the platelets was 100 μm, corresponding to the particle diameter scale. Differences in behavior for the sand particles and the glass beads were explained by the relative role of cutting and ploughing in the metal removal process, as discussed by Hutchings[14] and Levy and Yau.[15]

The present work showed particles with high microroughness eroded the metal at high rates by a cutting action of the sharp microedges. For particles with a smooth surface, the erosion mechanism changed to a ploughing action in which individual particle impacts caused indentations and extrusions on the metal surface that were forged and broken off by successive impacts, resulting in much lower erosion rates.

The difference of 2 orders of magnitude between the erosiveness of sand and smooth glass beads was observed over a wide variety of flow conditions in the complex geometry of the flow cell. Microroughness of the sand was reduced by exposure in the flow loop over a period of 24 h, but the resulting reduced erosion rates were still 2 orders of magnitude higher than those for the glass beads of similar size. The effect of overall particle angularity did not explain the large difference

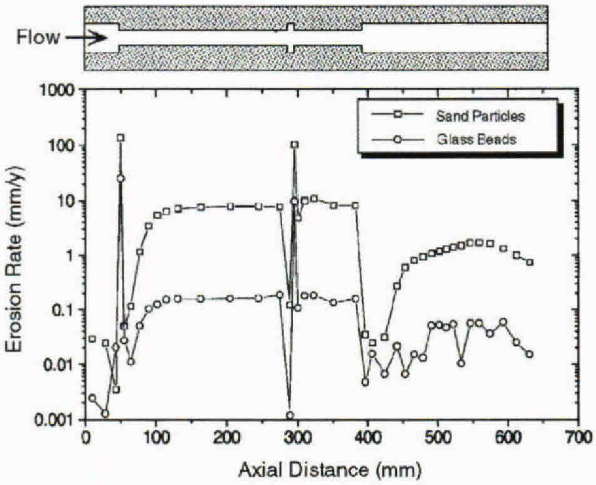
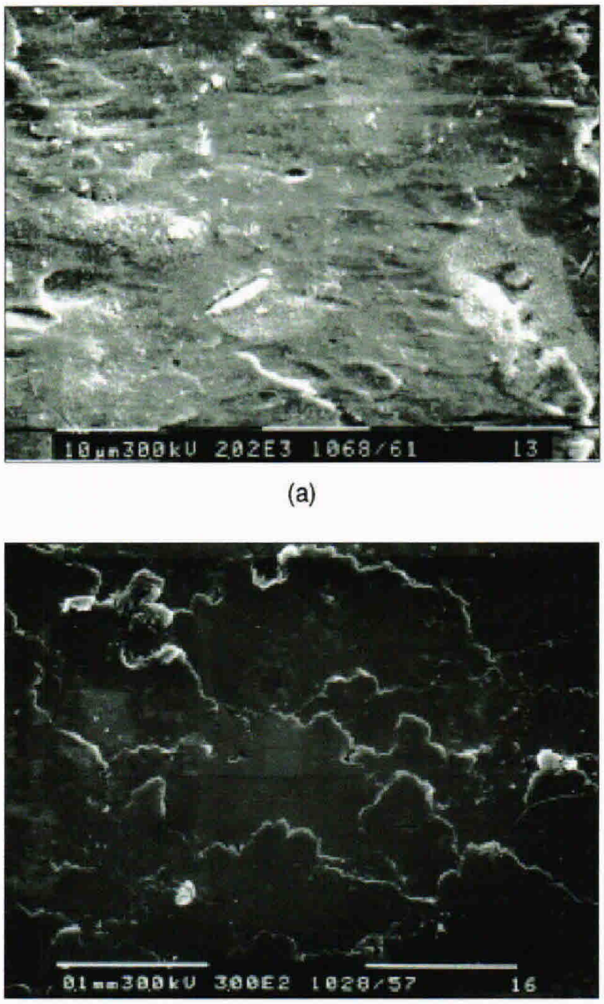


FIGURE 10. *Erosion rates with similarly sized sand particles and glass beads.*



(a)

(b)

FIGURE 11. *Surface of the metal at the erosion-rounded insert at the sudden constriction after erosion by: (a) sand particles and (b) glass beads. (2,000x, 24-h run)*

between the erosion rates by sand and the glass beads. Masden observed a wear rate 1.87 times higher with alundum than with silica sand slurries and attributed this to the greater angularity of the alundum particles.[6] Wellinger and Uetz used a dry shot-blasting technique and found a factor of 2 in the rates of erosion with angular and rounded shot.[10]

One additional experiment was performed using very small glass beads (average diam 10 µm), and the erosion rates obtained were extremely low (Figure 12). It is known that very small particles follow the fluid streamlines accurately because of low inertia. This feature is used in laser Doppler anemometry where small particles are used as tracers to follow fluid streamlines. Likewise, the 10-µm glass beads followed the fluid streamlines closely, resulting in infrequent wall impacts and low erosion rates.

One reason for studying erosion by glass beads was to permit their future use in studies to determine data for testing predictive corrosion models. Their regular shape would make for more accurate flow modeling and determination of particle trajectories. The present results, however, showed the erosion in particle/aqueous flow by glass beads was not representative of the erosion produced by particles normally encountered in industrial practice.

CONCLUSIONS

❖ Slurry erosion rates were reduced as a result of changes in the flow geometry caused by high material loss (rounding) at sudden constrictions and at the downstream edge of grooves. Erosion rates were reduced at points where high local wear rates were obtained and well downstream because of lower turbulence levels and particle dispersion in the presence of the rounded edges.

❖ Effects of geometry changes must be taken into account in the development of erosion models for disturbed flow systems. This will necessitate the development of unsteady state models and the modeling of the flow structure and erosion processes at curved surfaces.

❖ Particle microroughness was one of the key parameters determining particle erosiveness. In the present experiments, reduction in the microroughness of the sand particles, by exposure in the flow loop over a period of 24 h, reduced the erosion rates by a factor of two. However, the resulting erosion rates were still 2 orders of magnitude higher than those obtained with glass beads of similar size but with a smooth surface.

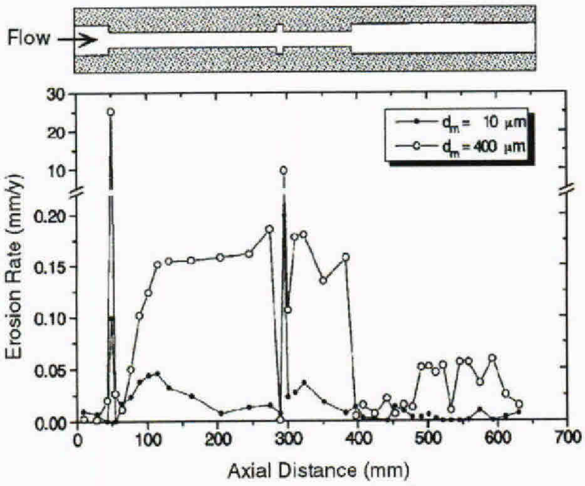


FIGURE 12. *Erosion rates obtained with two sizes of glass beads.*

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CORROSION News

PH.D. RESEARCH GRANTS AVAILABLE

Texas A&M University in College Station, TX, has received more than $300,000 for corrosion research from the U.S. Department of Defense and plans to use the money to fund three-year Ph.D. studies of two graduate students studying the fundamentals of corrosion of aluminum alloys.

Since A&M graduate students must teach for a year, the program is equivalent to four years of support. The graduate students will receive salaries of $14,000 yearly for three years, and a teacher's salary from the university during the fourth year.

Candidates must pass through the graduate committee of the appropriate department in which their degree is in for acceptance. Candidates must be American citizens.

For more information, contact: John O'M. Bockris, Texas A&M University, Department of Chemistry, College Station, TX, 77843-3255, or call 409/845-5335 or fax 409/845-4205.

AEROSPACE ALLOYS CONSORTIUM LAUNCHED

Seven manufacturers, seven universities, three federal agencies, and one industry technical society have joined a program to improve the casting of metal alloys used in the aerospace industry.

The consortium is the largest cooperative research and development program in materials at the U.S. Commerce Department's National Institute of Standards and Technology. Research will be carried out by NIST and the consortium members.

A main component of the effort will be to create process models for predicting the development of microstructures, defects and other properties of cast aerospace components.

For more information, contact: Robert J. Schaefer, Office of Intelligent Processing of Materials, B344 Materials Building, NIST, Gaithersburg, MD, 20899-0001 or call 301/975-5727.