EFFECTS OF CORROSIVE TREATMENT ON STAINLESS STEEL SURFACE FINISHES AND BACTERIAL ATTACHMENT

J. W. Arnold, O. Suzuki

ABSTRACT. *Corrosion, an important factor for the durability of a metal finish after exposure to water and chemicals, is a real concern for many wet-process industries. The effects of rouging, corrosion, and biofouling are costly problems on the surface of stainless steel, the most common material in processing plants. We have developed a corrosive treatment that is indicative of the wet-processing conditions commonly used in food processing, pharmaceutical, and bioprocess applications to test the effects of surface corrosion on bacterial attachment. Samples of surface finishes (electropolished, steel-ball burnished, glass-beaded, acid-dipped, steel-shot burnished, and sandblasted) were compared with mill finish controls to determine the variation in bacterial attachment on each finish. A duplicate set of samples was exposed to the corrosive treatment to simulate processing conditions. All samples were examined by visual inspection and electron probe microanalysis for surface characteristics and elemental composition of the stainless steel finishes. Samples were exposed to natural bacterial populations from chicken carcass rinses to allow growth of bacteria and development of biofilms on the surfaces. The kinetics of bacterial growth during surface exposure was followed by UV-visible spectrophotometry, and counts of bacteria and early biofilm formation were determined from micrographs following scanning electron microscopy. Bacterial attachment on each surface finish was measured and compared with controls and the five other finishes. Exposure to the corrosive treatment conditions resulted in changes in the numbers of bacteria that attached to each surface finish. After exposure to corrosive treatment, significantly greater numbers of bacteria attached to steel-ball burnished and glass-beaded finishes. However, the control mill finish and electropolished samples had fewer bacteria attached after exposure. Electropolished samples were significantly most resistant, before and after exposure to corrosive treatment, than the seven other finishes tested.*

Keywords. *Adhesion, Bacteria, Biofilm, Corrosion, Electropolish, Stainless Steel, Surface.*

Bacterial attachment and biofilm formation have been associated with the contamination and fouling of many different inanimate surfaces in wet-processing environments (Mittelman, 1998; Wong, 1998). Attachment of bacteria to equipment surfaces can lead to product contamination, spoilage, and surface destruction. The nature of bacterial attachment to solid surfaces and the attachment rate depends on the bacterial species, cell density, and surface properties as well as environmental conditions (LeChevallier et al., 1993; Billman, 1997; Percival et al., 1997; Al-Ahmad et al., 2000). Stainless steel is the most common material found in the processing plant, and bacterial attachment to stainless steel typifies the attachment process for most other materials. Bacterial biofilms can create mechanical blockages, impedance of heat transfer processes, and biodeterioration of equipment components resulting in billions of dollars in losses each year for industrial processing operations (Mittelman, 1998; Videla, 2003). To produce the most sanitary metal surface conditions and to minimize the potential for contamination, wet-process industries treat interior surfaces first by mechanically polishing them to reduce surface roughness and to remove scratches that would otherwise become sites for bacterial adhesion (Suzuki et al., 1998).

Sanitation programs in processing facilities control bacterial contamination by physical and chemical methods. Physical methods include the use of heat, ultra-low temperatures, desiccation, osmotic pressure, filtration, and radiation (Arnold, 1998). The common steps in a processing plant sanitation program begin by pre-rinsing with a high-pressure water spray followed by washing or scrubbing with a chemical application. Each of these methods can cause degradation of the surface (Costerton et al., 1988). The initial phenomenon known as rouge, by which the interior surface becomes reddish, is a result of the formation of an iron oxide on the metal surface (Menon, 1990). Rouge may be the source of contaminants that may cause chemical deterioration of water quality. The amount of rouge that appears in a system may be affected by the roughness of the metal surfaces (Suzuki et al., 1998). Reduction of surface roughness has also been shown to reduce corrosion. Corrosion resistance in stainless steel may be enhanced by electropolishing and/or chemical treatment, such as passivation (Kerber and Tverberg, 2000; Suzuki, 2002).

A number of studies have attempted to more clearly define the relationship between corrosion and the surface finish of stainless steel (Lu and Duquette, 1990; Nordstrom and Bergquist, 1996; Campaignolle and Crolet, 1997; Laitinen, 2000). Unpolished metal surfaces pretreated with pickling

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The authors are **Judy W. Arnold,** Research Microbiologist, USDA-ARS Richard B. Russell Agricultural Research Center; Athens, Georgia; and **Osamu Suzuki,** Senior Researcher, JGC Corporation, Research and Development Division, Narita-cho, Oarai-machi, Ibaraki Prefecture, Japan. **Corresponding author:** Judy W. Arnold, USDA-ARS Russell Research Center; P.O. Box 5677, 950 College Station Road, Athens, GA 30605; phone: 706 546-3515; fax: 706 546-3068; e-mail: jarnold@ars.usda.gov.

and passivation offered the best resistance to surface discoloration in hot, high-purity steam and water environments (Suzuki et al., 1998). However, the effects of such treatment on bacterial contamination were unknown.

Increases in the roughness parameters of surface finishes have been shown to correspond with increased bacterial contamination and early biofilm formation (Arnold and Bailey, 2000; Jullien et al., 2003). However, bacterial attachment is a complicated process, not entirely dependent on surface roughness. Bacterial adhesion results from an interplay of forces, including van der Waals, electrostatic, and hydrophobic interactions (Arnold and Shimkets, 1988b; Ong et al., 1999). In our previous research, samples of new stainless steel were treated by physical and electrochemical methods and then tested for susceptibility to bacterial attachment, growth, and biofilm formation. At various times following exposure of the steel to bacteria, scanning electron microscopy (SEM) showed that bacterial counts on all of the treated surfaces were significantly less than on untreated surfaces with mill finish. The surface types varied in affinity for bacteria, and both physical and electrochemical treatments improved resistance of stainless steel to bacterial attachment. Electropolished stainless steel was the least rough surface and showed significantly fewer bacterial cells and beginning biofilm formations than the other surface finishes tested (Arnold and Bailey, 2000). The morphology of the surface was analyzed before and after treatments to characterize the changes in the surface finish that affected bacterial attachment and biofilm formation. Decreases in roughness parameters shown by atomic force microscopy for the treated surfaces corresponded with the reduction of bacterial contamination and early biofilm formation shown by SEM (Arnold et al., 2001).

Our previous research showed the importance of the surface finish for potential bacterial attachment and biofilm formation on equipment components. The design of appropriate materials for the reduction of bacterial contamination necessitates an understanding of the forces of bacterial attachment and biofilm formation. Appropriate finishing treatments on stainless steel surfaces can improve the resistance to bacterial contamination and thereby enhance product safety during processing.

The purpose of this work is to study the effects of corrosive treatment on stainless steel finishes and the propensity for subsequent bacterial attachment. The data presented in this article will serve as a useful reference for the parameters of all the surface finishes, allowing manufacturers and processors to compare and select the most appropriate finish for specific locations and functions.

Materials and Methods

We compared samples from an experimental set of surface finishes with mill finish controls to determine the variation in bacterial attachment and the elemental composition for each finish. A duplicate set of samples was exposed to corrosive treatment to simulate processing conditions. The treatment was indicative of wet-processing conditions commonly used in food processing, pharmaceutical, and bioprocess applications. We measured and compared discoloration, elemental composition, and bacterial attachment for each surface finish after exposure to corrosive treatment.

Processing of Stainless Steel Surface Finishes

The steel used in this study was 11 gauge (3.04 mm) 304 American Iron and Steel Institute (AISI) SS601-477-25M-GP stainless steel plate with a 2B mill finish (annealed, pickled, and bright cold rolled). The plate was processed as described below, and then disks (circles) were either stamped or laser-cut from the plate for testing. The size of the disks allowed treatment and data analysis of each disk by all of the methods in this article. The test disks were divided into two groups, each acquired from a different equipment manufacturer. The plate was prepared by the equipment manufacturers in the same manner that they prepare the finishes for their equipment components.

For Group 1, control disks (mill finish) received no surface treatment, but all others received one of the following surface treatments:

Electropolished: Processed by immersion in Metaglo electrolyte (<75% phosphoric acid, <15% sulphuric acid) (Global Stainless Technology, Toccoa, Ga.) and exposed for 9 min at 7 to 9 VDC, with the processed part being the anode, providing current flow through the part to stainless steel bars (cathode) immersed in the electrolyte. Subsequently, the part was triple rinsed to remove any electrolytic residue and air dried.

Steel-ball burnished: Processed in a spiral-channel vibratory finishing machine with 1816 kg of 1.58 mm round carbon steel media for a cycle time of 45 min at approximately 1200 vibrations per minute. During this cycle, parts and media were continually rinsed with a 2.3% solution, pH 4.4, of Bio-Clean D-543 compound (Bio-Clean Co., Atlanta, Ga.) in water at a rate of 83 L/h. This process was followed by immersion in an ambient-temperature 20% nitric acid solution for 20 to 30 min, rinsing with distilled water, and air drying to provide a passive surface.

Glass-beaded: Processed in a manually operated glass-bead cabinet at 90 psi with 801-208M glass media (70 to 100 microns) for approximately 10 to 20 s per side.

For Group 2, control disks (mill finish) received no surface treatment. The acid-dipped treatment was a combination of 80% hydrofluoric acid and 20% nitric acid, a metal treatment commonly used to remove discoloration after welding. The burnished samples were from plate processed in a vibratory tunnel, with 7.9 mm diameter stainless steel shot. The sandblasted samples were from plates treated with sand particles under high pressure (100 to 125 psi), 100 to 170 U.S. screen.

All disks were cleaned prior to further testing by sonication for 30 min in distilled water and then air dried overnight in a biological safety cabinet under ultraviolet lamps.

Group 1 (9 mm diameter disks) was divided into groups according to surface finish: electropolished, steel-ball burnished, glass-beaded, and control (mill finish). Group 2 (14 mm diameter disks) was similarly divided into groups: acid-dipped, steel-shot burnished, sandblasted, and control (mill finish).

Corrosive Treatment

The effects of corrosion on the stainless steel finishes were examined by the following method. Stainless steel disks were exposed to highly purified water, such as that used in the pharmaceutical industry to produce clean steam, generated in an autoclave. Half the disks were exposed to the corrosive

treatment, and the other half were not exposed. After soaking in 100 mL purified water, the disks to be exposed were placed in the autoclave at 126.1°C, 15 psi, for 1 h. After the temperature was brought to room temperature, purified water was added up to 100 mL to supplement partially evaporated water, and the disks were re-treated under the same conditions. These procedures were repeated 50 times, and the process was carried out two times per day. The high temperatures of the repeated procedure are used for water-for-injection (WFI) manufacturing and in biotechnology, food, and pharmaceutical industries.

SEM And EPMA of Surface Composition

Subsequent analysis of the surfaces of the disks by SEM and electron probe microanalysis (EPMA) required no additional processing of finishes. After the corrosive treatment, the surface of the two sets of stainless steel disks (one set with corrosive treatment and one without) were qualitatively examined by a JXA-8800M Electron Probe Microanalyzer (JEOL, Tokyo, Japan) to investigate the surface composition of the disks before exposure to bacteria. The samples were mounted on carbon stubs and carbon coated. Analyses were performed at accelerating voltages of 15 kV to determine elements present, chosen for resolving the elemental peaks and minimizing charging effects (Koehler, 1978). The probe diameter was 5 µm. The center in the SEM micrographs was the area analyzed.

Bacterial Growth and Attachment on Disks

After analysis of the surfaces of the two sets, all samples were exposed to bacteria. Spectrophotometry and SEM were used to analyze bacterial growth and attachment. For these analyses, the disks were immersed in bacterial suspensions and processed as described below.

Whole broiler carcasses were collected from a commercial poultry processing plant, bagged, weighed, and each rinsed in 100 mL sterile phosphate-buffered saline (Boothe and Arnold, 2002). Aliquots (1 mL) of the pooled rinses were added to trypticase soy broth (9 mL, Difco, Detroit, Mich.) and incubated 18 h at 37°C. Subsequent dilution of cultures in trypticase soy broth to an absorbance of 0.3 (410 nm) at 37°C was monitored with a Beckman DU640 spectrophotometer (Beckman Instruments, Fullerton, Cal.) equipped with a Peltier temperature controller and auto cell holder. The wavelength was chosen empirically by scanning all visible and UV wavelengths of the rinse and choosing the highest for the experiment.

The 9 mm stainless steel disks were placed in spectrophotometer cuvettes (10 × 4 × 45 mm, Sarstedt Co., Sarstedt, Germany) on a ledge in the cuvette above the light path of the photomultiplier tube. The cuvettes contained the rinse culture and were maintained at 37°C until an absorbance of 0.6 to 0.7 was attained (approximately 1.5 to 2 h). This incubation period allowed the bacteria to adjust to the new media and attach to the disks. Because the size of the disks was dictated by the manufacturer, the 14 mm stainless steel disks, too large for cuvettes, were placed in test tubes (15 × 120 mm) and treated similarly, maintaining the same ratio of surface area to volume of bacterial suspension used in the cuvettes. Therefore, the same rate of bacterial growth was maintained, as shown by bacterial counts.

Bacterial counts in the cuvettes and the test tubes at the beginning and ending of the incubation period were determined by the following method. One-milliliter aliquots of culture were serially diluted into trypticase soy broth, and dilutions from 10^{-1} to 10^{-10} were plated (0.1 mL aliquot) in triplicate on plate count agar. Plates were incubated 24 h at 37°C, and counts of bacteria on the respective plates were subsequently used to determine the number of bacterial colony forming units (cfu) per mL in the original cultures. For each experiment, negative controls were test disks incubated in broth without bacteria.

Scanning Electron Microscopy of Bacteria on Surfaces

SEM was used to assess bacterial attachment to the stainless disks following their exposure to the bacterial suspensions. The initial fixation step for microscopic analysis included: removing disks from the bacterial suspensions, rinsing disks in 0.1 M sodium cacodylate buffer (Sigma Chemical Co., St. Louis, Mo.), and fixing material on the disks in a 2% glutaraldehyde, 2% paraformaldehyde, and 0.1 M cacodylate buffer for 2 h. Transport of the disks to the electron microscopy facility required storage of the disks in 0.1 M cacodylate buffer. The final steps in preparation of the disks included dehydration in 50% to 100% ethanol, critical-point drying, and sputter coating (Postek et al., 1980). Microscopic analysis of the disks utilized a LEO 982 SEM (LEO Electron Microscopy, Inc., Thornwood, N.Y.) operating at an accelerating voltage of 5 kV to obtain images (magnification = 1000X) of ten random fields of view per disk within 7 mm diameter on center, eliminating outer edges. Beginning biofilm was measured as clumps of cells showing extensive intercellular fibrils (Arnold and Shimkets, 1988a).

Micrographs (120 × 84 ìm) were processed for the ten random fields of view per disk for each of the eight groups. Five micrograph files with the best resolution for each sample were printed for data collection (40 files). Replicate counts of the bacterial cells were made separately by two individuals. The counts for each micrograph were analyzed for the effects of surface finish and corrosive exposure as compared with controls that were not exposed to the corrosive treatment.

Statistical Analysis

The data for numerical assessments of microbial densities and disk surface measurements between the two sets of disks, before and after exposure to the corrosive treatment, were

Table 1. Surface discoloration after exposure to corrosive treatment.

Surface Finish	Visual Inspection[a]
Group 1	
Electropolished	+
Steel-ball burnished	+
Glass-beaded	++++
Control (mill finish)	+++
Group 2	
Acid-dipped	+
Steel-shot burnished	++
Sandblasted	+++
Control (mill finish)	+++

[a] The number of "+" symbols indicates the degree of discoloration into reddish-brown color. Duplicate samples were compared with a set of finishes that were not exposed to the corrosive treatment (n = 32).

Table 2. Composition of elements[a] from stainless steel by EPMA.

Surface Finish[b]	Not Exposed	After Exposure
Group 1		
Electropolished	F, Si, P, Cr, Mn, Fe, Ni, Mo	F, Si, Cr, Mn, Fe, Ni
Steel-ball burnished	F, Si, P, Cr, Mn, Fe, Ni, Mo	C, O, F, Si, P, Cr, Mn, Fe, Ni, Cu, Mo, Pb
Glass-beaded	O, F, Na, Mg, Al, Si, Ca, V, Cr, Mn, Fe, Ni, Mo	O, F, Al, Si, P, Cr, Mn, Fe, Ni, Cu, Mo
Control (mill finish)	F, Si, P, Cr, Mn, Fe, Ni, Mo	O, F, Si, P, Cr, Mn, Fe, Ni, Cu, Mo
Group 2		
Acid-dipped	F, Si, P, Cl, Cr, Mn, Fe, Ni, Cu, Sr, Mo	Si, P, Cr, Fe, Ni, Mo
Steel-shot burnished	F, Al, Si, P, Cr, Mn, Fe, Ni, Cu, Mo	O, F, Al, Si, P, Cr, Mn, Fe, Ni, Cu, Mo
Sandblasted	O, F, Na, Mg, Si, P, Ca, V, Cr, Mn, Fe, Ni, Cu, Mo	C, O, F, Al, Si, P, Cr, Mn, Fe, Ni, Mo
Control (mill finish)	C, O, F, Al, Si, P, S, Cl, Ca, Cr, Mn, Fe, Ni, Zn, Mo, Re	O, F, Al, Si, P, Cr, Mn, Fe, Ni, Mo

[a] Elements are listed in order of quantity, from greatest to least. Abbreviations: Fe = iron, C = carbon, Cr = chromium, F = fluorine, Ni = nickel, Mn = manganese, Si = silicon, Al = aluminum, O = oxygen, P = phosphorus, Mo = molybdenum, Na = sodium, Mg = magnesium, Ca = calcium, V = vanadium, Cl = chlorine, Cu = copper, Sr = strontium, S = sulfur, Zn = zinc, Re = rhenium.

[b] Duplicate samples were tested for each finish (n = 32).

analyzed by the *t*-test and ANOVA (Microsoft Excel, Microsoft Corp., Redmond, Wash.). The general linear models procedure of SAS (SAS for Windows, version 8, SAS Institute, Cary, N.C.) was used to analyze numerical data and compare the treatments within Groups 1 and 2 to controls. Duncan's multiple range test was used to separate the means of bacterial counts for each finish tested.

Results and Discussion

Visual Inspection for Discoloration After Corrosive Treatment

Plant maintenance begins with visual inspection of equipment. The corrosive treatment generated discoloration experimentally that would be unacceptable by plant inspection, although the discolorations are not strong. If the degree of discoloration is high, the discoloration may be evaluated by instrumental techniques, such as Auger electron spectroscopy by monitoring oxygen as an index of oxidation. However, it is difficult to examine the degree of rouging in the early stage of discoloration quantitatively. Visual inspection with the use of a hand-held flashlight can be used for the evaluation of such rouging, although it is qualitative expression (Suzuki et al., 1998). Slight discoloration of the metal surface was noticeable, but the observed visual changes were difficult to photograph using a camera without special optics because of the reflective nature of the stainless steel surfaces and interference from shading. Table 1 illustrates the degree of discoloration of each finish after exposure to the corrosive treatment in comparison with the set of untreated samples. All of the samples showed increased discoloration. The electropolished, steel-ball burnished, and acid-dipped samples showed the least increase, while the sandblasted, mill finish, and glass-beaded samples showed the most increase. No differences could be distinguished by SEM between the surfaces of the two sets of disks, before and after exposure to the corrosive treatment.

Surface Composition of Disks by EPMA

Table 2 shows the elemental composition for each sample surface in order of quantity. The depth of surface analysis for EPMA is about one micrometer beneath the surface. The method is qualitative, and the order of quantity, from greatest to least, can be determined, but not the exact percentages or quantity of each element. Note that the mill finish control in Group 2 contains more elements than the mill finish control in Group 1, indicating possible surface contamination from the processor source. Most of the additional elements were removed after exposure to the corrosive treatment. In Group 1, the finish for the electropolished, steel-ball burnished, and control samples contained the same elements, in the same order, before exposure to the corrosive treatment.

All of the samples contained elements such as iron and manganese that are commonly known to enhance bacterial attachment. Oxygen, which may correspond to surface iron oxidation, was clearly detected after exposure in the steel-ball burnished, steel-shot burnished, and mill finish samples from Group 1 and Group 2. The electropolished and acid-dipped samples seem to resist surface oxidation, corresponding with the visual observation of lower discoloration than the other samples. The sandblasted and glass-beaded samples differed from the other surface finishes in that intensities for oxygen and silicon decreased after exposure, suggesting that the surfaces were subjected to composition change by the corrosive treatment. Both contained oxygen in the samples before exposure to the corrosive treatment and showed more visible discoloration than the other samples after exposure. It has been suggested that bacterial activity that consumes oxygen at metal surfaces

Table 3. Effect of surface finish and exposure to corrosive treatment on bacterial attachment.[a]

	Not Exposed		After Exposure		
Surface Finish	No. of Bacteria	Std Error	No. of Bacteria[b]	Std Error	% Change
Group 1					
Electropolished	200	104	25*	4	-88
Steel-ball burnished	363	47	1089***	65	200
Glass-beaded	918	68	1291**	125	41
Control[c]	949	46	458***	35	-52
Group 2					
Acid-dipped	1387	225	190***	12	-86
Steel-shot burnished	1371	58	1260	183	-8
Sandblasted	1816	60	1506*	179	-17
Control[c]	1000	179	983	141	-2

[a] Mean values are duplicate counts of bacterial cells from each of five trials by SEM.

[b] Experimental values after exposure that are different from unexposed finish: * = P < 0.10, ** = P < 0.05, and *** = P < 0.001.

[c] Control was type 304 stainless steel sheet with a 2B mill finish.

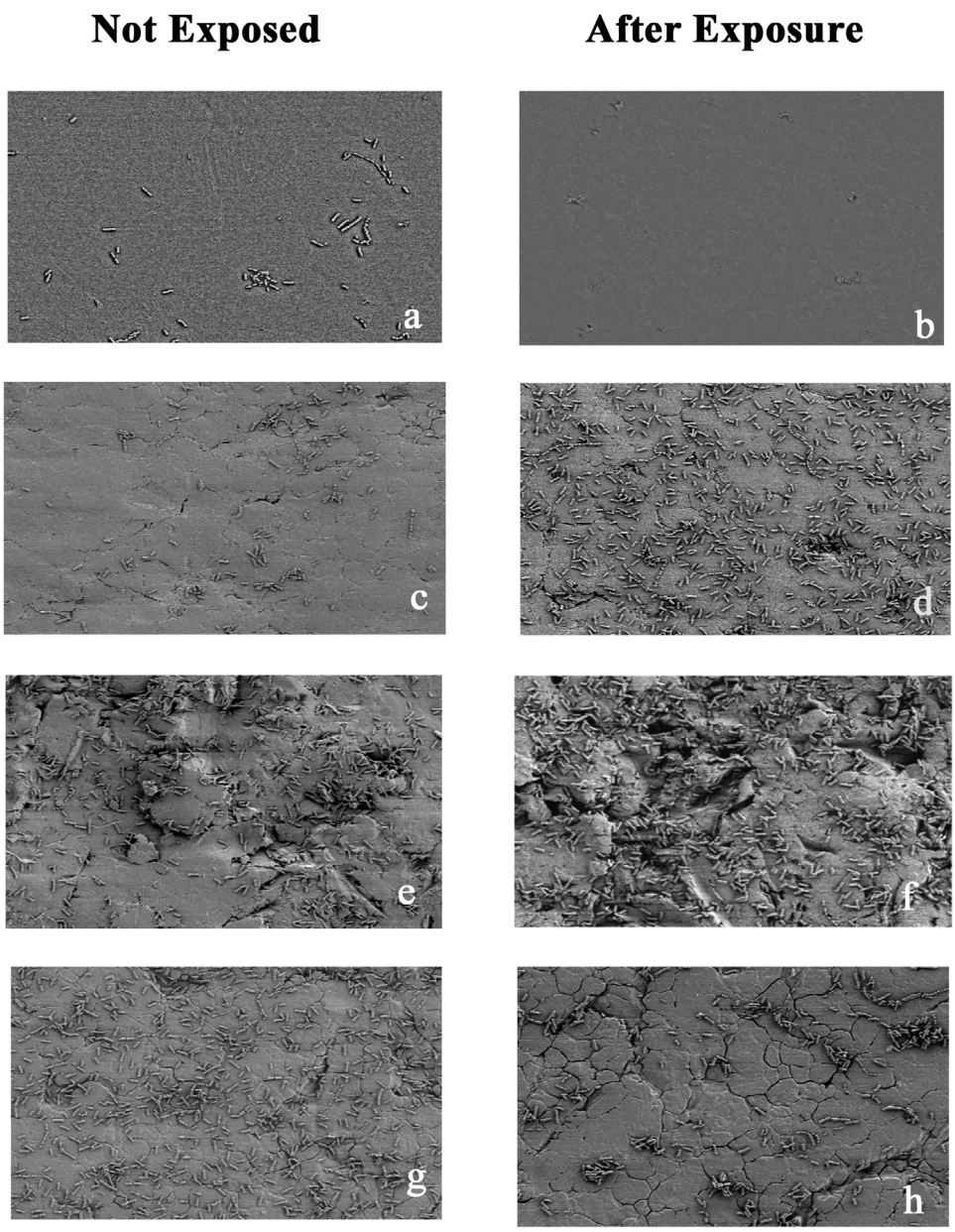

Figure 1. Scanning electron micrograph of bacterial attachment to each of the stainless steel surface finishes in Group 1: unexposed finish (left column) and finish after exposure to corrosive treatment (right column). Finish types are electropolished (a, b), steel-ball burnished (c, d), glass-beaded (e, f), and mill finish control (g, h).

plays a role in corrosion inhibition (Hernandez et al., 1994; Jayaraman et al., 1997; Potekhina et al., 1999).

Comparison of Bacterial Attachment Before Exposure to Corrosive Treatment

SEM was used to compare the set of disks that were not exposed to the corrosive treatment within each group to determine the differences in the bacterial counts. Statistical analysis of the sample set with unexposed finishes was in agreement with our previous research (Arnold and Bailey, 2000; Arnold et al., 2001). Bacterial attachment to stainless steel samples varied for each surface finish (table 3). For Group 1, the number of bacterial cells on the control mill finish was 949, and each of the other finishes reduced this number, i.e., were more resistant to bacterial attachment. The surface finishes, before exposure to the corrosive treatment, were ranked, based on numbers of bacteria that attached to the samples. From most resistant to bacterial attachment to least resistant, the finishes were: electropolished > steel-ball burnished > glass-beaded > mill finish control (table 3). Representative samples in figure 1, left column, illustrate bacterial attachment to each finish before exposure to the corrosive treatment. The bacterial counts on the electropolished (fig. 1a) and steel-ball burnished (fig. 1c) finishes were significantly less than for the mill finish control (fig. 1g), but the glass-beaded (fig. 1e) was not. Electropolished surfaces were more resistant to bacterial attachment than all stainless steel finishes in previous studies with materials from other sources (Arnold and Bailey, 2000; Arnold et al., 2001). For Group 2, each of the finishes retained more bacteria than the mill finish control, which had 1000 bacterial cells. The

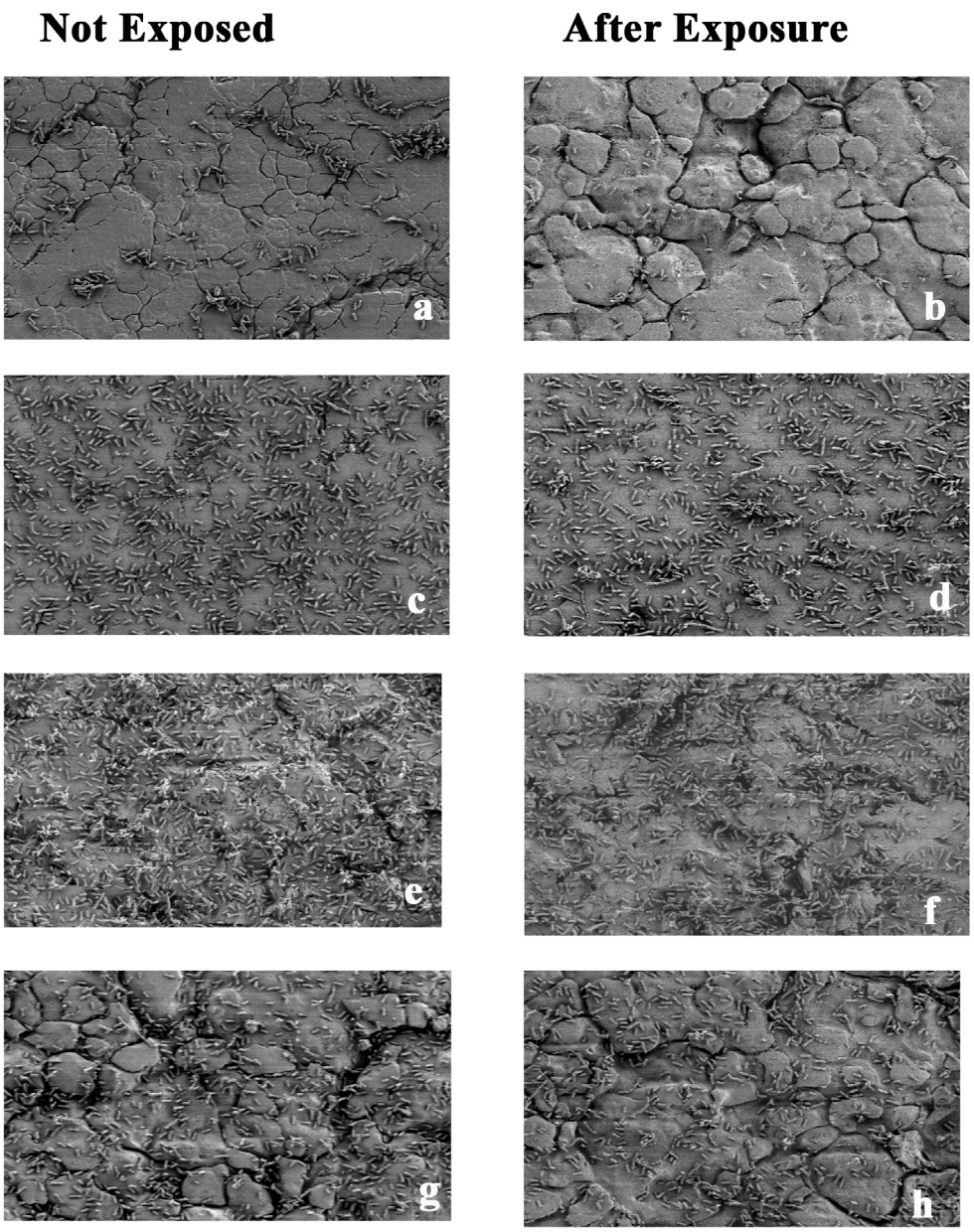

Figure 2. Scanning electron micrograph of bacterial attachment to each of the stainless steel surface finishes in Group 2: unexposed finish (left column) and after exposure to corrosive treatment (right column). Finish types are acid-dipped (a, b), steel-shot burnished (c, d), sandblasted (e, f), and mill finish control (g, h).

ranking, from most resistant to bacterial attachment to least resistant, was steel-shot burnished > acid-dipped > mill finish control > sandblasted (table 3). Figure 2, left column, illustrates bacterial attachment to each finish before exposure to the corrosive treatment. All finishes (fig. 2a, 2c, and 2e) were less resistant to bacterial attachment than the mill finish control (fig. 2g).

Comparison of Bacterial Attachment After Exposure to Corrosive Treatment

Exposure to the corrosive treatment resulted in changes in the numbers of bacteria that attached to the surfaces of each finish (table 3) within each group. In Group 1, the steel-ball burnished and glass-beaded finishes retained more than twice the bacteria as the control, while the electropolished finish retained only 5% as many cells. In comparison with the mill finish after exposure (fig. 1h), SEM showed that the electropolished finish (fig. 1b) had significantly fewer cells, and the glass-beaded (fig. 1f) and steel-ball burnished (fig. 1d) finishes had significantly more. In Group 2, the steel-shot burnished and sandblasted finishes (figs. 2d and 2f) retained one third to two thirds more cells that the control, while the acid-dipped finish retained only about one tenth the number of cells as the control. The sandblasted finish (fig. 2f) had significantly more cells attached, and the acid-dipped finish (fig. 2b) had significantly fewer. The steel-shot burnished finish (fig. 2d) had more cells attached than the control (fig. 2h), but was not significantly different.

Comparison of Bacterial Attachment Before and After Exposure to Corrosive Treatment

Each finish was compared for bacterial attachment before and after exposure. The percentage of change in bacterial counts for each finish after exposure is shown in table 3. After

exposure, in Group 1, the control retained only about half as many bacteria as before exposure, the glass-beaded finish about a third more, the steel ball burnished finish three times more, and the electropolished finish five times less. Significantly greater numbers of bacteria attached to the steel-ball burnished (figs. 1c and 1d) and glass-beaded (figs. 1e and 1f) finishes than to the finishes before exposure in Group 1. However, the control (figs. 1g and 1h) and the electropolished finish (figs. 1a and 1b) had significantly fewer bacteria attach after exposure than before exposure to the corrosive treatment. In Group 2, the control remained about the same, while the sandblasted finish increased, and the steel-shot burnished and acid-dipped finishes decreased. The acid-dipped finish was the most resistant in this group after exposure and had significantly fewer cells attach after exposure than before (figs. 2a and 2b). The other finishes (figs. 2c to 2h) had decreased bacterial attachment in comparison with the same finish before exposure.

Effects of Surface Changes

The data from our experiments show that corrosive changes in surface finish can impede or enhance bacterial contamination. These results were unexpected. One might expect that any degraded surface would enhance bacterial contamination, and therefore enhance further corrosion by bacterial processes (Ringas and Robinson, 1987; Xu et al., 1999). In this study, the 1.5 to 2 h of incubation of the bacteria with the surface was not sufficient to allow further corrosion by the bacteria. Standard corrosion tests require a minimum 24 h of exposure.

Removal of metal ions reduces the chemical reactivity of the surface, rendering the surface less susceptible to bacterial attachment. Surface composition can control the reactivity of the surface (Hochella, 1988), influencing the binding of substrates including bacterial extracellular polymers. Electropolishing removes metal from an object's surface through an electrochemical process similar to, but the reverse of, electroplating (Foulke, 1975). The interface behavior between various adsorbate molecules and the stainless steel surface is a fundamental aspect controlling the function of the material (Suzuki, 2002). The electropolished finish was the least reactive surface finish.

Conclusions

This research has shown the importance of the surface finish for potential corrosion, bacterial attachment, and biofilm formation on equipment components. The sandblasted and glass-beaded surfaces were the least resistant to discoloration and bacterial contamination before and after corrosive treatment. Electropolished surfaces contained few reactive elements and were the most resistant to discoloration and bacterial attachment, before and after exposure to corrosive treatment. The design of appropriate materials for the reduction of corrosion and contamination during food processing necessitates an understanding of the interactive forces of bacterial attachment and biofilm formation. Appropriate finishing treatments on stainless steel surfaces can improve the resistance and thereby enhance food safety and economy during processing.

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