Optimization of High Purity Product Contact Surfaces on Nickel Alloys via Electropolishing

R. Keith Raney
R. Keith Raney

- Has been active in electropolishing since 1975 when he and his family started the first electropolish company in the southern US.
- Developed on site electropolishing in the petro-chemical facilities in Texas.
- Worked extensively with nuclear industry electropolishing recirculation piping systems and reactor containments.
- Developed procedures for electropolishing 20’ stainless steel tubing for semi-conductor industry.
- Designed, Installed, and trained several US based vessel manufactures electropolish systems.
- Active member of ASTM BPE since 2001.
Do You Think This Surface is Easier to Clean or.....
20Ra

Would This Surface Be Better?
Surface Roughness

• The previous two slides both measure 20 Ra.
• To achieve this I had the electropolished coupon sanded to and 80 grit (35 Ra) then electropolished to the 20Ra seen.
• 20 Ra mechanically polished coupon was sanded to a 180 grit.
• The purpose is to illustrate that Ra is not as critical to performance as is the micro-surface finish!
2B Sheet Metal 10Ra, 1500X

How About This

vs. ......
2B – Electropolished 7Ra, 1500X

This?
Mechanical Polishing - Sanding

To achieve a specified Ra on product contact surfaces most fabricated products must receive some form of mechanical sanding, grinding, or polishing.
Mechanical Polishing - Sanding

MILL FINISH - Hot Rolled Annealed 316 Plate Material

Most alloy plate material used in fabrication is purchased in this condition.

120 Ra
All mechanical operations impart a finish similar to the surface shown here.
Mechanical Polishing - Sanding

Title: Area 3 (#4) 05
Note: 3/16 Stainless Steel Sheet Metal

Surface Parameters
Ra: 11.5 uin
Surface Area: 1.75e+007 uin²
Sdr: 4.304 %
Mechanical Polishing - Sanding

- Mechanical Polishing/Sanding/Grinding to achieve a specific Ra will cause a damaged layer and/or heat effected zone (Bielby Layer) to be produced.
Mechanical Polishing - Sanding

• This damaged layer will include material smeared over impurities such as:

  • Abrasive material/compounds
  • Iron or other contamination from handling/forming equipment
  • Paint, dye, grease, adhesives

• Mechanical finishing operations all cause damage to the material for some depth below the surface. The depth of this damage will vary depending on how aggressively the material was worked.
The Bielby Layer

Mechanical finishing is performed to achieve required Ra on metal surfaces will result in crystal fractures and other structural changes.

These conditions allow the formation of surface corrosion cells.

This condition is known as the Bielby layer.

Electropolishing can completely remove this damaged layer which is believed to be the biggest contribution to rouge formation in WFI systems.
J. Wulff illustrates this damage on honed, ground, and electropolished samples of 18-8 CrNi.

On the honed sample a layer of “Austenite and Cold Deformed Ferrite” sits atop of a layer of “Cold Deformed Ferrite” to a depth of 5 µm (.00002”). The ground sample had seven distinct layers of non-austenite material atop the pure stainless.

The seven layers top to bottom;

1. Austenite only
2. Austenite and Cold Deformed Ferrite (29-34µm) = (.00134”)
3. Cold Deformed Ferrite (25-29µm)
4. Cold Deformed Ferrite and Deformed Austenite (22-25µm)
5. Deformed Austenite (18-22µm)
6. Deformed Oxide with Grit Inclusions (5-18µm)
7. Oxide (0-5µm)
Electropolishing

Why Bother?
**Damaged Layer – “Bielby Layer”**

The damage in the uppermost grains can be seen here after sanding.

Once electropolished the damaged layer is removed leaving undistorted metal crystal structure at the surface.
ELECTROPOLISH

The Ultimate Product Contact Surface!

• Electropolishing provides optimum micro-surface finish!
• Electropolishing provides the minimum total surface area!
• Electropolishing provides pure alloy without contamination or damage at the materials surface (product contact interface)!
ELECTROPOLISH
The Cleanest Surface Possible

• Electropolished alloy surfaces offer optimum **cleanability**!
• Electropolished alloy surfaces offer optimum **sterility**!
• Electropolished surface offers optimum **resistance to corrosion** for any given alloy!
• Electropolished surface offers **rouge formation resistance** when base material condition is the cause!
Vocabulary

• **Electropolish**: the electrolytic removal of metal in a highly ionic solution by means of electrical potential and current.

• **Anode**: the work piece, part, or component connected to the positive side of a DC power source that becomes a sacrificial anode when the part is exposed to the electropolish process.

• **Cathode**: the necessary conductor that is connected to the negative side of a DC power source and is present in the circuit during the electropolishing process.

• **Electrolyte**: An acid blend into which the work piece is placed for processing. The bath is the ionic solution which wets the work piece and carries the metal ions from anode to cathode.
Electropolishing; How it Works

- A surface to be electropolished is made anodic (+) in a DC power circuit.

- The work is then exposed to an acid electrolyte (dipped or wetted).

- A cathode (-) is present adjacent to the portion of the work that requires electropolishing.
Electropolishing; How it Works

Spot Electropolishing
Tools moves over work while power applied & electropolishing takes place.

Power Supply

(+) positive cable

Spot EP Tool (−)

Work Piece (+)

Electrolyte Flow

Electrolyte Catch Tank

Recirculating Pump

(−) negative cable
Electropolishing; How it Works

When the power is applied an anodic film forms on the surface of the work and the material begins to be removed ion by ion.

The effect on the microscopic surface is to smooth and level as the microscopic “peaks” dissolve more rapidly than the microscopic “valleys” due to the increase in resistance to current flow as the film get thicker in the valleys.
Electropolishing; How it Works

When the process is allowed to continue for an adequate amount of time the surface becomes microscopically smooth and virtually featureless.

As the anodic film becomes uniform in thickness the benefits of electropolishing have been accomplished and material will continue to be removed uniformly until the process is stopped.
Electropolishing; How it Works

MILL FINISH - Hot Rolled Annealed 316 Plate Material

120 Ra
Electropolishing; How it Works

As Electropolishing Exposure Increases Microscopic Smoothing Continues Until Optimum Improvement is Achieved
Electropolishing; How it Works

ELECTROPOLISHED - Hot Rolled Annealed 316 Plate Material

35 Ra
On Site (In Situ) Electropolishing

- Electropolish equipment purchased without the finish, a capitalized “value added” service.
- Remediation of poor or damaged “factory” electropolished equipment.
- WFI System Vessels electropolished to control rouge formation and re-deposition on loop components.
- Autoclaves, sterilizer trays, parts washers, steam traps, “lyo” trays can all be electropolished to remove “steam” rouge and retard reformation.
In Situ Remediation
Shop Repair

After Mechanical Polish & EP  Before Mechanical Polish & EP
Remediation instead of replacement!
In this case 12 vessels were returned to service saving $M in replacement.
Field Repair

Magnetic agitator damage  Repaired agitator damage
Optimized Micro Surface & Surface Area Reduction

• Electropolishing offers a microscopic featureless surface.
• Electropolishing offers a total surface area that has been dramatically reduced.
• The only comparable surface finish on metal is produced by “lapping” as on metallurgical samples, and gage blocks.
2B Stainless Sheet Metal

SEM 1500X – 304 Stainless Steel

Note the cross section in the following slide to see illustration of surface roughness
2B Stainless Sheet Metal

White Light Interferometric Surface Analysis

Title: Area 1 (2B) 03
Note: 3/16 Stainless Steel Sheet Metal

Observe this cross section

Surface Parameters
Ra: 7.4uin
Surface Area: 1.79e+007 uin²
Sdr: 0.312 %
#4 Stainless Sheet Metal

SEM 1500X – 180 grit 304 Stainless Steel
#4 Stainless Sheet Metal

Title: Area 3 (#4) 05

Note: 3/16 Stainless Steel Sheet Metal

Ra 11.5 μin

Surface Parameters

Ra: 11.5 μin
Surface Area: 1.75e+007 μin²
Sdr: 4.304 %
Electropolished Stainless Coupon

SEM 1500X - 304 Stainless Steel
Damaged Layer – “Bielby Layer”

180 grit sanded surface

180 Grit - Electropolished

.0003”
Electropolished Stainless Sheet Metal

Compare this to previous slides

Ra 2.3μin

Surface Parameters

Ra: 2.3 μin
Surface Area: 1.88e+007 μin²
Sdr: 0.043 %
Bacterial Control

The Cold Worked, Damaged, or Beibly layer offers significant site for bacterial adhesion and bio-film formation.

Bacterial bio-films can contribute to corrosion as they can breakdown the passive film underlying the formations.

If the bio-film is then successfully removed an “active site” (non-passivated) can allow corrosion to initiate via a galvanic effect.
The disks were placed in 100 mL purified water, autoclaved for 1 hour, brought to room temperature and water supplemented to 100 mL. These procedures were repeated 50 times.
“Multiple imaging techniques demonstrate the manipulation of surface to reduce bacterial contamination and corrosion”


Fig. 2. Comparison of bacterial attachment with stainless steel samples from two manufacturers. The numbers of attached bacteria on electropolished samples (dark bars) were significantly reduced from the control samples (light bars). The data represent replicate counts of bacterial cells on micrographs from two trials that each included 10 random fields of view (n = 20).

Fig. 4. Comparison of surface roughness on stainless steel samples from two manufacturers. The average roughness for the electropolished samples (dark bars) was reduced from the control samples (light bars). Decreased surface roughness by AFM on the electropolished samples corresponded with reduced bacterial attachment shown by SEM (n = 20).
Bacterial Control

• “Bugs like to hide and form colonies”
Bacterial Control

• “Electropolishing eliminates the hideouts”

From: Edstrom Industries, Inc. (Update7)
Ra – How Important Is It?

“Ra is the most important thing to me“
(famous engineer)

Both surfaces shown here measure 20Ra.

Which surface is best for high purity applications?
Determination of surface roughness by contact profilometry

Traces of 90° diamond cone (5 μmR, force 0.8 mN) on electro polished surface, $Ra = 0.15 \, \mu m$
Electropolishing VS. Buffing

Although similar in appearance; buffing should never be allowed to be the final surface finish on product contact surfaces.

Embedded aluminum-oxide abrasive residue

Buffed

Electropolished
### Table SF-2  Acceptance Criteria for Mechanically Polished and Electropolished Product Contact Surface Finishes

<table>
<thead>
<tr>
<th>Anomaly or Indication</th>
<th>Acceptance Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blistering</td>
<td>None accepted</td>
</tr>
<tr>
<td>Buffing</td>
<td>None accepted (following electropolishing)</td>
</tr>
<tr>
<td>Cloudiness</td>
<td>None accepted</td>
</tr>
<tr>
<td>End grain effect</td>
<td>Acceptable if $R_a$ max. is met</td>
</tr>
<tr>
<td>Fixture marks</td>
<td>Acceptable if electropolished</td>
</tr>
<tr>
<td>Haze</td>
<td>None accepted</td>
</tr>
<tr>
<td>Orange peel</td>
<td>Acceptable if $R_a$ max. is met</td>
</tr>
<tr>
<td>Stringer indication</td>
<td>Acceptable if $R_a$ max. is met</td>
</tr>
<tr>
<td>Weld whitening</td>
<td>Acceptable if $R_a$ max. is met</td>
</tr>
</tbody>
</table>

GENERAL NOTE: Mechanically polished or any other finishing method that meets the $R_a$ max.
SF-7 ELECTROPOLISHING PROCEDURE QUALIFICATION

Electropolishing service providers shall maintain and implement a quality control program for their electropolishing procedures. They shall also qualify their electropolishing method(s) in accordance with a written procedure. This procedure shall specify the acceptable ranges of the electropolishing essential variables. Flash electropolishing shall not be accepted. Spot electropolishing shall be acceptable if it meets the requirements in this section.
ASME BPE-2009

The latest revision of the BPE standard will include:

“NONMANDATORY APPENDIX H – ELECTROPOLISHING PROCEDURE QUALIFICATION”

Which defines a method for qualifying the electropolish process used for electropolishing component(s) surfaces that will be exposed to the product(s) in bioprocessing, pharmaceutical, and personal care products systems and ancillary equipment”
ASME BPE

• The ASME BPE Committee Meetings will be held January 18-21 at the Rio Mar Hotel. Participation by Bio-Pharm Manufactures is always encouraged.
  – Wednesday (1/20) 1:00 PM -3:00PM a “white paper” will be presented;

• Determining Acceptable Levels of Weld Discoloration on Mechanically Polished and Electropolished Surfaces

• By: Ken Kimbrel

• Abstract: This paper will identify acceptable levels of weld discoloration on mechanically polished and electropolished surfaces and also show proven shop and field remediation practices to removes excessive heat tint. Additionally, we will show the effect of various oxygen levels and its contribution to heat tint as well as impact on corrosion resistance. The information herein is based on actual field experiences and successful methods of field remediation.
Qualifying Vendors

• End users are encouraged to develop a program for qualifying an electropolish vendor.

• A good electropolish vendor should be able to produce a procedure for the process used, including independent verification that the procedure used is capable of producing the desired improvements to the micro-surface that have been described during this presentation.

  • Featureless micro-surface
  • Removal of damaged / heat affected zone
  • Optimized corrosion resistance
“Buffing Looks Good”

- Buffing is used to make a component look bright and mirror like. Unfortunately this practice is often used to make equipment required to be electropolished look cosmetically more appealing or to touch up electropolished surfaces.

Buffing offers no improvement in corrosion resistance

Buffing will in all cases embed grease, adhesives, and any other “dirt” present under a layer of smeared and torn material.
“Buffing is Not Good”

- When a high purity surface is required buffing should never be used.

- Proper electropolishing over buffing will remove completely any reflectivity achieved making the practice unnecessary

- End users should insist “no buffing” be performed on any product contact surfaces.
Buffed either side of final weld appears “white” where surface damaged by chloride exposure – NOTE: Electropolished surfaces above and below buffed area unaffected by corrosion!

Buffing vs. Electropolishing AL6XN
New vessel VP-3200 during fabrication, dimpled cooling jacket shown
Top head to sidewall weld

New vessel VP-3200, AL6XN, far wall from manway, June 2006
Electropolishing; How it Works

Large Head
Electropolish

Power Supply

Cathode (-)

Electrolyte

WORK (+) PIECE
Anode
Rouge

- Rouge is a naturally occurring phenomenon in Stainless Steel high purity water or pure steam systems. The degree to which it forms depends upon:
  
  (a) The stainless steel material used for each component within the system.

  (b) How the system was fabricated; i.e. welding, surface finish, passivation treatment.

  (c) What process service conditions the system is exposed to; i.e. water purity, process chemicals, temperatures, pressures, mechanical stresses, surface velocity and oxygen exposure.

  (d) How the system is maintained.
Fe$_2$O$_3$ Hematite Type II Rouge

Typical Rouge is caused by hot purified water or clean steam exposure.
Fe₂O₃ Hematite Type II Rouge

Corrosion damage from concentrated chloride exposure over many years.
Fe₂O₃ Magnetite or Type III Rouge

Believed to have been caused in WFI system running 90°C water. Not removed during typical de-rouging procedure.
Spray Ball Rouge
Rouge

• Rouge is corrosion! Sometimes staining from product manufacturing is mistaken for rouge.

• Rouge indicates the passive layer has been compromised!

• Rouge can become loose particles that move throughout the system. Once mobile the rouge particles may be considered an additive which is prohibited by FDA requirements.

• Rouge can dramatically effect surface roughness: In a recent field observation on a consistently rouged non-electropolished PW vessel surface roughness Ra readings were observed as high as 90Ra when read on the rouged surface, following rouge removal the same surface measured < 20Ra.
Proper Electropolishing has been proven very effective in slowing the formation of rouge on 316 stainless steel surfaces.

Electropolishing allows the product contact surfaces to be free of the physical and metallurgical damage (Bielby layer) that takes place during mechanical polishing that can significantly contribute to rouge formation.

Case Study 1 - Rouge Control

In WFI systems all 316 stainless steel exposed to the high purity water should be properly electropolished to insure complete removal of any “damaged layer” from mechanical polishing.

In this hot WFI vessel the band and bottom head were electropolished 30 months ago – no rouge here, yet reformed everywhere else!
Case Study WFI Systems

These vessels and entire loop have never required de-rouging or passivation since being Electropolished!
Case Study WFI System Tanks

Two WFI (80°C) vessels 36,000L & 20,000L both with a 180 grit factory interior finish and a history of rouging required chemically cleaned and (citric) passivated every 12 months.

The owner had the vessels completely electropolished “in situ” over the original 180 grit factory finish followed by (citric) passivation.

After 4 years in service the owner reported that no de-rouging and passivation had been required as no rouge has returned in the entire system!

One time Electropolishing cost $50K* per vessel eliminating cost of yearly cleaning and passivation as had been routine.

* CAPITOLIZED Average cost per vessel (size & conditions will impact actual charges)
Electrochemical Cleaning (ECC)™

• The same techniques used to provide spot electropolishing can be used as an extremely effective cleaning / de-rouging process.

• Much faster than complete electropolishing, electrochemical cleaning has proven very effective in removing;
  – Product residue resistant to conventional cleaning
  – Staining from SIP operations
  – Grey residue in non-electropolished equipment
  – Rouge from WFI Systems, Clean Steam Systems, Autoclaves, Parts Washers, and related equipment.
  – Electrochemical Cleaning like electropolishing removes material from the surface being cleaned with no risk of damage!
Surface Comparison Study

- Mech. Polish
- Mech. Polish & Passivate
- Electrochemical Cleaned
- Electropolished
Electrochemical Cleaning (ECC)™

This technique is an extremely effective process. It utilizes specifically formulated abstraction chemistry in conjunction with electrolysis. To some degree it replicates electropolishing however it is a process that removes only the readily soluble passive film contaminates such as iron, nickel, aluminum (grinding residue, etc.)

ASTM B 912 Standard Specification for Passivation of Stainless Steels using Electropolishing recognizes both ECC and electropolishing as a suitable form of passivation as long as a citric acid or nitric acid flush is performed before final rinsing and drying.
Chemical Passivation

Chemical passivation procedures require first cleaning and de-rouging then introduction of nitric acid or citric acid to remove free iron. If citric acid is used in order for the surface to form a passive layer it must be exposed to an oxidizer or allowed to dry and be exposed to oxygen for several hours. If nitric acid (oxidizer) is used the oxygen is produced when the acid comes in contact with the stainless steel and no extended dry period is necessary as the passive film is already established.

Electropolishing & ECC liberates oxygen during the operation on the metals surface which provides, like nitric acid an simultaneous passive layer. Following electropolishing or ECC the surface simply needs to be flushed with a room temperature citric or nitric acid to remove any residual acid salts.

Electropolishing or ECC components can be passivated as part of a system without risk of damage unlike some chemical cleaning that may use strong etching agents as part of the cleaning process.
Standard Cleaning and Passivation Treatment Process

- DI Water Flush
- Derouging with Organic Acid Intensifiers and Reducing Agents (phase optional based on presence of rouge)
- High Purity Water Rinse
- Decontamination with Alkaline and/or Detergents
- High Purity Water Rinse
- Citric/Chelant or 20% Solution Nitric Acid Passivation
- High Purity Water Rinse
- Oxidizer or Sanitization with Peroxides (Citric process only)
- Final High Purity Water Rinse
Field Assembled New System Passivation - Yes or No?

• Even if the components are passivated or electropolished at the "factory" this is an essential step on new systems.
• The Cr/Fe ratio Must be >1.5 for best corrosion resistance performance once in service.
• Field assembled systems usually include Orbital Welds which in the as welded condition have Cr/Fe Ratios of 0.11 Plus High Manganese + Silicon
• Unless the Cr/Fe Ratio is increased and the Mn + Si is reduced, The corrosion resistance will be poor on these welds.
• Installation practices can introduce contaminants in components, plus the presence of field welds make final cleaning and passivation of the entire system essential before placing the system into service.
Weld Seam Analysis Before Passivation

Heat Affected Zone

- OXYGEN
- IRON
- CHROMIUM

Article By: K. Balmer
Weld Seam Analysis After Passivation

Heat Affected Zone

OXYGEN
IRON
CHROMIUM

Article by: K. Balmer
ESCA Tests on 316L Passivation Time

Passivation Systems: Commercial Citric Acid system

Performed on Weld of 316L EP Tubing

![Passivation versus Time](chart.png)
<table>
<thead>
<tr>
<th>Process Type</th>
<th>Process Description</th>
<th>Comments</th>
<th>Conditions of Process</th>
<th>Chemistry</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nitric acid</td>
<td>Proven method under ASTM A 380/A 967. Can be processed at ambient conditions depending on formulation</td>
<td>30 to 90 minutes at ambient temperature or higher, depending on concentration used</td>
<td>10 to 40% nitric acid</td>
<td></td>
</tr>
<tr>
<td>Phosphoric acid</td>
<td>Effective at removing iron oxides in addition to free iron</td>
<td></td>
<td>5 to 25% phosphoric acid</td>
<td></td>
</tr>
<tr>
<td>Phosphoric acid blends</td>
<td>Can be used at a variety of temperatures and conditions</td>
<td></td>
<td>5 to 25% phosphoric acid plus either citric acid or nitric acid at various concentrations</td>
<td></td>
</tr>
<tr>
<td>Citric acid</td>
<td>Specific for free iron removal. Should be processed at elevated temperatures. Takes longer to process than mineral acid systems. Meets or exceeds ASTM A 967</td>
<td>1 to 4 hours at heated conditions</td>
<td>10% citric acid</td>
<td></td>
</tr>
<tr>
<td>Chelant systems</td>
<td>Should be processed at elevated temperatures; Takes longer to process than mineral acid systems. Removes iron oxides in addition to free iron. Meets or exceeds ASTM A 967</td>
<td></td>
<td>3 to 10% citric acid with various chelants, buffers, and surfactants</td>
<td></td>
</tr>
<tr>
<td>Electropolishing</td>
<td>This process is generally limited to components rather than installed systems. Process should be performed according to a qualified procedure. This process removes metal from the surface. Electropolishing should be performed in such way as to meet or exceed ASTM B 912</td>
<td>Exposure time must be calculated to insure 5 to 10 micrometers material removal from all surfaces requiring passivation. Rinsing must include a step to insure removal of residual film that may adversely affect the appearance or performance of the product.</td>
<td>Phosphoric acid based electrolyte</td>
<td></td>
</tr>
</tbody>
</table>
ASME BPE 2009 Revision

The 2009 Revision of this standard will include newly added information we have discussed here today that includes;

Section SF- Stainless Steel and Higher Alloy Product Contact surface Finishes
● Table SF-1 Acceptance Criteria for Stainless Steel and Higher Alloy Mechanically Polished Product Contact Surface Finishes
● Table SF Acceptance Criteria for Mechanically and Electropolished Product Contact Surface Finishes

Appendix D Rouge and Stainless Steel

Appendix E Passivation Procedure Qualification

Appendix H Electropolishing Procedure Qualification
Conclusions

1. Mechanical Polishing including buffing, even if cleaned and passivated can be a source of product contamination from the manufacturing process, bacterial contamination due to surface profiles that can harbor bio-films making them very difficult to remove, easily form rouge when exposed to high purity water (PW, WFI) or clean steam.

2. Surface roughness (Ra) is not a suitable method of specifying product contact surfaces.

3. Proper Electropolishing offers the optimum product contact surface as it;
   
   3.1 Removes damaged surface layer present after mechanical polishing or sanding.
   
   3.2 Removes any embedded abrasive or metallic residue present after mechanical polishing or sanding.
   
   3.3 Provides a microscopic featureless surface that offers best resistance to bacterial contamination, corrosion, rouge formation, product residue retention.
   
   3.4 Allows for an extremely uniform “passive layer” with no “thin” spots for failure.
Conclusions

4. Passivation is a naturally occurring process on stainless steel that can be accelerated in its formation and potentially enhanced in its Cr/Fe ratio with “Passivation” processes including Electropolishing.

5. Electropolishing is an excellent passivation process that when properly performed per ASTM B 912 requires no additional “Passivation”.
Referenced Specifications

- ASTM A 380
  - Standard Practice for Cleaning, Descaling and Passivation of Stainless Steel Parts, Equipment and Systems
- ASTM A 967
  - Standard Specification for Chemical Passivation Treatments for Stainless Steel parts
- ASTM B 912-02
  - Standard Specification for Passivation of Stainless Steel Using Electropolishing
- Semi F19
  - Specification for the Surface Condition of the Wetted Surfaces of Stainless Steel Components
Referenced Specifications (cont.)

  - Passivation of Stainless Steel – R.R. Maller; 3-A and EHEDG

- SAE AMS QQ-P-35 (Fed Std QQ-P-35C)
  - Passivation Treatments for Corrosion-Resistant Steel, Federal Standard/Specification

- MIL-STD-753C
  - Corrosion Resistant Steel Parts: Sampling, Inspection and Testing for Surface Passivation

- ASTM BPE-2009