

This article will identify acceptable levels of weld discoloration on mechanically polished and electropolished stainless steel surfaces and also show proven shop and field remediation practices to remove excessive heat tint. Additionally, we will show the effect of various oxygen levels and the impact heat tint has on corrosion resistance. The information herein is based on actual field experiences and successful methods of field remediation.

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

by Ken Kimbrel

Introduction

For years the pharmaceutical industry has relied heavily upon the American Welding Society's AWS D18.2 weld discoloration chart¹ to gage the acceptability of color in the Heat Affected Zone (HAZ) for welds in piping systems. The current ASME-BPE ©2009 edition, Table MJ-3 states in part discoloration in the heat affected zone of product contact surfaces "may be permitted to have light straw to light blue color" (for example, AWS D18.2 samples 1 through 3 may be used as a guide)." The AWS D18.2 chart in Figure 10 attempts to offer a guide based on welds made with oxygen contents of 10 to 25,000 PPM and identifying a corresponding sample number and thus identifying not only color, but acceptable oxygen ranges in the backing gas. However, there has been little proof established if color beyond level 3 impacts the corrosion resistance of the weld area or heat affected zone on austenitic stainless steels.

During the inspection process of a piping system, color determination and acceptance of color is at best subjective. Many individuals making acceptance determinations have not been adequately trained to determine the acceptability of color, nor have they undergone an annual visual color acuity test. Without standards giving clear direction on illumination and inspection equipment, many may be using inappropriate or outdated equipment with poor lighting sources which can affect the clarity and representation of the color.

Dr. Lisa Nath, lead eye surgeon at the University of Pittsburgh, contacted regarding the

importance of color acuity tests, stated, "If the ability of these inspectors' job duties depends on the subjective nature of their vision, I would think that an annual exam is warranted." She further explains, "Color vision comes about from our possessing three types of cone cells: red sensitive, blue sensitive, and green sensitive. Wavelengths of light are absorbed by these cone cells, and each cone pigment absorbs a broad range of wavelength although each wavelength is not absorbed equally. Our brain, in a very complex way, interprets the wavelengths by mixing excitatory receptive (brain cortex) fields and inhibitory receptive fields and we interpret color."

Color vision defects can be divided into congenital and acquired. Hereditary color defects are almost always red-green and affect 8% of all males and 0.5% of all females. Acquired defects are more often of the blue-yellow variety and affect males and females equally.

Congenital color vision defects usually are not associated with any noticeable retinal or optic nerve pathology, but acquired color vision defects frequently are associated with observable ocular pathology.

Ideally, a color vision test should detect the presence or absence of normal color vision and also distinguish between red-green defects and blue-yellow defects (remember that blue-yellow defects are primarily acquired color vision losses)."

The ASME-BPE 2009 edition in regard to Inspector/Examiner qualifications states in GR-4.1.3 "Certification," "The employer is responsible for training, testing, and certification

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of employees. The employer shall establish a written practice in accordance with the guidelines of ASNT-SNT-TC-1A including:

- a. the requirements listed in Table GR-1
- b. training programs
- c. certification testing requirements
- d. eye exam requirements
- e. certification documentation

The owner/user is responsible for verifying the requirements of this section are met.”

The SNT-TC-1A is a guideline to be used by employers to develop their own in-house program to cover training, qualification, and certification of their employees performing nondestructive tests.

It is important to point out that the SNT-TC-1A is a guideline and not a mandatory set of rules. It should also be noted that SNT-TC-1A is revised every few years, but, unless otherwise required, there is no requirement that the latest version be adopted. In other words, the SNT-TC-1A can be as broad or as limited as you need it to be.

In many instances, welds in stainless steel have been rejected to err on the side of caution. When this happens, it is typically much easier to cut out a weld and re-weld with the expense being absorbed by contractors rather than discuss the merit of the rejection. This ultimately increases cost to the owner of the system, if not at the time of the re-weld, during the installation process in the form of change orders and overruns, then in future installations by forcing the contractors to increase prices.

This weld discoloration or “heat tint” should not be confused with the naturally occurring, transparent oxide film present on all stainless steel which is largely responsible for the alloys corrosion resistance in aggressive environments. The content of the heat tint layer may vary, but most often is a mixture of chromium and iron oxides, and the heavier the oxide layer, the darker the color appears. Underneath the oxide layer, the base metal is typically depleted in chromium and therefore affects the corrosion resistance of the steel in this area. Unless a uniform passive oxide film is restored, these areas in the welds and HAZ where the heavy oxides have formed are prone to corrosion attack, most often in the form of pitting and crevice corrosion.

Many inspectors, customers, and even manufacturers are under the impression that in order to remove heat tint and restore corrosion resistance, the area affected must be ground to remove metal and passivate or electropolish the area afterwards. This paper will show the effects of these processes and benefits provided.

A high percentage of pharmaceutical systems in service today are fabricated using electropolished 316L stainless steel tubing and fittings. The AWS D18.2 color chart being used for color comparison and acceptance criteria was established on mechanically polished 304L stainless steel. Although the color chart includes a notation “there was not significant difference in heat tint color from UNS S31603 (steel number 1.4404, Type 316L),” there is no allowance made for the use of electropolished components in determination of color acceptance and how the increased corrosion resistance benefited the components from the electropolishing process. It is also known that the corrosion resistance of high alloy austenitic stainless steels is usually less affected by weld heat tinting.² This article will introduce for consideration color samples similar to those shown on the AWS D18.2 chart performed on electropolished 316L stainless steel in an effort to show the need to for an industry accepted color chart for electropolished material.

As stated in the paper by L.H. Boulton and R.E. Avery, published in April 2004 *Stainless Steel World*, when defining acceptance criteria for heat tint on stainless steel welds, consideration should be given to post weld cleaning methods that will be carried out on the welds or whether it is deemed that a certain level of heat tinting present on the joints will provide acceptable corrosion resistance in the particular application or environment.²

Inspection Equipment

A major impact on the amount of color that can be seen and a problem given very little consideration is the way the weld is being viewed during inspection. Color can vary whether being viewed by the naked eye under room lighting or LED lighting, or by using electronic devices such as a boroscope. Dependent upon the type of lamp being used to the type of scope the image is viewed on may impact the “acceptance of color” on a weld.

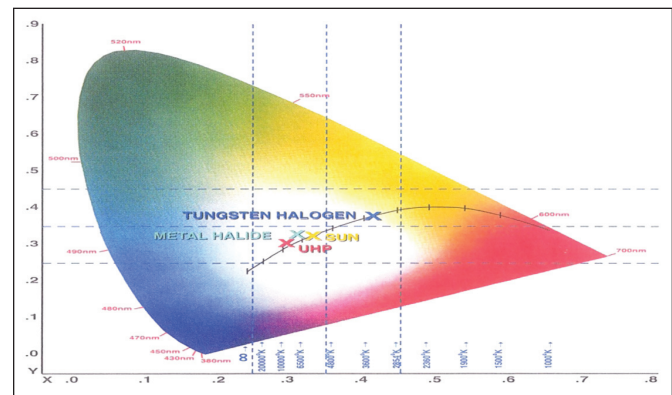


Figure 1. Spectral Output Chart Kelvin vs. Wave Length.

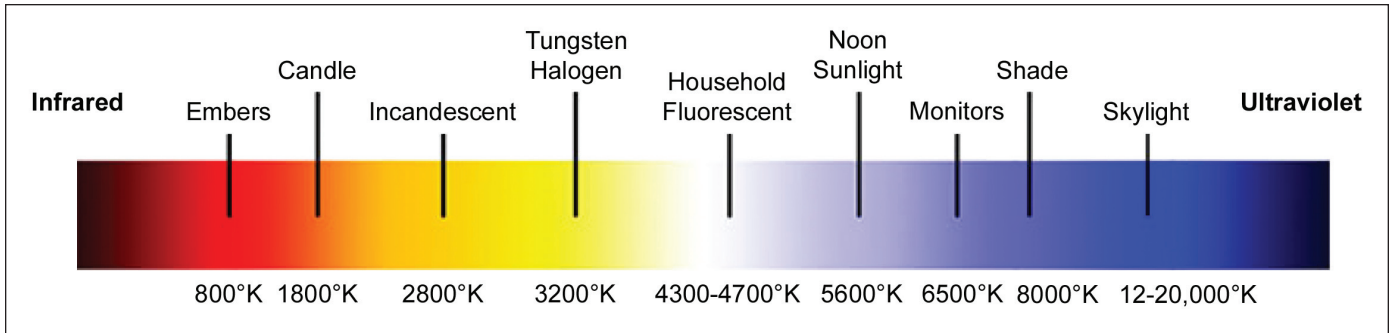


Figure 2. Color temperature imaging.

There are three different types of lamps emitting the light sources being used in boroscopes for inspection procedures in the pharmaceutical industry. These are UHP, which will emit a blue hue, tungsten, which will emit a yellow hue, and metal-halide, which will emit a blue/green hue on the surface. The following chart shows a color hue curve base on the actual light source being used.

Spectral Output

The spectral output of a lamp details the amount of electromagnetic radiation produced across a range of wavelengths, from ultra-violet (UV), through the visible spectrum, to infra-red (IR) - *Figure 1*. Radiation wavelengths are expressed in nanometers (nm), one nanometer being 10⁻⁹ meters.

The visible spectrum is between approximately 390 and 770 nm, with ultra-violet being below and infra-red being above this range. In order to give true color images, the light source should have a relatively even output across the visible spectrum. Ideally, the amount of IR radiation produced should be minimized, as IR radiation is converted to heat, which may then require a dissipation system. The spectral outputs of the three most frequently used lamp types are shown in *Figure 1* and compared with that of the sun.

Color Temperature

The color temperature of a lamp is an indication of its radiance and is measured in degrees absolute (°K in SI units) - *Figure 2*. Typically, tungsten-halogen lamps have a color temperature of 3,200°K, while metal-halide and UHP arc lamps are around 5,600°K. The color temperature of the sun is 5,900°K. With tungsten-halogen lamps, the color temperature can be reduced by decreasing the voltage across the lamp filament. Some light sources use this method to adjust the “intensity” of the light output. Unfortunately, this “rheostat” type control increases the “yellowing” of the resultant illumination.

According to boroscope manufacturers contacted during the research of this paper, the metal halide is considered to be the closest to sunlight available. An interesting side note is most boroscopes being used in industry are found in the aerospace sector with little consideration being given to pharmaceutical applications where color may be more of a concern.

To further illustrate the effect the light source can have on color, *Figures 3, 4, and 5* show the impact of viewing color on welds at different oxygen levels. Each photo in the following three examples show autogenous weld on the outside diameter of a piece of 1-1/2" 316L stainless steel tube split in half. Each

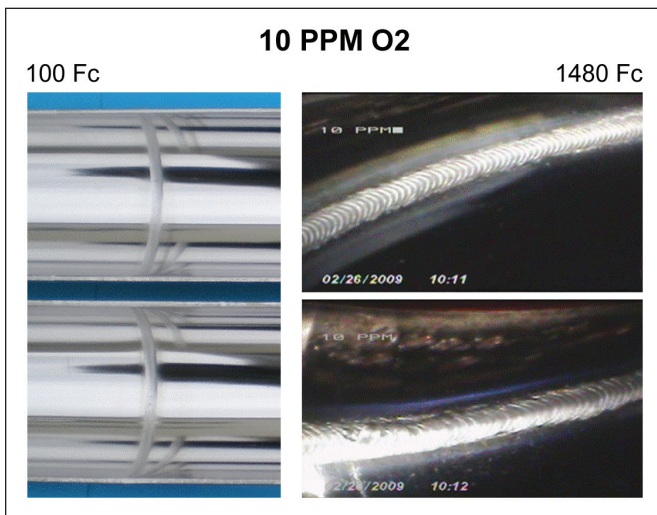


Figure 3. The photo at left illustrates the color on the weld and in the HAZ of a weld made with 10 ppm O₂. The photos far left show the weld discoloration using the naked eye while the photos nearest show the same weld as viewed with a boroscope at 1480 Fc power.

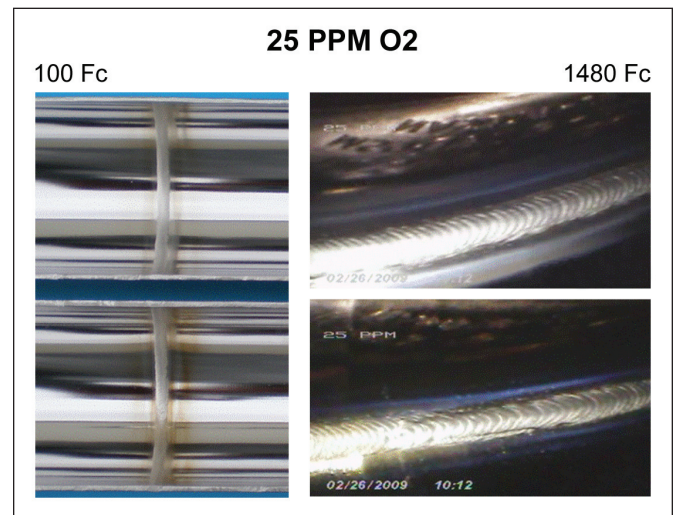


Figure 4. The photo at left illustrates the color on the weld and in the HAZ of a weld made with 25 ppm O₂. The photos far left show the weld discoloration using the naked eye while the photos nearest show the same weld as viewed with a boroscope at 1480 Fc power.

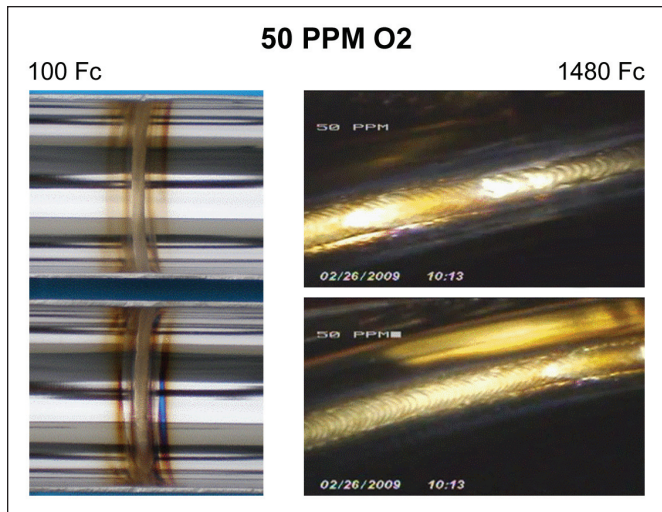


Figure 5. The photo at left illustrates the color on the weld and in the HAZ of a weld made with 50 ppm O₂. The photos far left show the weld discoloration using the naked eye while the photos nearest show the same weld as viewed with a boroscope at 1480 Fc power.

is then examined using the naked eye vs. 1480 Foot candle (Fc) power under a boroscope utilizing a 50W metal-halide lamp.

The identification of weld color is not new to the biopharmaceutical industry and should continue to be identified as a potential problem when necessary. However, with the acceptance of color being fairly subjective, it is important to make sure those responsible for the determination are as well equipped and trained as possible, not only in the determination, but methods for repair. In the following case study, I will illustrate how the difference of opinions can impact a project though both financial and scheduling issues.

Case

In February 2009, a major US-based pharmaceutical company installing new piping and transfer panels contacted the fabricator of the panels indicating over thirty welds were rejected by the third party inspection company based on unacceptable color in the HAZ of the welds as illustrated on the AWS D18.2 color chart. The panels themselves had been inspected and accepted in the fabricators facility nearly two years earlier by a different inspector employed by the same inspection company and had been kept in storage up until this point of installation. The current third-party inspector on site had not only rejected the welds based upon his determination of color, but also had indicated to the owner the weld must be cut out and replaced. After several discussions with the owner, third-party inspection, and hired consultants, it was agreed there was the possibility of using alternative methods to remove the questionable color and maintain the corrosion resistance in the weld area without cutting out the welds and re-welding in new sections.

In considering alternatives, there were several factors discussed. If the welds were cut out and replaced, spools would have to be fabricated incorporating additional welds over those cut out due to shortening of the section and the new

spools being welded in. Several weeks would be added to the project to allow time to cut out the existing welds, fabricate, and weld in the new spool pieces. The introduction of several new welds over the amount of existing welds and the purging challenges of the piping runs offered the opportunity for additional problems to occur. In addition, accessibility to the welds in question were challenging in many cases.

Consultants hired by the third party inspection company insisted that in order to achieve optimum corrosion resistance, if the current welds were to be left in place, they must be ground out and the area passivated or electropolished afterwards. This in itself is an impossible task when dealing with field welds as there is no way to access the area for grinding. Another method considered in lieu of cutting and rewelding the sections was a process known as ElectroChemical Cleaning or (ECC). This was developed as an alternative to using standard passivation procedures for cleaning rouge and other surface stains and had been successful in removing heat tint from heat affected zones in welds in past cases. It was argued the electrochemical cleaning process could achieve the same or improved results by removal of metal by the amount of time and current actually applied to the surface while exposed to electrolyte and achieves a passive surface equal to or exceeding standard passivation practices while not damaging the surrounding electropolished finish.

It was determined by the group that a range of sample pieces would be made on 316L stainless steel tubing with

	Coupon #00	Coupon #01	Coupon #02	Coupon #03
	Clean ELECTROPOLISH TUBE with no weld	~ 20 ppm O ₂	~ 50 ppm O ₂	~ 80 ppm O ₂
Coupon Set "A"	A-00	A-01	A-02	
Coupon Set "B"	B-00	B-01	B-02	
Coupon Set "D"		D-01	D-02	
Coupon Set "E", No ELECTROPOLISH-Citric Acid Passivated		E-01	E-02	E-03
Coupon Set "F", Mech. Pol. and EP		F-01	F-02	
<p>Coupon #00 Set "A" and "B" were clean 316L factory supplied electropolished tube which was tested to determine the CPP of the material only to establish a baseline for corrosion resistance of the base metal for comparison of corrosion resistance in the weld and heat affected zones of the other samples after the cleaning process.</p> <p>Coupon #01 Sets "A", "B", "D", "E", and "F" were coupons with circumferential welds welded with 20 ppm oxygen and inspected to color equal to #2 as found on the AWS D18.2 color chart.</p> <p>Coupon #02 Sets "A", "B", "D", "E", and "F" were coupons with circumferential welds welded with 50 ppm oxygen and inspected to color equal to #3 as found on the AWS D18.2 color chart.</p> <p>Coupon #03 Set "E" was coupons with circumferential welds welded with 80 ppm oxygen and inspected to color between #3 and #4 as found on the AWS D18.2 color.</p>				

Table A. Thirteen sample coupons with representative color in the HAZ of the welds.



Figure 6. Coupon Set A-01.

the same color discrepancies on the surface. These samples would then be exposed to different methods of remediation, (i.e., electrochemical cleaning, mechanically polished and cleaned), in an effort to determine if in fact the color in question could be removed and if there was an impact on corrosion resistance.

Samples

Thirteen sample coupons with representative color in the HAZ of the welds were provided as indicated in Table A. A modified ASTM G 61 cyclic polarization test to determine the critical pitting potential (CPP) of type 316L stainless steel was used to evaluate each sample after a specific process as listed below. The test solution consisted of 1000 ppm chloride mixed from NaCl with an adjusted pH of 5.0. The CPP is defined as the potential where the current density reaches a level 100 microamps/cm². The photographs seen in Figures 6, 7, and 8 are representative samples of those shown in Table A and tested with the results in Figure 9.

The Figure 9 graph is a sample shown for reference of the Cyclic Polarization Measurements as charted in Table B. Table B is a summary showing the resulting value of the Critical Pitting Potential as determined by the Cyclic Polarization tests for the 13 control samples. The higher the pitting potential number, the better the corrosion resistance.

Evaluation

In order to evaluate the findings shown in the Cyclic Polarization Results Table, a typical 2B mill finished passive 316L stainless steel will have a CPP near the mid 400 mV level



Figure 8. Coupon Set A-01.

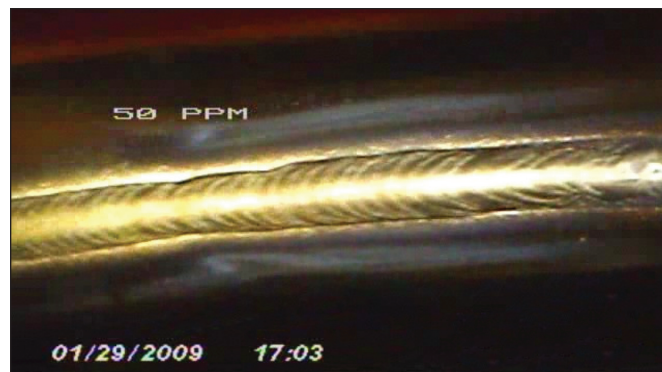


Figure 7. Coupon Set E-03.

which is an adequate surface for typical corrosion resistance. To further demonstrate the validity of the claim above, a recent study on the evaluation of passive surfaces by Dr. Jim Fritz looked at samples of 316L stainless steel and evaluated the passive surfaces using the Koslow Passivation Tester #2026.³ The samples had a sulfur range of 0.005-0.017% and had a full penetration weld with color levels between 2-3 on the D18.2 weld color chart. These samples were provided as (1) welded, no post weld cleaning, (2) color cleaned, heat tint removed using Scotch-Bright™ pad (3) ground to 120 grit finish. All samples were then passivated on 9.5% nitric acid at 55°C for 30 minutes. Those results are shown in Table C and Table D.

Review of Color Charts

For comparison of color being viewed through a boroscope in a field application and the AWS D18.2 chart shown in Figure 10 being used to establish acceptable color levels, it is important to point out the chart is being viewed on a cut piece of tubing with an unknown light source being emitted on the surface using the naked eye. In most field applications, the welds are being viewed utilizing a boroscope with an unspecified light source or viewing monitor which can emit variations on the outcome as described in the “Inspection Equipment” section above.

Additionally, the findings above suggest that even with color on the welds, the passive surface in relation to mechanically polished vs. electropolished material is impacted to different degrees. The studies clearly show even with higher

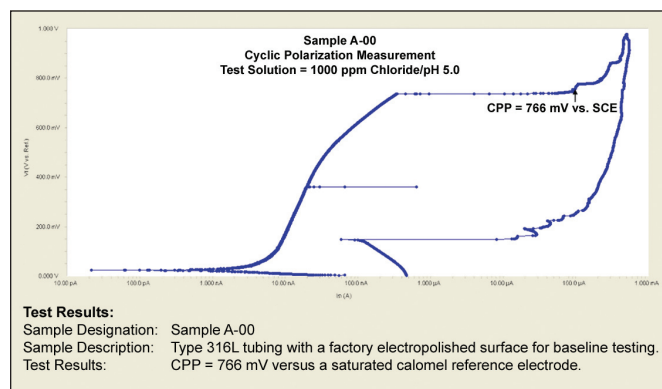


Figure 9. Cyclic polarization measurements.

Sample ID	Sample Description	Critical Pitting Potential (mV vs. SCE)
A-00	Baseline sample – Factory Electropolish	766
A-01	Welded with 20 ppm O ₂ – ELECTROPOLISH for 5 min.	728
A-02	Welded with 50 ppm O ₂ – ELECTROPOLISH for 5 min.	455
B-00	Baseline sample – Factory Electropolish	764
B-01	Welded with 20 ppm O ₂ – ELECTROPOLISH for 7 min.	699
B-02	Welded with 50 ppm O ₂ – ELECTROPOLISH for 7 min.	459
D-01	As-welded with 20 ppm O ₂	453
D-02	As-welded with 50 ppm O ₂	242
E-01	Welded (20 ppm O ₂) – citric acid passivation	841
E-02	Welded (50 ppm O ₂) – citric acid passivation	451
E-03	Welded (80 ppm O ₂) – citric acid passivation	385
F-01	Welded (20 ppm O ₂) – Mech. Polished + Electropolish	310
F-02	Welded (50 ppm O ₂) – Mech. Polished + Electropolish	423

Table B. Type 316L tube samples – cyclic polarization results.

levels of color present, that the electropolished surfaces are more corrosion resistance than those receiving only a mechanical polish. Therefore, color levels on electropolished surfaces may vary from those shown in the industry accepted AWS-D18.2 chart. Figure 10 (AWS D18.2) shows the different colors associated with O₂ levels on mechanically polished tubing in comparison with Figure 11 (Cotter Bros. Chart #143)

Sample	Unpassivated	Passivated
As Welded (HAZ)	- 780 mV	- 215 mV
Color Cleaned (HAZ)	- 450 mV	- 322 mV
Ground (HAZ)	- 220 mV	- 298 mV
Base Metal (2B Finish)	- 221 mV	- 258 mV
0 to -400 mV = Passive, -400 to -500 mV = Indeterminate, -500 to -1100 mV = Unpassivated		

Table C. Summary of Koslow passivation test.

Sample	Unpassivated	Passivated
As Welded (HAZ)	276 mV	525 mV
Color Cleaned (HAZ)	230 mV	475 mV
Ground (HAZ)	343 mV	495 mV
Base Metal (2B Finish)	506 mV	494 mV
Weld		603 mV

Table D. Summary of CPP measurements.

illustrating color levels typically found on electropolished tubing with similar O₂ levels.

Conclusion

The corrosion testing presented above suggest even with color in the heat affected zones, enhancements such as passivation, electrochemical cleaning, or electropolishing when performed

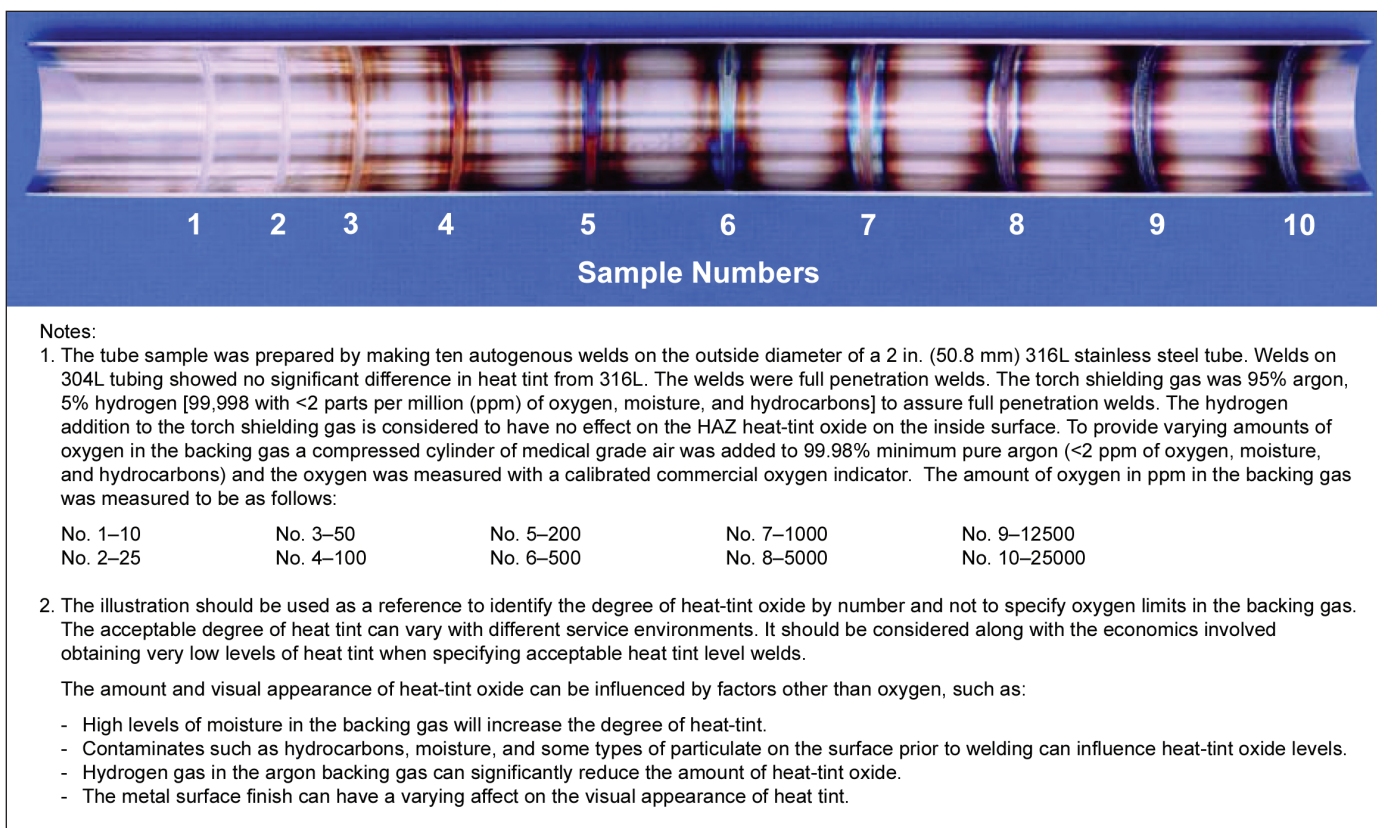


Figure 10. AWS D18.2 weld discoloration chart.

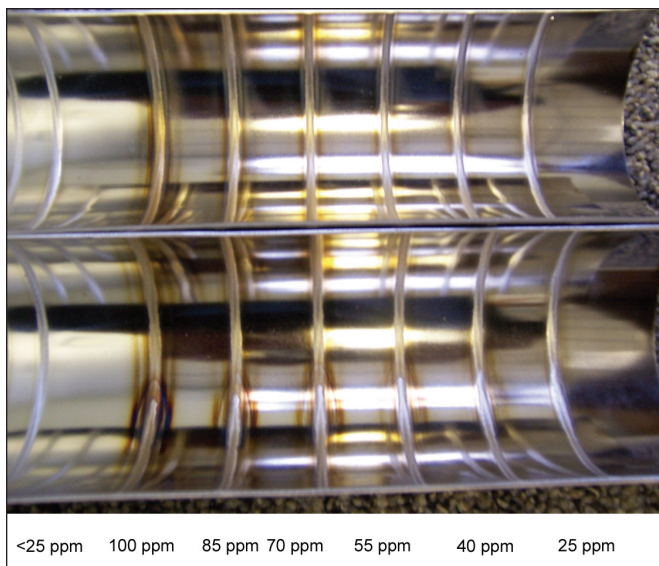


Figure 11. Cotter Bros. chart #143 weld discoloration chart for electropolished material.

properly will further improve the corrosion resistance in that area of concern.

The passivation process may not completely remove color from the HAZ but will improve the corrosion resistance to acceptable levels. Electrochemical cleaning and electropolishing will not only remove the color from the welds and HAZ, but also improve corrosion resistance to acceptable ranges without requiring welds be ground to remove metal and without further passivation processes.

Furthermore, the information above indicates that any resultant weld discoloration up to and including an O_2 exposure of 50 ppm will have no effect on the corrosion resistance recognized in the biopharmaceutical industry for electropolished 316L Stainless Steel material.

It is an inherent problem that inadequate purging of field welds have resulted in residual heat tint formed on stainless steel which may affect the corrosion resistance of the material. To compound this problem, the evaluation of color in the HAZ of welds is subjective at best, and may or may not be evaluated by qualified personnel. There is an inadequacy of industry standards for inspection personnel, equipment standardizing on illumination, image magnification and viewing which can result in enhancing or masking color resulting in either increases in weld rejection, or acceptance of inappropriate welds.

Passivation, although effective at improving the corrosion resistance, may not remove color from the weld or heat affected zone. The current acceptable practice to remove weld color is to grind the area to remove metal and passivate or electropolish the affected area, or cut out and replace on site trying to control the color through proper purging techniques. The corrosion studies have shown, that on-site electropolishing or electrochemical cleaning can effectively remove material and heat tint from the welds and HAZ while improving the corrosion resistance to levels similar to that of the base metal

without grinding or mechanical polishing being performed.

A color chart recognizing the effects of color for electropolished material should be developed and adopted for the pharmaceutical industry showing accurate acceptable levels of color - *Figure 11*. Inspectors and those responsible for evaluating color on welds should undergo color visual acuity tests yearly and should provide documentation of testing as deemed necessary by the owner or equipment supplier prior to the inspection process.

References

1. AWS D18.2 Weld Discoloration Chart.
2. Boulton, L.H., and Avery, R.E., "Heat Tinted Stainless Steel Welds – Guidelines for Acceptance," *Stainless Steel World*, April 2004.
3. Fritz, J., "ASME-BPE Evaluation of Passive Surfaces," *TMR Stainless Inc.*, March 2009.

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