1995046

Designing Components Made of High Strength Steel to Resist Stress Corrosion Cracking Through the Application of Controlled Shot Peening

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ABSTRACT

Stress corrosion cracking (SCC) is material fatigue associated with the combined presence of stress and corrosive environment. The events leading to catastrophic failure usually begin with the mechanical rupture of the material's protective oxide coating. These microscopic ruptures grow into pits and propagate into the substrate material, whereupon due to surface tensile stresses, crack propagation begins, which is further exacerbated by chemical attack at the crack tip. SCC is an insidious enemy to aerospace, boiler and naval engineers. Amazingly, a component designed for infinite life in an inert atmosphere, may last only a few months or several hours in a corrosive environment. Several methods exist which prevent SCC or delay initial crack propagation. The application of shot peening imparts compressive stress to the exposed subsurface layers of the material, which delays crack initiation and slows crack propagation in the compressive zone. In conjunction with proper material selection and component synthesis, shot peening allows the possibility of manufacturing and assembling SCC resistant parts.

KEY WORDS: corrosion, high carbon steel, intergranular fracture, nickel alloy, residual compressive stress, shot peening, stainless steel, stress corrosion cracking, transgranular fracture.

INTRODUCTION

Stress corrosion first became noticed at the end of the 19th century. Then, it was termed 'caustic cracking', or 'season cracking', as the SCC cracks were analogous to the season cracks in dried wood. It occurred in the brass cartridges of bullet casings and in unalloyed boiler steel.

Since then, several observations have been recorded of the results of SCC testing, but much remains to be known how to predict it and how to control it. SCC is an important topic due to the rapidly increasing rate of technological advancement. Engineering alloys are used in high risk areas such as aerospace applications (aircraft, rockets, and spacecraft exposed to moisture and coastal atmosphere), offshore oil rigs (sea environment + "sour crude" oil), and pressurized water reactors (chlorides, lead, tap water, oxygen).

Shot peening is an effective tool in the preparation of steel alloys for SCC environments. Resistance to SCC through the use of shot peening has increased material lifetimes on the order of tens. The need for a reliable SCC improvement method is recognized by the frequency of SCC failures due to an increase in technological advancement in recent decades. A significant factor in the importance of SCC research is the proximity of human life to such SCC failures.

SCC TESTS

Since not much is known theoretically about SCC, empirical observations derived from macroscopic test samples are fairly common. Consequent analyses which investigate microfeatures and fracture morphology are normally performed after the macrosample has failed. Together, these areas of research give the designer the SCC characteristics of particular materials, and a basic understanding of the nature of SCC in general. Macroscopic tests are performed on smooth or precracked specimens bathed in corrosive environments. Microscopic studies are performed using high magnification optics up to 1000X and electron microscopy up to around 6000X [1,2].

Environment

If a material is being studied for means of improving its service life and the service environment can be defined, it is best to test the material in the service environment. When the possibility of defining the service environment does not exist, one must look to natural environments (e.g., sea water, coastal atmosphere), or standardized laboratory solutions, such as:

- ASTM artificial seawater
- ASTM G36, boiling magnesium chloride for stainless steels
- ASTM G44, sodium chloride immersion at RT,

and several other updated versions. Consult ASTM Section G for detailed laboratory standards. Study has shown that no difference in high strength steel SCC results are obtained when testing with a 3.5% NaCl solution or natural seawater [12].

Testing for the worst case scenario is commonly discouraged. Frequently, it is difficult to define what a worst case may be for a particular alloy. Secondly, this assumption leads to over-rejection of alloys [1].

Smooth Specimen Tests

A common smooth specimen is the U-bend specimen (ASTM G30-79), made by bending a strip of metal into a U shape and retaining its ends with a long bolt or other means. Its popularity is due in part to the fact that along its cross section, a wide band of stresses are represented ranging from over the yield stress to zero stress. It is also possible to design a U-bend specimen which does not exceed the yield stress so that only elastic stresses are present.

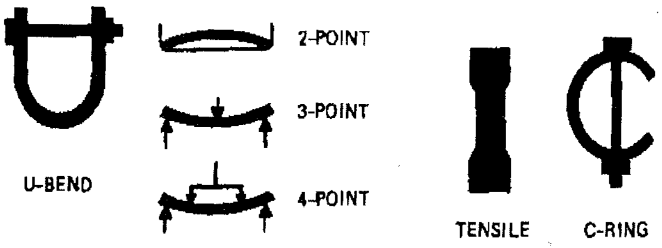

Figure 1. Smooth SCC Specimens.

Other specimens which are useful in determining stress dependence are the C-ring specimen and the uniaxial tensile specimen. ASTM Recommended Practices outlining these methods, including stress calculating procedures, are readily available in reference libraries.

SCC in smooth specimens occurs in the generalized sequence of events which characterize SCC in most service failures. These are: film breakdown, pit formation, initiation of crack, and propagation leading to rupture. Because of this, the researcher has the opportunity to study localized behavior in the pit region. This is increasingly important, since as SCC theory moves from a mechanical approach, to one that includes the chemical mechanism, it has been discovered that pits contain corrodent in much higher concentration than the bulk solution. This produces a chemical intensifier, nearly as important as the mechanical stress riser provided by the pit geometry [1].

When performing the smooth specimen test, data is collected as the 'time to crack' parameter. This is defined as the time from the start of the experiment to the time when a crack is first visibly ascertainable. It includes the time for film breakdown, pit formation, SCC initiation and some small amount of crack growth.

Also used by experimentalists is the 'time to failure' approach, which includes the occurrence of final rupture in the time parameter. The time to failure approach shows two important considerations not visible in the time to crack approach. First, failure depends not only on SCC, but on non-SCC parameters as well, such as specimen size, toughness and stress behavior. For instance, if several specimens were heat treated to different toughness levels, the tougher specimens would require a longer crack and a longer failure time, than a more brittle specimen. This is true even if the SCC characteristics are identical.

Secondly, the time to failure test method exposes a threshold stress value, when stress is plotted as a function of time [1].

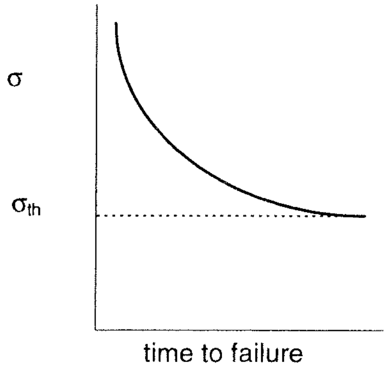

Figure 2. A Schematic of SCC Data from a Smooth Specimen.

Precracked Specimen Tests

Precracked specimen testing involves fracture mechanics. Because of this, several benefits are elucidated:

- a relationship between applied stress, crack length and crack growth is provided
- crack velocity can be expressed, which aids in the designation of inspection intervals
- the known flaw geometry allows stress analysis through fracture mechanics
- the stress intensity factor is developed.

Stress corrosion cracks are brittle, occurring before the onset of yielding while the material is subjected to an elastic stress field. This is true even for ductile materials. Initially, the fracture mechanics approach to SCC was not accepted, due to high plasticity at the crack tip. However, SCC failure occurs at such low stress levels that linear elastic fracture mechanics does apply. Recall that there is an even more plasticity at the crack tip for mechanical fractures, and LEFM has proven very useful in this regime.

Common SCC fracture specimen geometries are shown in Figure 3 below. Unique relationships for calculating K values can be found in the handbooks [2].

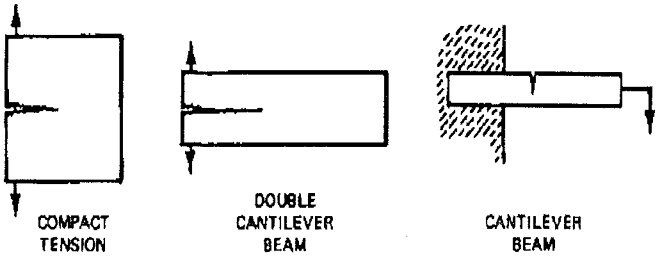

Figure 3. Precracked SCC Specimens.

Routinely, the SCC crack growth rate is plotted as a function of K, shown below in Figure 4. In region I, the log of the crack growth is linearly proportional to K. Here, the crack propagation remains normal to direction of the applied tensile field. Branching of the crack front is rare in region I, as any branch would have a lower K value, thus relieving the stress field it is experiencing. This is explained by the preference the main crack receives due to the powerful log relationship.

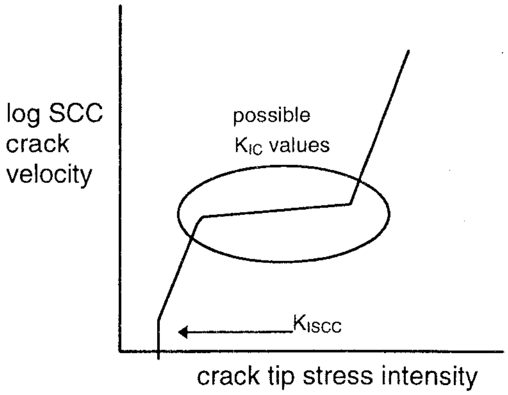

Figure 4. Schematic of SCC Stress Intensity, showing possible KIC Values.

In region II, the plastic deformation mechanism and/or the electrochemical concentration becomes saturated and propagation rates are unaffected by increasing K. Side branching is possible in region II, and has been described as a characteristic of SCC.

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As in several mechanical instances, there appears to be a value below which SCC is halted, called the SCC threshold value, KISCC. This is true for high strength steels as well as titanium alloys.

In very brittle alloys, it is possible to reach KIC before the arrival of region III. In alloys of extremely low fracture toughness, region II may not even be reached.

In general, the Irwin equation is considered.

$$K^2 = \frac{1.2\,\pi\,\sigma^2 a}{\phi^2 - 0.212(\sigma/\sigma y)^2} \qquad (1)$$

where a is the crack depth, σ is the applied stress, σy is the yield stress, and ϕ is the shape factor of the crack. Typical values of ϕ^2 are shown in Table 1.

Table 1. Values of ϕ^2

a/b		ϕ^2
0.	very long, thin	1.00
0.25		1.14
0.5		1.46
0.75		1.89
1.0	semicircular	2.46

If the assumption that a long, thin crack exists in the field of a yield stress then,

$$a_{cr}=0.2\,(K_{ISCC}/\sigma y)^2 \qquad (2)$$

defines the critical conditions under which crack propagation occurs. It also combines the SCC crack growth resistance K_{ISCC} with the contribution of the yield stress.

It is in this manner that handbooks publish the useful K_{ISCC} vs. σy plots. Equation (2) is plotted for various values of acr and results in a convenient method of comparing SCC characteristics. The K_{ISCC} is linearly proportional to the load carry capability of a material for a given flaw size.

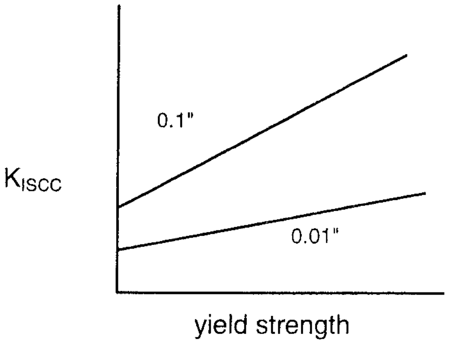

Figure 5. A Plot of Equation 2 for Two Values of a_{cr}.

SCC AND ITS MECHANISMS

It has been difficult for researchers to develop cohesive SCC theories which combine the coexisting disciplines of metallurgy, chemistry and mechanics. The most widely accepted theory is that a 'Grand Unified Theory' of SCC which applies to all alloy systems, may never be found. Thus far, all SCC preventive practices are based on past experiences or macroscopic experimentation. Nonetheless, qualitative theories have been suggested.

The film rupture model describes a reoccurring series of events that begins with the formation of a brittle oxide film upon contact of the metal with a corrosive solution. Tensile stresses at the surface cause breakdown and removal of a localized area of the oxide film, whereupon exposed surface metal reacts to form a new oxide film which is broken down yet again. The process repeats until a pit forms and crack propagation occurs when the pit reaches a critical depth. Mechanical crack dynamics takes over, possibly with some increased dissolution at the crack tip due to the corrodent, leading to final fast rupture. Evidence is provided by striation markings seen under SEM.

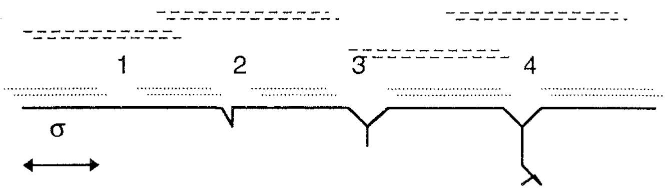

Figure 6. Schematic Representation of SCC Events.

The embrittlement model considers a electromechanical cycle in which a corrodent embrittles a metal just below the crack tip, whereby the crack fractures and fresh metal is exposed. It is known from pH measurements and potentials that localized conditions for this are met in high strength steels. Corrosion generated hydrogen cracking is not an unreasonable hypothesis [13].

The adsorption theory models the reduction in energy required to form new surfaces through the reduction in surface energy due to corrosion [14].

The mechano-chemical theory submits that there are paths predisposed to chemical attack, and providing the proper tensile stresses are present to open crack sites and allow electrochemical activity, crack propagation will occur [15].

Also mentioned in the literature are theories which shed light on the mechanism of increased crack growth rate. Based on the fact that most SCC failures occur on intergranular paths, anodic/cathodic reactions causing SCC between the grain boundary and the grains, and between precipitates and the grain boundaries have been proposed. Also suggested has been the increased mobility of dislocations in the plastic zone due to chemical depletion in this localized region [16].

SHOT PEENING TESTS

The effectiveness of shot peening in producing a quality part with uniform residual compressive stress cannot be evaluated directly nor nondestructively. Thus, it is necessary to rely on the so called Almen gage to judge the level of relative compressive stress imparted to shot peened parts. It is through the Almen gage that shot peening intensities are reported in the literature. The Almen gage is used because it is simple, inexpensive and quite free from error [3].

The Almen test is performed by shot blasting a 18.95mm x 76.2mm strip of 1070 steel. Upon impact of the shot, compressive stress is imparted to one side of the strip. After the strip is removed from its mount, the forces in the strip cause a curvature, in effect placing the strip in equilibrium again. The resultant curvature, called the arc height, is measured on a gage and becomes the Almen intensity measurement [4]. The arc height is affected by the following sets of parameters:

Blast	**Exposure**	**Test Strip**
Velocity	Time	Dimensions
Size	Angle	Mechanical
Shape	Flow Rate	
Density		
Type		
Hardness		

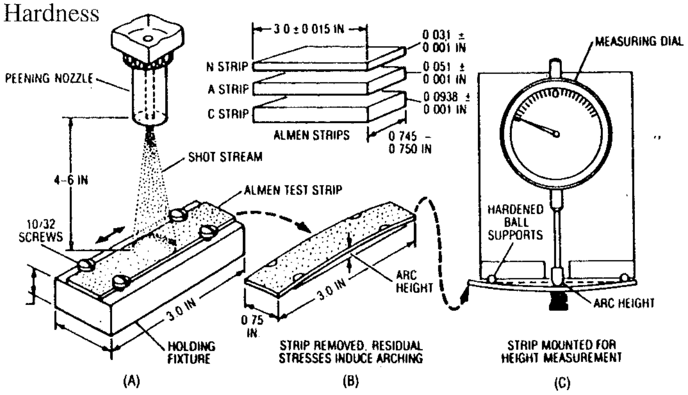

Figure 7. Schematic Diagram of the Almen Intensity System.

The Almen intensity measurement is fully investigated in SAE J442 and MIL-S-13165.

In order to ensure proper surface coverage, visual examination using a 10X microscope is accepted. For hard to reach areas, such as fillets in gears, the Peenscan process is used. Peenscan utilizes a brittle fluorescent coating that reacts to UV light. The coating is removed upon application of sufficient coverage and unpeened areas are exposed by the UV light.

SHOT PEENING

SCC occurs during the combination of four parameters: tensile stress, alloy susceptibility, corrosive environment and time/temperature considerations. Remove one of the parameters and the tendency for SCC to occur is reduced. Shot peening deals with the tensile stress parameter.

When a metallic part is shot peened, it is blasted with spherical media .005-.030" in diameter. Initially, the impact of the media strikes the surface, stretching the exposed surface fibers causing a tensile stress approximately one diameter deep. Immediately after the media is rebounded, a plastic impression is left about 0.1 diameter deep, whereupon the unaffected core exerts a uniform layer of compression on the stressed region, attempting to restore the surface to its original geometry [6].

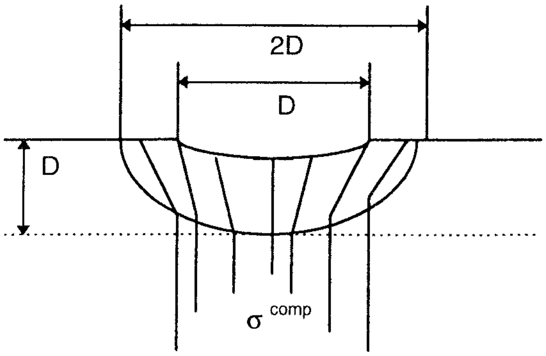

Figure 8. How Shot Peening Works

In order to improve the fatigue life and SCC characteristics of metals, it is necessary to blast the surface with a media of equal or greater hardness than the workpiece. In this manner, a sufficient compressive layer will be developed which can increase the part life in the SCC environment 3-7 times over a nonpeened part.

The maximum amount of compressive stress which can be generated in a high strength steel by shot peening is,

$$|(\sigma)^{comp}_{max}| \cong 0.5\ \sigma_{uts}\,. \quad (3)$$

It is this compressive stress intensity which is responsible for reducing SCC. In a non-shot peened part, tensile stresses due to metal preparation exist, which pull the surface fibers and break down the protective oxide coating of metals. Shot peening does not merely relieve stress at the surface - it changes it from tension to compression, so that the metal surface cannot be stretched, thus preventing film breakdown [7].

It appears that the fundamental benefit of shot peening is not in slowing crack propagation, but actually in delaying or preventing crack initiation. Positive effects in reducing the crack growth rate are seen, but only insofar as the crack tip remains in the compressive zone.

RATIONALE BEHIND THE USE OF SHOT PEENING

Tensile stresses which cause SCC can be a result of the following:

- cooling distortion
- abusive grinding and machining
- welding
- cold-forming
- protective metallic coatings
- dead load, thermal expansion
- misalignment during installation

Shot peening has the capability to deal with all of these stresses in the most efficient manner, by not only reducing tensile stresses, but imparting beneficial compressive stresses. Furthermore, the compressive zone is imparted where it is most needed, at the surface. In applications where thermal stress relief would cause strength reduction and/or sensitization, such as in stainless steel where chromium carbide precipitation at the grain boundaries is problematical, shot peening has been successful in reducing stress without imparting unwanted material characteristics.

Because the process is fully controlled, no residual distortion of the part is brought about. Today, the process is so adaptable it is even possible to shot peen the ID of thin walled PWR tubes.

Upon the application of service loads, it is possible to tailor a part such that no surface region will be in the dangerous tensile zone. This is only true provided that the compressive zone is rich enough to combat the tensile load. This is demonstrated in Figure 9. The application of a load on a non-peened part causes a tensile stress on the upper surface. After shot peening, an unloaded part has a compressive zone on the upper and lower surfaces. When the same tensile load is applied to the part, the resultant stress is still compressive - SCC is diminished. This concept is visualized on the next page.

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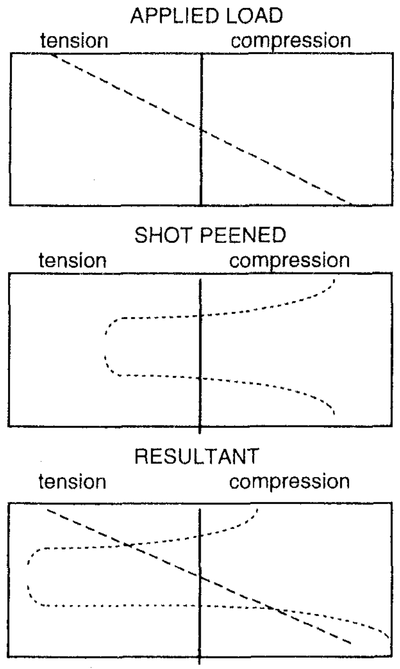

Figure 9. Resultant Stress Process in a Shot Peened Part.

Unlike coatings, which may get scratched during assembly, or crack during service, a shot peened part is plant-friendly. Furthermore, shot peening facilitates the use of brittle chromium and nickel coatings.

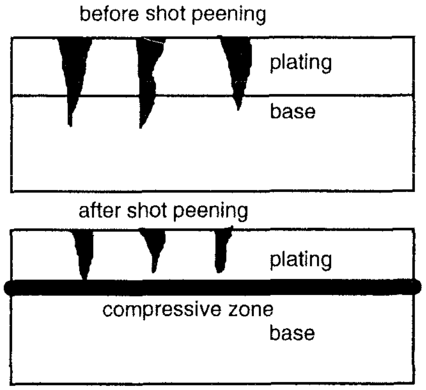

Figure 10. Shot Peening Prevents Plating Crack Propagation.

Usually, the application of plating allows the formation of microscopic cracks which propagate into the substrate material during service, causing premature failure. After shot peening, the presence of the compressive zone prevents propagation of the plating cracks into the substrate material.

RESULTS AND DISCUSSION

Shot peening has been used extensively in research and industry to improve the fatigue life of metals. Unfortunately, not much has been published in the literature about the positive effect of shot peening on SCC.

Stainless Steels

Characterization of failure

Stainless steels do not experience SCC in room temperature sea water, although pitting is likely [8]. SCC has been observed in sensitized types of stainless steel immersed in polythionic acids, fluoride solution, seawater and marine atmosphere [1]. The role of sensitization in stainless steels cannot be overemphasized. It occurs when chromium carbides in the region of the grain boundary precipitate out of solution, leaving chromium depleted zones. Very often, the heat treatment causing sensitization (above 1065°C for austenitic and above 790°C for ferritic stainless steels) was employed for purposes of stress reduction after welding. SCC may have been avoided if shot peening was used for stress relief.

The susceptibility of stainless steels to chloride ion induced SCC is very high. In austenitic stainless steels, it occurs transgranularly, showing extensive branching. In sensitized austenitic alloys, IGSCC is possible. Chloride SCC in ferritic alloys is almost always IGSCC, although TGSCC has been observed in magnesium chloride solutions. Stainless steel can fail from chloride SCC in a very brittle manner, even under low stresses [1]. Theories have been discussed. One suggestion is the slip dissolution model. It describes how the crack tip remains chemically active (dissolving metal) because of the constant supply of fresh surface material due to plastic deformation.

Stainless steel is not susceptible to uniform corrosion. Instead, it is pitting which is the most common form of dissolution [8]. Thus, most SCC fractures occur from cracks that initiated from pits. The uniform compressive zone imparted by shot peening acts as a plastic zone at a fatigue crack tip, closing the SCC crack at the pit tip. However, this is only true insofar as the pit tip does not extend below the depth of the plastic zone.

Results of shot peening

Work performed by Friske and Page showed that shot peening improved the SCC resistance of both sensitized and unsensitized type 304 in 42% boiling magnesium chloride [9]. They attributed the improvement to the presence of the compressive zone and the highly cold worked surface of the steel. They discovered that the plastic flow on the surface, marked by folds under SEM, was sufficient enough to modify the surface microstructure, preventing IGSCC from sensitization.

Wang, et al., found that shot peening could increase the corrosion fatigue life of austenitic and martensitic stainless steels in chloride solution of both pitted and non-pitted test specimens [9]. The compressive layer is responsible for, in effect, fatigue crack closure on the surface of already pitted test specimens.

The effect of shot peening has been studied by Syrett, Wing and Wittig [10]. Shot peened and non-shot peened corrosion coupons and corrosion fatigue samples were prepared from 17-4 precipitation hardening (PH) stainless steel. They were tested in the chloride environment. The results under this experiment were mixed. At low stress levels, shot peening showed little effect on the corrosion and SCC susceptibility of the 17-4 PH alloy.

Much of the positive effects of shot peening are believed to have been offset by the negative effects of microstructure and surface plasticity. The shot peening transformed the surface layers of the 17-4 PH alloy from reformed austenite into untempered martensite, which exhibits poor corrosion characteristics. Secondly, the shot peening roughened the surface of the material, which favors increased SCC susceptibility. However, at higher stress levels (>280Mpa), the effects of shot peening were beneficial in increasing the corrosion resistance and fatigue life of the alloy.

High Carbon Low-Alloy Steel

Characterization of failure

SCC in high carbon steel can be intergranular, transgranular with respect to prior austenite grains, or it can consist of microvoid coalescence. All three modes are shown below.

Steel is unique in that the mode of cracking is highly dependent upon the level of K, not upon the corrodent as seen in other alloys. At low levels of K, intergranular cracking is observed. Intermediate levels allow quasi-cleavage, and at high K levels microvoid coalescence is prevalent. Interestingly, SCC and hydrogen embrittlement are indistinguishable in steel, prompting researchers to suggest that SCC is related to hydrogen embrittlement at the stress corrosion crack tip [1].

Results of shot peening

The standard 3% sodium chloride environment has been used by Baxa, Chang, and Burck to study the effects of shot peening on AISI 6150 steel during corrosion fatigue [5]. Corrosion fatigue exhibits the same theoretical crack initiation process as SCC. Except that a large part of the total corrosion life is altered by cyclic stresses, which can be considered cyclic SCC. Most fatigue samples tested in dry air exhibited an infinite life. NaCl solution drastically reduced the life of 6150 in cyclic loading, however shot peening improved the corrosion life of 6150 over that of unpeened specimens. Shot peening had the most effect on low stress samples (< 400 MPa), where the fatigue life was increased 10 fold over unpeened specimens. At higher stress levels, there was a threefold increase in the corrosion fatigue life.

All of the dry air specimens that fractured showed a single fatigue fracture. The unpeened NaCl samples exhibited 3 to 5 small fatigue crack initiation sites which propagated, with several other crack initiation sites which had not propagated due to stress shielding from the major cracks.

The peened NaCl samples showed 10 to 20 individual corrosion fatigue sites on the fracture surface, with a major fracture surface. Although the number of crack sites in the peened samples is higher than for the unpeened samples, the average size of each crack is smaller. Nonetheless, the corrosion fatigue lifetimes were dramatically longer.

The peening operation showed a stronger effect at lower stress levels. As the stress is lowered, a larger part of fatigue life is associated with crack initiation. It has been suggested that the compressive zone is effective in lengthening corrosion lifetimes by virtue of fatigue crack initiation suppression. However, these results suggest that the increase in cyclic SCC lifetime is a result of lower fatigue crack propagation rates as influenced by the crack tip lying in the region of the compressive zone.

Nickel-Based Alloys

Characterization of failure

FCC nickel alloys are used extensively in the chemical and power industries. The majority of SCC cracks in this family are intergranular, with extensive branching [1]. Almost all documented cases of SCC in nickel alloys occur in those which are sensitized, a process resulting from stress-reducing heat treatments. This suggests that the nickel alloys would be an ideal candidate for shot peening stress relief, since shot peening does not cause sensitization.

Alloy 600 is a nickel alloy which has been used for the past 40 years in the fossil fuel and nuclear power industry. SCC resistance has been high for this alloy, except when high stresses and crevices are involved. In the instances of high stress, shot peening could be successfully employed to reduce SCC and the dangerous tensile stresses.

Results of shot peening

The effects of shot peening on sensitized Alloy 600 subjected to SCC tests in 95C thiosulfate solution (pH=6) has been studied by Tsai, Chang and Lee [9]. Previously, it was confirmed that alloy 600 is susceptible to SCC in thiosulfate solution. For comparison purposes, the following heat treatments were made into U-bend specimens:

Specimen	**Treatment**
AR	As received
SA	Solution Annealed, 1,100C/1 h + WQ
S2	SA + sensitized, 700C/2 h + WQ
S5	SA + sensitized, 700C/5 h + WQ
SP2	S2 + shot peening for 25 min
SP5	S5 + shot peening for 25 min

The SCC specimens were immersion tested at different electrochemical potentials. The results are summarized in Table 2. At the open circuit, SCC was observed on the sensitized specimens (S2 and S5) after 1,100 h of immersion. The cracks were intergranular in nature and quickly propagated, leading to fast fracture of the specimens. No cracks were observed on the AR and SA specimens. After 2,400 h testing, no visible cracks were seen on the SP2 and SP5 specimens.

TABLE 2

Crack initiation time [h] of alloy 600 in 0.1M $Na_2S_2O_3$ at 95C for different potentials

	POTENTIAL (mV)				
Specimen	OCP	+100	+150	+250	+500
AR	1,800	480	360	360	48
	NC	NC	NC	NC	NC
SA	1,800	480	360	360	48
	NC	NC	NC	NC	NC
S2	1,100	5	3.5	4	0.5
S5	1,100	7	3	2	0.5
SP2	2,400	480	360	160	10
	NC	NC	NC		
SP5	2,400	480	360	150	7.5
	NC	NC	NC		

(NC = no crack)

As the potential was increased from 100 to 500 mV, the SCC lifetime of the sensitized specimens decreased from 5-7 hours, down to half an hour. Meanwhile, the sensitized and shot peened specimens initially exhibited a 480 h crack initiation time, until they became severely affected at >250 mV. Even at +500 mV, the crack initiation time was still an order of magnitude greater than the sensitized specimens. This demonstrates that shot peening improves the SCC resistance of even sensitized alloy 600. Comparison of results found earlier by the same researchers with current results, show that shot peening improves SCC resistance more than a stabilization heat treatment.

All cracks which were discovered occurred intergranularly. Final fractures occurred in the transgranular mode. It is assumed that shot peening improves SCC resistance in sensitized alloy 600 by two mechanisms.

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- Compressive stresses at the surface delayed crack initiation.
- Plastic flow at the surface modified the surface microstructure of the material, partially eliminating the sensitized grain boundaries. Although, the surface deformation may not have been sufficient because intergranular cracking still occurred.

Hornbogen, et al., in previous research have noted that beneficial effects may be due to the homogeneously deformed surface layer (a change in the dislocation distribution), which is free from small slip steps. This could also slow down crack propagation.

SELECTION OF MATERIALS

Stainless Steels

The most important factor in the selection of stainless steels is procuring unsensitized alloys. SS with carbide stabilizers are also used. Least favorable is the use of stabilization annealing, which shows unpredictable reliability. Through better processing methods, carbon levels can reduced which further aids in sensitization reduction. Argon-Oxygen Decarburization (AOD) and vacuum induction melting (VIM) produce carbon levels less than 0.02% and are widely available.

Higher chromium contents improve SCC resistance, as do the addition of nickel, molybdenum, copper and silicon. For instance, alloy 94L (20Cr, 25Ni, 4.5Mo, 1.5Cu, L denoting low carbon) was originally developed for sulfuric and phosphoric acid environments, but is now widely used for many SCC applications.

High Carbon Low-Alloy Steels

The use of steel in critical SCC environments is based on the susceptibility to SCC. Low risk alloys include those made from premium melting stock and melt practices, with low levels of sulfur, phosphorous and oxides. Twinned martensite is particularly prone to SCC and heat treatments which produce this microstructure should be avoided.

Nickel-Based Alloys

As we have seen from the literature, it is best to start with a nickel alloy free from sensitization, since this is where most IGSCC occurs. To further reduce IGSCC, use of low carbon alloys is suggested, for instance alloy 201 in place of alloy 200. Carbide stabilizers such as Ti, have been introduced which are successful in slowing IGSCC as well, although total carbon reduction is a more reliable method.

GENERAL DESIGN CONSIDERATIONS

Designers should keep in mind the effects of a corrodent, which significantly reduces K_{IC} to the K_{ISCC} value. For example, the K_{ISCC} of a martensitic steel in tap water is 10 $\text{ksi}\sqrt{\text{in}}$. At yield strength, equation (2) can be applied to find the critical crack length. We find that $0.2(10/200)^2 = 0.0005$ in., an incredibly small crack! A crack such as this could easily be provided by an inclusion lying at the surface or an assembly scratch. Hence, we find that designing to the K_{ISCC} specification for crack tolerance is a crucial step.

Care must also be observed during assembly. Rough handling may cause rupture of protective coatings. Misalignment or improper fit are causes of tensile stresses which promote SCC.

K_{ISCC} is highly dependent on the yield strength of the material, decreasing sharply with increasing yield strength. For this reason, it is prudent to specify a maximum strength in addition to a minimum strength requirement. This is sound practice for dealing with brittle fracture, as well as SCC.

CONCLUSIONS

1. SCC is a ubiquitous form of attack and must be dealt with in efficient and reliable means.
2. Shot peening has improved the SCC resistance of high strength steels by the addition of a residual compressive stress zone.
3. The compressive zone is responsible for suppression of crack initiation due to the compressive surface stresses which tend to prevent oxide coatings from rupturing under tensile loads.
4. Shot peening reduces the crack propagation rate of cracks emanating from SCC pits insofar as the crack tip does not extend past the boundary of the compressive zone.
5. Shot peening has been successful in reducing the crack propagation rate of unpeened, as-pitted samples due to the compressive zone inducing crack closure.

REFERENCES

1. Brown, R.F., SCC Control Measures, National Bureau of Standards, Washington, D.C., 1977.
2. Sandoz, G., SCC in High Strength Steels and in Titanium and Aluminum Alloys, ONRL, Washington, D.C., 1972.
3. Champaigne, J., Shot Peening Intensity Measurement, Michigan, 1993.
4. Almen, J.O., U.S. Patent No. 2,350,440.
5. Baxa, M.S., et al., Effects of NaCl and Shot Peening on Corrosion Fatigue of AISI 6150 Steel, Metallurgical Transactions A, No. 9, August 1978.
6. Welsch, W., Controlling Shot Peening for Stress Relief, Heat Treating, September 1991.
7. Harrison, J., Controlling Shot Peening: Cold Working to Improve Fatigue Strength, Heat Treating, August 1987.
8. Henderson, S., et al., Stainless Steel-Its Types and Uses, The Chemical Engineer, August 1990.
9. Tsai, W.T., et al., Effects of Shot Peening On Corrosion and Stress Corrosion Cracking Behaviors of Sensitized Alloy 600 in Thiosulfate Solution, Corrosion Science, No. 50, February 1994.
10. Syrett, B.C., et al., Effect of Microstructure on Pitting and Corrosion Fatigue of 17-4 PH Turbine Blade Steel in Chloride Environments, Special Report, February 1982.
11. Pitner, P., Statistical Evaluation of the Effects of Shot Peening on Stress Corrosion of Alloy 600 in PWR Steam Generators, The Minerals, Metals & Materials Society, 1993.
12. Sandoz, G., A Comparison of Laboratory Salt Water and Flowing Natural Seawater as an Environment for Tests of Stress Corrosion Cracking Susceptability, ONRL, Washington, D.C. May 1969.
13. Keating, F.H., Symposium on Internal Stresses in Metals, London, 1944.
14. Coleman, E.G., et al., The Stress Corrosion of Metals, Wiley, New York, 1966.
15. Hoar, T.P., Proc. Roy. Soc., No. 268, 304, 1962.
16. Staehle, R.W., Fundamental Aspects of Stress Corrosion Cracking, NACA, 1969.