

IMPROVING STRESS CORROSION CRACKING LIFE OF COMPONENTS BY SHOT PEENING

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ABSTRACT

Stress corrosion cracking(SCC) is a progressive fracture mechanism in metals that is caused by the simultaneous interaction of a corrosive agent or "corrodent" and a sustained tensile stress. Structural failures due to SCC is often sudden and unpredictable, occurring after as little as a few hours of exposure, or after months or even years of satisfactory service. It is frequently encountered in the absence of any other obvious kinds of corrosive attack. Virtually all alloy systems are susceptible to SCC by a specific corrodent under a specific set of conditions.

The tensile Stresses necessary for SCC are "static" and they may be residual and/or applied Progressive cracking due to "cyclic" stresses in a corrosive environment is termed "corrosion fatigue". The boundary between SCC and corrosion fatigue is sometimes vague; nevertheless, because the environments that cause them are not the same, the two are treated as separate and distinct metal fracture mechanisms. Compressive residual stresses, such as those induced in the surface layers of a structure by controlled shot peening is often used to prevent or delay both phenomena.

It will be presented in this paper the mechanisms of SCC, some Environment-Alloy combinations known to result in SCC, the evaluation of shot peening effects on SCC and varius applications in the industry.

MECHANISMS OF SCC

SCC is a complex phenomom and the basic fracture mechanisms are still not completely understood. Adding to the complexity is the fact that crack initiation and crack growth are related but different processes. No single mechanism has adequately explained SCC in the large variety of materials in which it has been observed. It is likely that more than one process is involved. Ignoring many of the complexities, the proposed mechanism can be broadly classified as either anodic or cathodic. The most obvious anodic mechanism involves hydrogen evolution, absorption, diffusion and embrittlement.

Most metals have thin, passive oxide film which forms on the surface during exposure to the environment. This film, if unbroken, protects the underlying metal. When the passive film is ruptured by chemical attack or mechanical action, a clean, unoxidized active metal surface is exposed. There is an electrochemical potential difference between the newly exposed, active metal surface (anode) and the passive film (cathode). A small electrical current is generated between the anodic metal and the cathodic film.

The relatively small area of the active, anodic new metal surface, compared to the larger surface area of the surrounding cathodic passive film result in an unfavorable anode-to cathode ratio. This cause a high local current density and induces high metal dissolution (anodic dissolution) at the anode. The fresh metal surface actually acts as a sacrificial anode in a galvanic couple, protecting the adjacent film from attack. If the fresh metal surface can form a new passive film (become repassivated) faster than a new, fresh metal surface is created by film rupture, the attack will stop. If however, the repassivation process is suppressed, as is the case in the presence of certain ions like chlorides, or if the repassivated film is continuously ruptured by strain, as when the materials reacts to tensile stresses, the localized attack proceeds. The result is the formation of crack like crevice, and an increase in the concentration of hydrogen with an accompanying decrease in the pH of the solution, within the crevice. The hydrogen ions result from a chemical reaction between the exposed fresh metal and the water within the cavity. The hydrogen ions are reduced by picking up electrons from the environment resulting in the formation of hydrogen gas, which diffuses into the metal. Reduction of hydrogen is generally a "cathodic reaction."

CATHODIC MECHANISM

In some materials the absorbtion of hydrogen produces localized cracking due to a hydrogen embrittlement mechanism. The fresh metal exposed at the crack tip, as the crack propagates by virtues of hydrogen embrittlement and applied stresses, is anodic to to the oxidized sides of the crack and the adjacent surface. Because of this, the electrochemical attack continues, as does the evolution and absorption of more hydrogen. A triaxial state of stress and high stress concentration at the crack tip enhance hydrogen embrittlement and provide a driving force for crack propagation. Hydrogen-induced crack growth (cathodic mechanism) has been suggested as the dominant SCC mechanism for ferritic steels, nickel base alloys, titanium alloys, and aluminium alloys. The ferritic steels, however, show the most evidence of this mechanism.

ANODIC MECHANISM

In materials that are insensitive to hydrogen embrittlement, SCC can proceed by the anodic dissolution process with no assistance from hydrogen. Alloys are not homogeneous and when differences in chemical composition or variations in internal strain occur, electrochemical potential differences arise between various areas within the microstructure. As an example, grain boundaries are usual anodic to the materials within the grains and are, therefore, subject to preferential anodic dissolution. Inclusions and precipitates can exhibit potential differences with respect to the surrounding matrix, as can strained and unstrained regions within the material. These anode cathode coupling can initiate and propagated dissolution cracks or fissures regard to hydrogen.

Anodic SCC has been suggested as the dominant mechanism for copper alloy, monel and for intergranular SCC of some austenitic stainless steels.

Of primary importance is the fact that inducement of residual compressive stresses in the surface of the metal, due to shot peening, can be an effective measure for preventing SCC, regardless of the dominant SCC mechanism, the material of construction, or the corrosive environment. This is illustrated in figure 1, the "SCC triangle". If any leg of the triangle is broken, such as the absence of surface tensile stress due to shot peening, SCC will not occur.

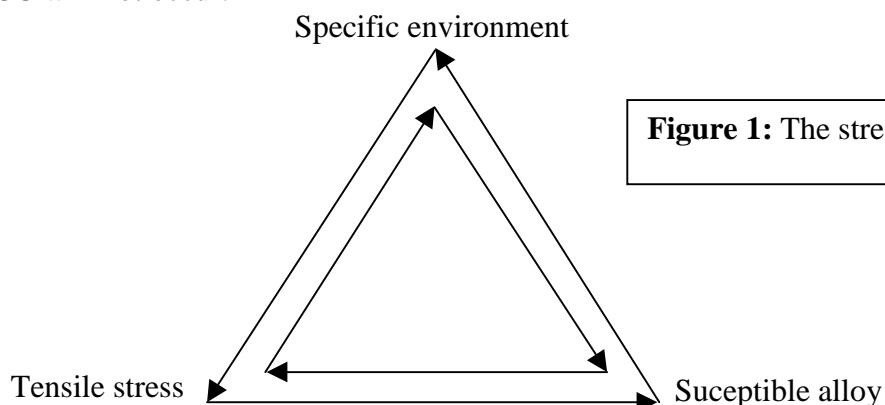


Figure 1: The stress corrosion triangle

SUSCEPTIBLE ALLOY SYSTEM/ CORRODENT COMBINATIONS

SCC was first recognized in the last half of the 19th century when spontaneous cracks appeared in the thin walled necks of brass cartridge cases used during the Indian campaigns of the British Army. Because the problem generally occurred during the monsoon season, it was termed "season cracking". Traces of ammonia in the air, high temperature and high humidity acting in concert with the tensile hoop stresses in the cartridge case neck incurred when the bullet was inserted, was responsible for the SCC.

In the years since this discovery, the number of alloy system and corrodent combinations that have been recognized as susceptible to SCC has been continually expanded. It is safe to say that possibilities are virtually limitless. The National Association of Corrosion Engineers, the Materials Technology Institute of the Chemical Process Industries, as well as other organizations have published list of corrodents known to cause SCC in various alloy systems. Table 1 is a condensed summary of such lists. While valuable, it should not be viewed as a complete or exhaustive compilation.

Table 1: Some environment-alloy combination known to result in SCC [1]

Environment	Alloy system								
	Aluminum alloy	Carbon steel	Copper alloy	Nickel alloy	Stainless steel			Titanium alloy	Zirconium
					austenitic	duplex	martensitic		
Amines, aqueous	...	λ	λ	...	...	...	...	...	...
Ammonia, anhydrous	...	λ	λ	...	...	...	...	...	...
Ammonia, aqueous	...	λ	...	...	...	...	...	...	...
Bromine	λ
Carbonates, aqueous	...	λ	...	...	...	...	...	...	...
CO/CO ₂ /water mixture	...	λ	...	...	...	...	...	...	...
Chloride aqueous	λ	...	...	λ	λ	λ	...	...	λ
Chloride, concentrated, boiling	λ	λ	λ	...	...	...
Chloride, dry, hot	λ	...	...	...	λ	...
Chlorinated solvents	λ	λ
Cyanides, aqueous, acidified	...	λ	...	...	...	...	...	...	...
Fluorides, aqueous	λ	...	...	...	...	...
Hydrochloric acid	λ	...
Hydrofluoric acid	λ	...	...	...	...	...
Hydroxides, aqueous	...	λ	...	...	λ	λ	λ	...	...
Hydroxydes, concentrated, hot	λ	λ	λ	λ	...	...
Methanol plus halides	λ	λ
Nitrates, aqueous	...	λ	λ	...	...	...	λ	...	...
Nitric acid, concentrated	λ
Nitric acid, fuming	λ	...
Nitrite, aqueous	λ	...	...	...	...	...	...
Nitrogen tetroxide	λ	...
Polythionic acids	λ	λ	...	...	...	...
Steam	λ	...	...	...	...	...	...
Sulfides plus chlorides, aqueous	λ	λ	λ	...	...
Sulfurous acid	λ	...	...	...	...
Water, high purity, hot	λ	...	...	λ	...	...	...	...	...

SHOT PEENING PROCESS

Shot peening is a cold working process that uses millions of tiny spheres of steel, glass or ceramic. Usual diameters are from 0,1 mm to 3 mm. These spheres can be propelled up to 120m/s onto the surfaces of metal parts. The process is used in a great variety of industries including aerospace, automobile, heavy equipment, power generation, petrochemical, and aircraft.

Each particle striking the material acts as a tiny peening hammer, imparting a small indentation or dimple onto the surface. For the dimple to form, the tension of the surface fibers of the material must be yield. Below the dimple's surface, the fibers try to restore the surface to its original shape, thereby producing a hemisphere of cold-worked material highly stressed in compression (figure 2).

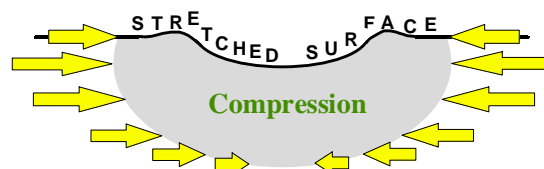


Figure 2

Overlapping dimples develop a uniform layer of residual compressive stress in the metal. Cracks will not initiate or propagate in a compressively stressed zone. Since nearly all fatigue and stress corrosion failures originate at the surface of the part, compressive stresses induced by shot peening provide considerable increases in part life. The maximum compressive residual stress produced at or under the surface of the part by shot peening is at least as great as one half the yield strength of the material being peened. Many materials will also increase in surface hardness due to the cold working effect of shot peening.

The residual compressive stresses introduced by shot peening have a major benefit not only upon metal fatigue, but also upon all the tensile stress related modes of failure, such as stress corrosion cracking, corrosion fatigue, thermal fatigue, and fretting fatigue. To these can be added the purely mechanical effects of a peened surface that can reduce galling, improve lubricity, close porosity, increase sealing properties, and even form parts or correct their shape.

The following photos (figure 3; 4) illustrate the effectiveness of controlled shot peening in preventing SCC in simple U-bend test samples of type 304 austenitic stainless steel exposed to a severe laboratory producing SCC environment (Boiling 42% $MgCl_2$).

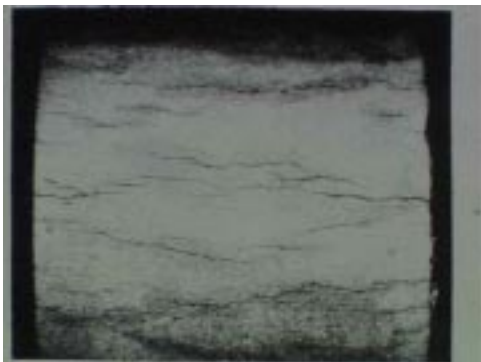


Figure 3: Unpeened sample after 2 hours



Figure 4: Peened sample after 1000 hours

It should also be stressed that shot peening is not "shot or grit blasting" neither "sand blasting" which are processes used to remove deposits or mill scale from surfaces. The applications for shot peening are much more demanding and require a process that is predictable, uniform and repeatable. While controlled shot peening is considered a mature process, it continues to evolve and gain ever increasing acceptance.

SELECT SHOT PEENING PARAMETERS

It remains the responsibility of the peening specialist to select the type, hardness and size of shot. The specialist should also ensure that the part drawing, or a sketch of a part requiring shot peening includes the following:

- Area to be peened.
- Area to be masked.
- Optional peening areas.
- Areas where peening fades out, if any.
- Shot size hardness and material.
- Location for intensity verification and intensity range at each location.
- Coverage requirements for all area to be peened, including the method to be used for verifying coverage.
- Applicable shot peening specification.

Optimization of the shot peening process requires careful selection of the basic parameters. These include the composition, hardness and size of the peening media, the transferred energy at impact (which control the depth of the compressive layer), and the percentage of coverage. The many possible combinations of

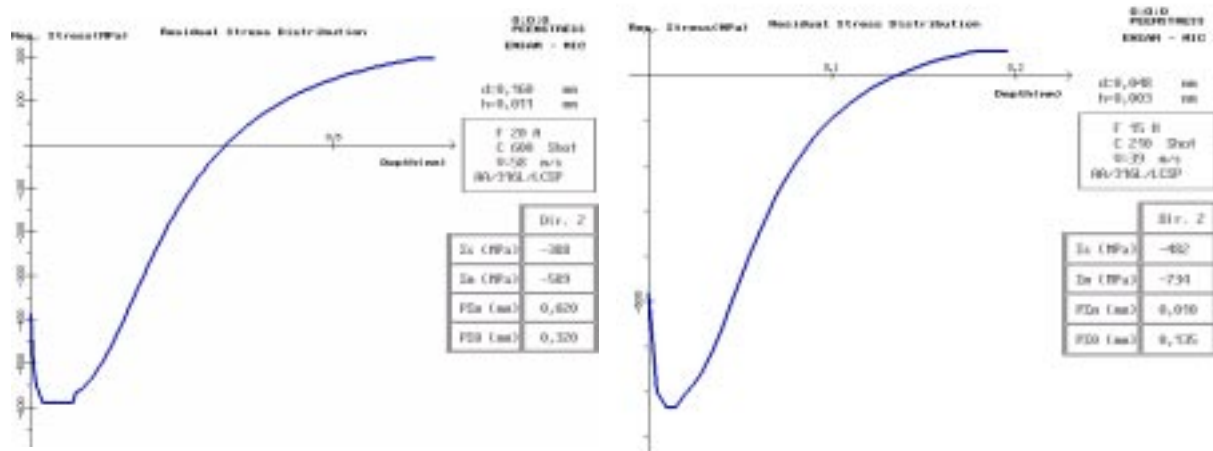
these factors make the correct choice difficult. Given the potential for premature failure, it is of the utmost importance that the first selection should be the best.

For this reason, Metal Improvement Company (MIC), in collaboration with ENSAM, a french advanced engineering school, developed PeenstressSM, a computer program capable of predicting the residual stresses that are introduced by controlled shot peening.

The peenstress program works with most of the engineering metal: mild and high strength steel, stainless steel, carburized carbonitrited steels, aluminium alloys, titanium and nickel alloys.

The program calculates the elastic deformation caused during peening of the selected material using material behavior laws. Then we select a similar geometry of the component to be peened and we can get a modelization of the residual stress.

Figure 5: Optimization of shot peening parameters on an AISI 316L; thickness: 2 mm.



First modelization: Note the pick of tensile stress (+200 Mpa) below the residual compressive stress which create a reduced maximum compressive stress (-589 Mpa).

Second modelization: The pick of tensile stress is reduced to +70 Mpa only which increase the maximum compressive stress to -734 Mpa.

SOME APPLICATIONS RELATED TO STRESS CORROSION CRACKING

The following study[2] was done to define the best economical and technical solution to manufacture a 5000 liters storage tank with various austenitic stainless steel.

The specimen were exposed to 42% MgCl₂ solution at a constant temperature of 145°C.

Material		Load			
		50%	70%	80%	90%
1.4541 X6CrNiTi18.10	Not peened	11 h	5 h	-	3,2
	Shot peened	-	>1000 h	-	>1000 h
1.4571 X6CrNiMoTi17.12.2	Not peened	17 h	11,3	-	7,5
	Shot peened	-	>1000 h	-	>1000 h
1.4462 X2CrNiMoN22.5.3	Not peened	5,3 h	3,3 h	-	1,3 h
	Shot peened	-	>1000 h	>1000 h	5,3 h
1.4529 X1NiCrMoCuN25.20.7	Not peened	-	500 h	-	37 h

Material	Cost evaluation for a 5000 liter storage tank	
1.4541 X6CrNiTi18.10	With shot peening	48 000 Euro
1.4571 X6CrNiMoTi17.12.2	With shot peening	50 000 Euro
1.4462 X2CrNiMoN22.5.3	Without shot peening	75 000 Euro
1.4529 X1NiCrMoCuN25.20.7	Without shot peening	90 000 Euro

SCC has been experienced in almost every industry including aerospace, chemical processing, pulp and paper, brewery, pharmaceutical, petroleum, petrochemical, power generation and electronics. No product is necessarily immune to SCC including, fasteners, aircraft structures, engine components, piping, boilers, reaction vessels and storage tank.

The following is a brief listing, by industry, of some of the major structures in which SCC has been documented. Controlled shot peening has been effectively utilized to control SCC in most if not all of these industries and material/corrosive combinations.

Aircraft: Aluminium airframe structures made from high strength 2xxx and 7xxx series alloy.
Landing gear components and fasteners made from ultra- high strength steels such as 300M and H11.

Tubing and fittings made from precipitation hardening steels such as AM350 and 17-4PH.

Chemical: Process vessels, storage tanks and piping made from austenitic stainless steels such as type 304, 316, 321 and 347.

Anhydrous ammonia storage vessels and spheres made from carbon and low alloy steels, as well as railroad tankcars used for transportation of anhydrous ammonia.

Zirconium-lined pressure vessels.

Copper-silicon alloy tanks for sulfuric acid.

Petroleum and petrochemical: Sulfide SCC in drill pipe and casing made from carbon steels.

Caustic SCC in carbon steel heat exchangers and vessels.

Chloride SCC in refining units made from type 300 series stainless steel.

Aqueous ammonia SCC in admiralty metal (copper-zinc alloy) heat exchanger tubes.

Nuclear power plants: Intergranular SCC in inconel alloy X-750(nickel base alloy) jet pump beams.

Outside and inside diameter SCC in inconel 600 steam generator tubing.

SCC in low pressure steam turbine rotors made from chrome-moly-vanadium steels.

Fossil fuel power plants: Steam and water side SCC in brass condenser units.

SCC of austenitic stainless steel superheater and reheater tubing and ferritic steel reheater tubing.

SCC of gas turbine compressor blading made from martensitic stainless steels.

Consumer products: Ammonia SCC of flexible, corrugated connectors for natural and LP gas appliances made from cartridge or admiralty brass.

REFERENCES

1 Metals Handbook, 9th ed., Volume 13.

2 Effect of shot peening on stress corrosion cracking on autenitic stainless steel; J. Kritzler