Shot Peening of Metals for Protection Against Stress Corrosion Cracking*  

By HENRY SUSS*  

Abstract  
Shot peening, when properly incorporated into a specific product design and effected by a properly designed and controlled process, will protect hardened (RC36-42) AISI 410 stainless steel from stress corrosion failure in high purity waters. This protection occurs at temperatures up to 300°F for a useful finite period at stresses up to 60,000 psi, and indefinitely at stresses up to approximately 45,000 psi, about one-third of the yield strength. Before shot peening is used for protection against stress corrosion attack, consideration must be given to the effects of the environment, anticipated stresses, and temperature of application on the fadeout of the surface residual layer. For most applications there should not be any problem in establishing adequate process and quality control procedures. The basic data developed on shot peening of AISI 410 could be made applicable to other susceptible alloys as means for protection against stress corrosion attack.  
5.9.3, 3.5.8, 6.2.3, 46.5  

Introduction  
AISI 410 TEMPERED to a hardness of RC 36-42 is susceptible to stress corrosion failure on exposure to high temperature, high purity waters at 300°F. One way to eliminate the probability of stress corrosion cracking is to impose a compressive layer on the surface to counteract any applied or residual tensile stresses. Materials will not be subject to stress corrosion failure in the absence of applied or surface residual tensile stresses. A compressive layer can be applied to a surface by surface rolling or shot peening.  
For an intended application to a thin walled (0.125-inch) round cylinder (cross section shown in Figure 1) with approximately a 4-inch ID, shot peening appeared to be the more practical method. Studies were therefore initiated on the value of and problems associated with shot peening for protection of hardened (RC 36-42) AISI 410 to stress corrosion cracking. The data reported apply to the specific problem. This information, even though specific for AISI 410, can be made applicable for protection of any other alloy or metal susceptible to stress corrosion cracking.  

Shot Peening Process  
Shot peening is a process of propelling, by a centrifugal impeller or by an air blast, a uniformly round (0.007-inch to 0.065-inch diameter) shot at a controlled uniform velocity against the surface of a part. This produces a compressive residual layer on the surface. The extent of this layer depends on the intensity of the process. The nature and depth of the residual surface stresses will be discussed later in this report.  
Shot peening for most applications is performed in conformance with the requirements of Military Specification MIL-S-13165A. The acceptance of the shot peening process has been aided by the use of standard specifications for shot and for the means of controlling the intensities of the shot stream. The shot specification covers materials, shape, and size. The specifications for intensities are based on measurement of the residual stress effects on a standard sample “Almen Strip.”  
The intensity is usually specified as a range such as 0.017 to 0.021-A.2. This means that a standard Type A Almen Strip, attached to a backup fixture and exposed to the shot stream in exactly the same manner as the work piece, will, when removed from the fixture, curve convexly toward the peened side. The curvature as measured by a standard gauge referenced in MIL-C-13165A must show an arc height between 0.017-inch and 0.021-inch.  
The intensity reading for a given situation depends on the time the surface is exposed to the stream of shot propelled at a constant pressure. Initially the arc height increases in proportion to the time exposed and will then reach a maximum value. A typical curve is shown in Figure 2. A specified intensity always implies that which is achieved at saturation (point X Figure 2). The minimum time to reach this saturation point is often referred to as time for 100 percent visual coverage.  

Shot Peening for Protection Against Stress Corrosion  
In a program at KAPL, to evaluate the effect of shot peening to protect hardened AISI 410 against stress corrosion cracking, 14 specimens that had been shot peened at 0.007-inch and 0.017-inch intensities with 0.025-inch nominal shot were exposed to 300°F air-saturated water with an applied stress of 60,000 psi. The test sample and holder are shown in Figure 3 and the variations in the chemistry of the air-saturated water with time are plotted in Figures 4 and 5. None of the shot-peened samples showed any failures after 8 weeks’ exposure, while the same material without shot peening exposed under the same conditions failed in one week or less. Figures 6 and 7 are typical microphotographs of the exposed shot-peened samples. The surface condition in these samples was similar to surface as-shot-peened prior to the exposure.  

1. Effect of shot peening on the structural reliability of the material.  
2. Extent of surface residual compressive and sub-surface residual tensile stresses.  
3. Effect of such factors as static and cyclic stresses, and temperature on the compressive residual stresses.  
4. Required shot size and peening intensity to produce the desired surface compressive layer.  
5. Quality control procedure to ensure adequate (at least 100 percent) surface coverage.  

Effect of Cyclic Applied Stresses  
A study of the effect of cyclic stresses on the surface residual layer was deemed advisable. Under certain operating conditions, the part of interest could be subject to a low degree and number of cyclic stresses.  
Data reported by H. F. Moore and H. O. Fuchs and E. R. Hutchinson and later substantiated by studies made by R. P. Felger indicated:  
1. Shot peening improves the high cycle fatigue strength of service parts. The shot peening could partially remove the effects of poor surface finish and residual stresses (factors which also accelerate stress corrosion failure) on the surface of the part, or set up beneficial

It is beyond the scope of this report to discuss bases for these efforts and relative effects of shot peening on improving the fatigue strength of material. These are adequately covered by H. F. Felgar.  

Effect of Exposure to Elevated Temperatures  
The residual stresses from shot peening can be erased by exposures to elevated temperature. For ordinary spring steels, temperatures under 500 F have no effect; at 550 F and higher the residual stresses are partially relieved until they are almost completely erased at 800 F. For Inconel and stainless steels, the compressive stresses start to be relieved at about 1050 or 1100 F. It is very probable that the effect of heat on fadeout of residual stresses could be related to the effect of exposure of operating temperature on the creep or long time dynamic yield strength of the material.

Surface and Subsurface Residual Stresses  
Shot peening of a surface tends to cause the top layer to spread, but the rigidity of the metal underneath prevents this spread from occurring. As a result, flat specimens will curve convexly toward the peened side. Cylinders peened on inside or outside diameters will show dimensional changes (growth). The extent of the curvature or growth is dependent on the intensity of the peening operation.

The as-peened surface will be in compression with a balancing layer underneath in tension. Brodrick has performed many studies on the stress distribution of shot-peened AISI 4340 (of comparable hardness to the AISI 410 of interest) as a function of depth below the surface. A typical curve is shown in Figure 8. It shows the same general shape regardless of the peening treatment. The magnitudes and relative depths increase with increasing peening intensities. Although high compressive stresses can be produced on the surface, the maximum subsurface tensile stress is appreciably lower. This is of significance for applications on use of shot peening for protection against stress corrosion failure.

In addition, Brodrick’s studies indicated that the degree of induced compressive stress is dependent on the tensile strength of the base material. Softer specimens (125,000 psi tensile strength) showed compressive stresses equivalent to the yield strength whereas harder materials (250,000 psi tensile strength) showed average compressive stresses of about 60 percent of the yield strength.

Establishing Peening Shot Size and Intensity  
The shot size and intensity specified must be able to produce an adequate compressive surface layer for intended service and at the same time should not:

1. Significantly affect the surface finish.
2. Cause significant distortion beyond allowable dimensional tolerances.
3. Cause shot to be so imbedded in the surface of the base metal to an extent that it cannot be removed practically by vapor blasting.

In order to produce a compressive layer at the desired level, and at the same time keep subsurface residual stresses at a safe minimum, it was calculated (on the assumption that the trapped residual stresses would be equivalent to 60 percent of the yield strength) that the growth of the part should be within 0.5 to 1.0 mils for the part of interest (preferably on the higher side of this range). The numbers can vary depending on the diameter and shape of the part.

Process procedures to develop specific trapped surface residual compressive stresses for AISI 4340 were reported by Brodrick. The shot peening conditions which produced the desired surface stresses in AISI 4340 of comparable hardness to AISI 410 of interest, were investigated initially. These specific shot sizes and intensities did not develop the required surface stresses or finish on the AISI 410 part of interest.

Re-evaluation of shot size and peening intensities was required. Final evaluation had to be based on exposure of actual production parts to various shot sizes and peening intensities followed by detailed dimensional inspection of critical areas. These tests seemed to indicate that use of smaller size shot sprayed to produce maximum or close to maximum practical intensity gave the desired results as to surface finish and controlled dimensional growth (controlled trapped compressive stresses).

Regardless of the care exercised in the handling and preparation of the shot, and in controls during the actual peening, it was not possible to prevent the shot from being imbedded. After being imbedded, the shot could not be removed by vapor blasting. Some shot was imbedded early during the operation. Subsequent peening caused surface metal to "flow" over the shot, thus anchoring the particles. Tests in high temperature hydro-ammoniated water (300 F) indicated that these imbedded particles did not create any corrosion problem.

Process and Quality Control  
Since the shot peening process is to be used for corrosion protection, a minimum of 100 percent coverage was deemed essential. The problem of inspection for 100 percent coverage, especially for inside walls, was not as easy as anticipated. Initially it was felt that experienced inspector could make adequate visual examination supplemented by inspection of inside diameter with aid of a 10 to 20X boroscope and tape film replicas of critical inside diameters.

Studies showed that no difficulties would be encountered on visual examination with or without aid of the boroscope (depending, of course, on the diameter of the parts). There should be no problems in training personnel. However, the use of fax film to produce replicas of internal surfaces did provide many difficulties such as:

1. Procurement of material
2. Subsequent studies (not conclusive) indicated that adequate protection is possible with 80 to 90 percent coverage. More studies are required.

---

Figure 1—This valved round cylinder subjected to shot peening.
2. Adequate adherence
3. Inclusion of gas bubbles

After several preliminary attempts with fax film, it was decided to drop this method of inspection.

After additional studies and review of the data, it was decided that the following process and quality control procedure should prove satisfactory to obtain desired results:

A. Process Procedure

1. All peening is to be carried out as specified in MIL-S-13165A with modifications listed below.

2. Shot is to be of cast steel, peening grade. The shot shall be pre-used or "conditioned" sufficiently to insure that all shot is roughly spherical and that irregular shapes which could imbed in the surface are removed or smoothed. Broken shot shall not exceed approximately half of the limits given in MIL-S-13165A. All shot shall be carefully screened and air-washed prior to shot peening each part.

3. The part is to be peened only in areas specifically requested. Complete protective masking is to be securely applied in all other areas so as to prevent any possibility of loosening during blasting. When tape is used, at least three layers must be applied to prevent any peening through to surfaces underneath, particularly on large diameter V threads. The intermediate layer of tape shall be of a contrasting color to the first and third layers to insure complete covering of each layer. This requirement shall apply also to threads which must be masked off during other peening operations. Blind areas, such as small holes or crevices in the part, are to be plugged or covered with tape which will not leave a residue in the vicinity of the area which could require extensive solvent cleaning.

4. All peening operations shall be set up for automatic uniform cycling (rolls, turntables, nozzle movement) to insure that coverage will be uniform over all areas, and to insure that nozzles are placed at the optimum angle. Nozzle movement shall be adjusted so that there are no dwells at the end of movement within the length specified to be peened so as to reduce the possibilities of local excess peening. No overlapping of sprays is allowable.

5. Both surfaces can be peened simultaneously. If equipment available allows peening operations on one surface only, the final peening operation should be performed on that surface requiring the highest residual stresses.

B. Quality Control

Based on the studies, the following quality control procedure was established:
1. Standard Almen Strip is mounted and tested in accordance with the requirements in MIL-S-13165A. The amount of deflection versus time is plotted to establish saturation arc height.

2. The peening time is to be set at twice the time determined to peen to the saturation arc height. Exposure to twice the time should indicate the same (± 0.001-inch) Almen intensity as in "1" above. This is equivalent to 200 percent coverage.

3. This latter time must be used for peening of all production parts. The operation must be performed in conjunction with a standard Almen strip. Since this strip is generally mounted at the end of the part, the nozzle stroke must be so adjusted that the nozzle does not dwell or reverse direction over the standard Almen strip. This Almen strip must also indicate the same intensity (± 0.001) as in "1" above.

4. In all areas, peening coverage shall be visually inspected by a qualified person with the aid of a 3 to 5X magnifying glass or boroscope, and shall be certified as being complete to saturation.

5. Recalibration steps 1 and 2 are required at each startup, at each change
in section being shot peened, and for each change in shot or after each 8 hours of operation.

Discussion
Based on the above data, it was decided that:
1. Since the cyclic and static stresses on parts of interest were less than one-third of the yield strength, it was felt that the conditions of operation, including 500°F and possibly as high as 850°F maximum temperature should not cause any fadeout of residual stresses in the part of interest.
2. Shot peening should not have any deleterious effects on the base metal.
3. Shot peening should offer at least temporary if not indefinite protection to hardened (RC 36-42) AISI 410 against stress corrosion failure.
4. There should be no problem in obtaining the desired surface conditions by shot peening, in following required process control procedures, and in providing adequate inspection to ensure at least 100 percent coverage. At present, actual shot-peened production parts have been exposed to conditions of end use. Data so far are very encouraging but not adequate for any detailed discussions or comments.
5. Shot peening can be used as a means of protection of other susceptible alloys against stress corrosion failure, provided that conditions of end use, anticipated stresses, and temperature will not cause fadeout or loss of the surface residual layer.

Acknowledgment
The writer wishes to acknowledge the efforts of the personnel at KAPL, especially Messrs. G. E. Galonian and H. M. Tymchyn for performance of the corrosion tests, F. M. Schmitt for the engineering analyses, and J. D. Dunbar for many constructive comments.

In addition, much of the studies and work would have been not possible without the assistance and advice received from Mr. H. Bumey and his associates at Metal Improvement Co., Hackensack, New Jersey.

References
1. H. Suss, Susceptibility of AISI 410 to Stress Corrosion Cracking in High Temperature High Purity Water, NACE Publication 60-13, Houston 2, Texas.
3. Private reports and correspondences.

DISCUSSION

Question by David H. Thompson, Anaconda American Brass Co., Waterbury, Connecticut:

Why should the water become more acid with time? What are the factors that favor stress corrosion cracking under these conditions?

Reply by Henry Suss:

Under certain reactor conditions, radiolytic decomposition can promote formation of nitric acid. At this time, the pH of the solution could drop to as low as 5.5. This solution is more corrosive to hardened 410 with a resultant increase in extent and decrease in time for stress corrosion cracking.

Questions by Warren E. Berry, Battelle Memorial Institute, 505 King Avenue, Columbus 1, Ohio:

1. In your first slide you did not include environmental temperature as a factor which affects susceptibility to stress-corrosion cracking. Have you investigated the effects of water temperature?
2. Does corrosion-produced hydrogen cause embrittlement of the 410 stainless steel?

Reply by Henry Suss:

1. The effect of water temperature (300 and 600°F) on stress corrosion properties of AISI 410 (tempered at 650°F to RC 36-42) was studied to a very limited degree only. The results did seem to indicate:
   (a) No temperature effects of significance in hydrogen-ammoniated water, (pH 8.5-9.5).
   (b) In low (0.5 to 2 ppm) oxygen containing waters, there was considerably less to no stress corrosion failure on exposure in 600°F water, as compared to almost 100 percent failures at 300°F.

Questions by Edward B. Evans, Case Institute of Technology, Cleveland 6, Ohio:

1. Did you detect any hardness increase as a result of shot peening?
2. Is the introduction of compressive stress due to plastic deformation of martensite or to transformation of retained austenite?

Reply by Henry Suss:

1. Surface hardness readings were not taken before or after shot peening. Since the process involves cold working, an increase in surface hardness should be anticipated.
2. Shot peening produces a surface compressive layer by cold working the surface. The process does not alter the metallurgical structure of the material.