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SURFACE STRESS MODIFICATION FOR REPAIR OF STRESS-RELIEVED CARBON STEEL FABRICATIONS

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ABSTRACT

Pitting corrosion was observed in welded carbon steel tanks which had been stress relieved to improve resistance to stress corrosion cracking. Successful repair required the development of a cleaning and repair method which would not increase residual tensile stresses at the steel surface. An experimental study indicated that uniform residual tensile stresses of 27.6 - 34.5 megapascals (4,000-5,000 psi) remained in the plate after the original stress relief. Grinding, shot peening, and grit blasting were evaluated. In laboratory tests, metal grit blasting changed the average residual stresses at the surface to 34.5 - 69 megapascals (5,000-10,000 psi) compressive. Moreover, the depth of the compressive zone was substantial - perhaps 138 megapascals (20,000 psi) at 0.25 mm (0.010 inch). This is beneficial and will contribute to an increase in resistance to stress corrosion cracking. The repair technique employed on the tanks consisted of blast cleaning the entire surface to a uniform Class II finish with minimum change in the configuration of the pits.

STRESS CORROSION CRACKING (SCC) near butt welds in large diameter carbon steel waste tanks used for storage of alkaline nitrate solutions occurred largely as a result of residual stresses.[1-3] This led to a requirement for in situ stress relief of all future tanks.

A uniform heat treatment can be applied only to new tanks. Following their fabrication, the tanks are heat treated by raising the temperature to 1,100°F, as required for stress relief. Following this in situ field heat treatment, the tanks are encased in concrete, precluding general reheating for stress relief purposes.

The heat treatment effectively relieves welding stresses and reduces long range reaction stresses sufficiently to prevent SCC in the solutions of interest.[3] Any additional work on or in the tanks subsequent to the stress relief is monitored closely to ensure that no long-term, localized stresses are produced. For example, work inside the 85-foot-diameter tank proceeds only after the vessel floor is protected from weld splatter and the possibility of mechanical damage.

In one case, the tank bottom was covered with 1/2-inch plywood sheeting during this period. The floor and plywood were often wet and after several months pitting was noted in the floor plates. Some pits were about 1/8-inch deep (25% of the wall thickness). A program to clean, characterize pit size and distribution, and develop a repair method was initiated.

The cleaning procedure consisted of metal grit blasting of the bottom surfaces. This was followed by examination of the pits. Blasting will remove scale, etc., and impart residual stress to the previously stress-relieved tank.[4] These stresses are additive to the working stresses and need to be considered in the overall stress analysis of the vessels.[5] In addition, complications can be expected at locations where repairs to the tank surfaces are made subsequent to the stress relief heat treatment and/or the blast cleaning. The levels of stressing and the possibilities for modifying and controlling the stress by additional surface treatments were unknown. To answer the questions about stress levels and to develop an acceptable post-heat-treatment repair technique for use in the stress-relieved structures, a study of residual stresses commenced.

EXPERIMENTAL

The blind hole drilling method[6] was applied to laboratory samples in order to determine the residual stresses which exist after the various treatments. The method uses strain gages and is semidestructive, requiring drilling of a small shallow hole. This precludes its application directly in the tank. On the other hand, the method is applicable to nearly any surface and may be used wherever a strain gage rosette pattern can be attached and a hole can be drilled with precision.

Data were taken at 0.005-inch increments of metal removal. The depth of stress and the stress profile were determined by repeated application of the basic equations.[6] The subsurface stress distribution was determined because it was believed that this could be even more important than the surface stress.

The bulk of the samples were 10 inch x 10 inch plates, large enough to prevent planar relaxation in the samples for the particular situations being evaluated. A rectangular rosette strain gage pattern was used (Figure 1). Both smooth plate and artificially pitted plates (predrilled 1/8-inch holes, 1/8-inch deep) were studied. Most of the samples were made form 1/2-inch A-537 Class I carbon steel plate as used in tank fabrication. Heat treatment, grinding, shot peening, and grit blasting variations were evaluated.

The heat treatment employed was the same as used in the field - uniform heating and cooling at 100°F/hour to 1,100°F with a 1-hour hold at the higher temperature. Type C Almen intensity strips[7] were used to establish control and reliability for blasting in both the field and laboratory.

RESULTS AND DISCUSSION

AS-FABRICATED STRESS VALUES - Application of the drilling method on samples of the as-received steel plate indicated an average surface tensile stress of 5,500 psi (Table 1), with a subsurface stress distribution as shown in Figure 2. This is a typical distribution, as all samples which had undergone some form of working exhibited a peak stress beneath the surface substantially greater than that on the surface. The sample plate had been formed by cross-rolling at the mill.

Stress remaining in the plate after the stress relief heat treatment is also shown in Figure 2. The surface stress is only slightly less than that before heat treating. However, a significant reduction of stress beneath the surface occurs, resulting in the establishment of a nearly uniform distribution of less than 4,500 psi.

The anticipated residual stress is approximately 7,000 psi for 50,000 psi yield strength steel, given the prescribed heat treatment.[8]

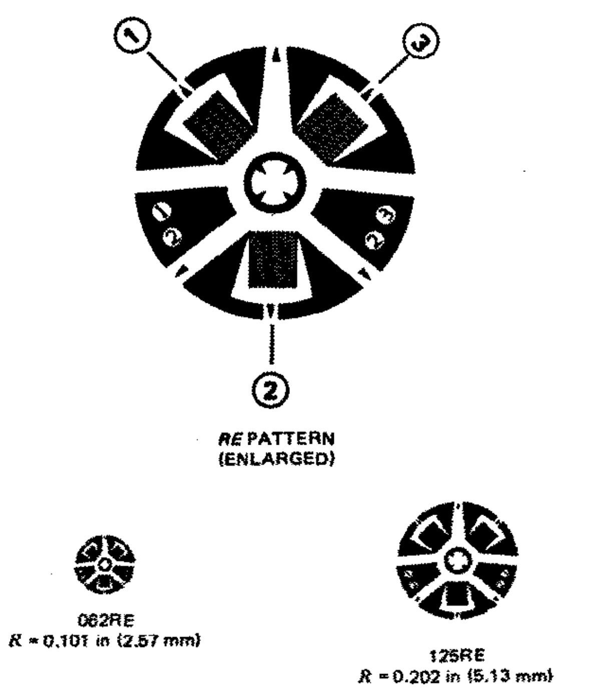

Fig. 1. Micro-measurements RE-pattern strain gage rosette for residual stress measurement (used in the present study)

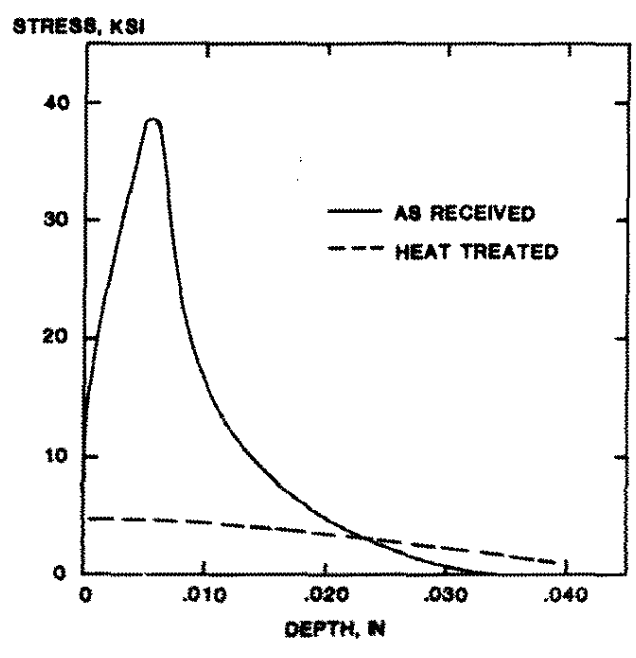

Fig. 2. Measured stress distribution in normalized and rolled ASTM A537 Class I steel plate before and after stress relief heat treatment

Jenkins

Table 1 - Residual Stresses in A537, Class 1 Carbon Steel Plate

Description	Average Surface Stress (psi)	Range of Maximum Stress, inches	Maximum Average Stress (psi)
As-Received	+5500	0.006	+38,000
Stress-Relieved	+4700	-	-
Class II Finish, Grit Blast	-1200	0.002 - 0.006	-53,000
Class I Finish, Grit Blast	-8000	0.002 - 0.006	-53,000
Class II Finish + Shot Peen	-10,000	0.002 - 0.006	-53,000
Abusively Ground	+19,000 to 29,000	0.002 - 0.010	+53,000
Abusive and Starr Blast	-5000 to +9000	0.002 - 0.006	-40,000 to -53,000
Abusive and Shot Peen	-5000	0.002 - 0.010	-53,000
Wet Grind (Nonabusive)	-2000 to +5000	0.005 - 0.006	+10,000 to +28,000
Wet Grind and Starr Blast	0 to -1000	0.002 - 0.005	-44,000
Wet Grind and Metal Grit Blast	-19,000	0.002 - 0.010	-53,000
Wet Grind and Shot Peen	-15,000 to -19,000	0.002 - 0.010	-53,000
Stone Grind/Spray Cool	+15,000	0.010	+38,000
Stone Grind + Shot Peen	-15,000	0.005	-53,000

Notes:
- Steel Grit: GL-40, 45-55 R_c
- Shot: Grade 230, 45-55 R_c; Blast: 200% Coverage
- Starr Blast: Silica-Zirconia Powder

STRESSES AND APPEARANCE AFTER GENERAL CLEANING - Effects of grit blasting are shown in Table 1 and Figure 3. The samples were prepared during actual cleaning operations and are representative of the tank bottom.

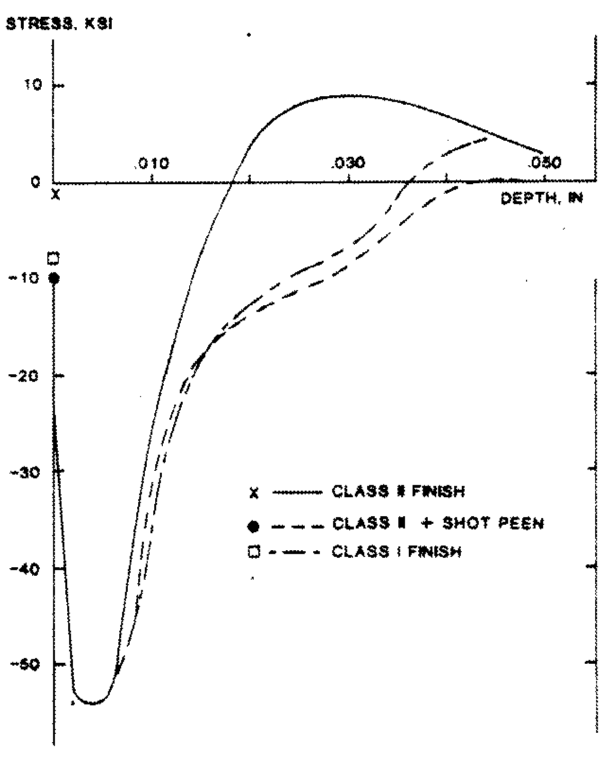

Fig. 3. Measured stress distributions in metal grit blasted steel plate

Surface stresses are compressive and range from -1,000 to -10,000 psi after cleaning. However, large compressive stresses are developed to significant depths by the blasting. Near-subsurface stress distributions for the commercial or Class II finish and for the "white" metal or Class I finish are similar, with yield strength being reached. The additional working of the metal beyond the Class II finish provided by Class I blasting or shot peening changes the stress distribution somewhat. Similar stress profiles have been reported for other materials after grit blasting or shot peening.[9]

Grit blasting is a metal removal technique as well as a cleaning method for metal surfaces. The erosion rate was not studied, but it will vary with the blast conditions. One data point obtained for zero degree impingement of the grit on the surface resulted in metal removal at a rate of 0.001 to 0.002 inch per second.

Grit blast cleaning was chosen because of its ability to remove scale. Photomicrographs in Figures 4 and 5 illustrate scale removal and surface roughening due to grit blasting. Care must be exercised to minimize development of surface flaws such as folds, entrapped grit, etc. The depth of subsurface plastic deformation due to grit blasting was observed to vary from 0.0005-inch to greater than 0.0040 inch (Figure 6). This correlates well with the stress measurements (Figure 3).

Grit blasting of pits roughens pit surfaces to the same extent as the plate surface (Figure 7). Compressive stresses in the pit bottoms will be similar to those measured for the plate. Moreover, edges will

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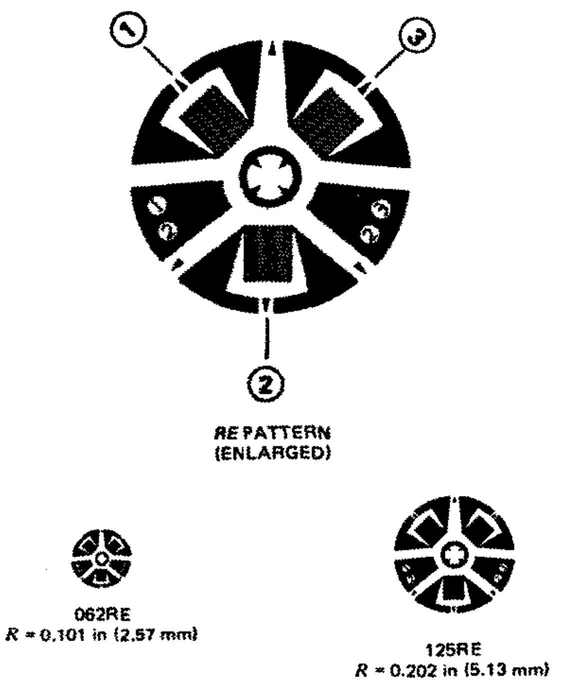

Fig. 1. Micro-measurements RE-pattern strain gage rosette for residual stress measurement (used in the present study)

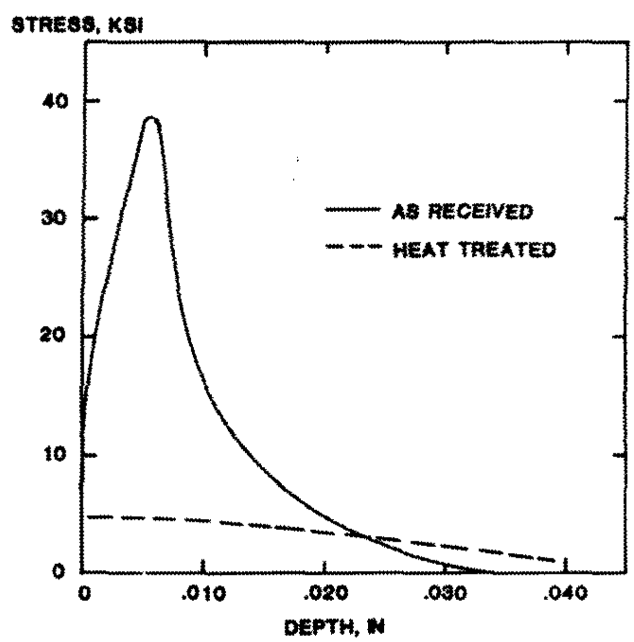

Fig. 2. Measured stress distribution in normalized and rolled ASTM A537 Class I steel plate before and after stress relief heat treatment

Stress relief heat treatment is designed to reduce residual stresses to the 4,000 to 7,000 psi level discussed previously. After the stress relief heat treatment, care is used to avoid any localized stressing of the tank walls and bottom.

Alternative repair methods include grinding of the pits to reduce their stress intensifying character. Basically this means enlarging the diameter without increasing the depth. The stress concentration factor and the stress intensity vary with pit geometry. Deeper, narrower pits produce greater concentrations of stress and result in lower allowable loads. Where deep pits occur, it should be beneficial to widen the affected area. However, the decision to repair by grinding to increase the aspect ratio of a pit must be made on an individual basis.

Residual stresses for a harshly ground steel surface are contained in Table 1, and a typical average stress profile is shown in Figure 8. Surface temperatures exceeded 400°F during grinding. Surface stress is high, +29,000 psi, and yielding occurs deep in the material. The advantage of shot peening the ground surface is also shown in Figure 8, where a compressive surface stress and subsurface deformation are in evidence.

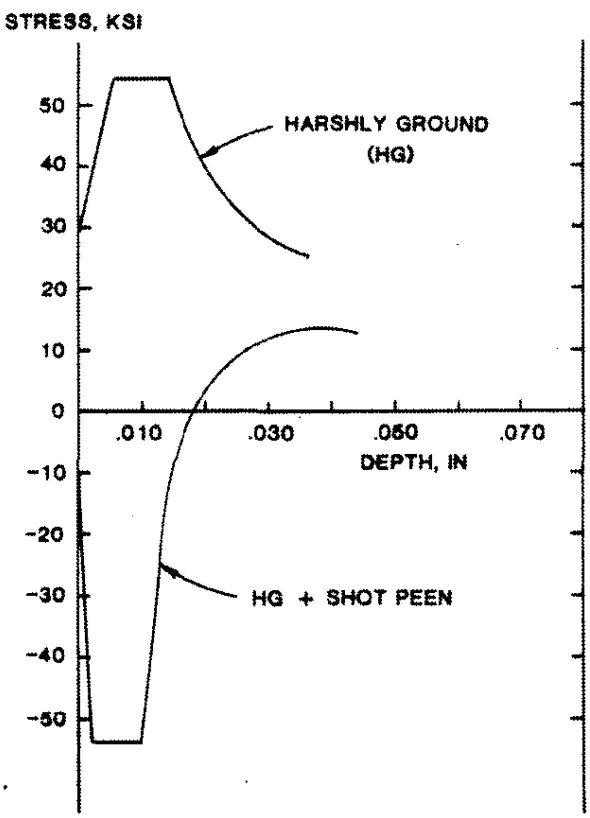

Fig. 8. Measured stress distributions in steel plate after abusive grinding and after shot peening

Other methods of grinding were evaluated. Wet-grinding, a slow non-abusive method which resulted in a very little surface temperature change, nevertheless caused an increase in subsurface tensile stress to about +29,000 psi (Figure 9). Subsequent blast finishing provided substantial compressive stresses and completely suppressed the tensile stresses resulting from grinding (Figure 9). Note that metal grit blasting induces a stress profile similar to that resulting from shot peening.

A more rapid method of nonabusive grinding utilizes an oxyacetylene nozzle for air/water spray cooling. With a coarse stone wheel, temperatures were maintained below 100°F.

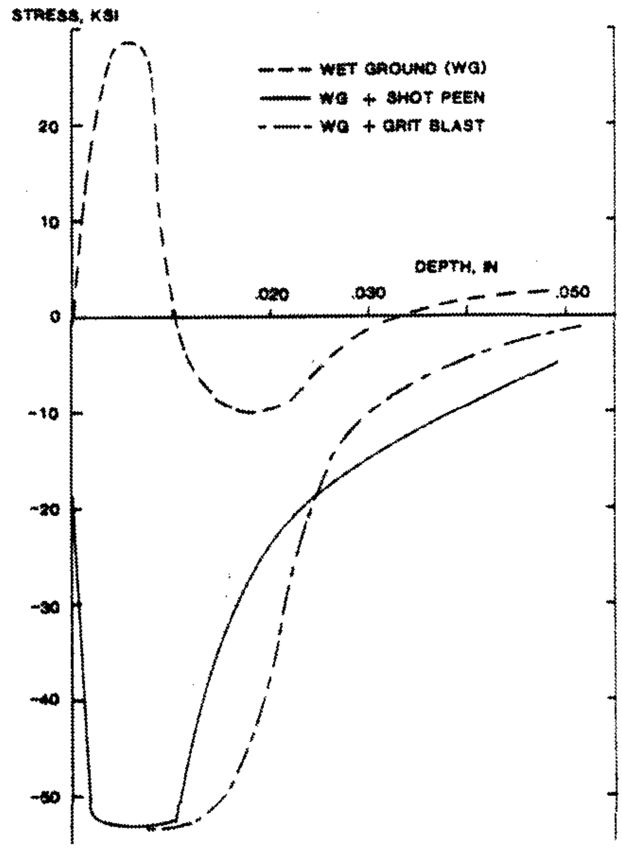

Fig. 9. A typical stress profile in a plate section following relatively gentle grinding. Effects of subsequent grit blasting or shot peening are also illustrated.

The spray cooling, stone grinding method was applied to samples which had not been heat treated (Table 1). An increase in surface stress to +15,000 psi tensile occurred, but the subsurface maximum stress was unchanged at +38,000 psi. Thus, it appears that this method allows rapid grinding without altering subsurface stresses significantly. Shot peening of the spray cooled/stone ground steel resulted in average compressive stresses of

-15,000 psi on the surface with a stress distribution similar to those noted in Figures 3, 8, and 9.

It is evident that metal grit blasting of the carbon steel surfaces yields residual stresses similar to those obtained by shot peening. Some variations can be expected with shot size or grit size, or if pressure or angle at the nozzle is changed.[4] However, metal grit blasting will suffice for post-grind finishing, and shot blasting is unnecessary. Almen intensities for both peening and blasting operations were 4-5C.

In evaluating the various repair methods, grinding, grit blasting, and shot peening were always applied over an area about 4 inches in diameter centered on a simulated 1/8-inch pit (1/8-inch drill bit, 1/8-inch deep). The outer part of the 4-inch area was a transition region receiving some metal work but not to the same depth or extent as at the center pit. Measurements in the transition zone indicate stresses intermediate between the center and the area outside the 4-inch zone.

The repair procedure recommended for removal of any flaw in the heat-treated structures is contained in Table 2. When applying the technique, it is important to create a gradual finish transition to avoid sudden changes of stress in the material. Thus, any ground area should be feathered. The grit blast finish should also be feathered.

CONCLUSION

Cleaning and repair of flaws in a stress-relieved structure should be finished by metal grit blasting. This will leave the surfaces in a state of compressive residual stress which is highly resistant to SCC. Stresses beneath the surface will also be compressive to substantial depths, and can approach the yield strength in the material. Consideration of grit blasting as a normal means of improving resistance to SCC is indicated.

ACKNOWLEDGEMENT

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Table 2 - Post Heat Treatment Repair Procedure for Pits or Other Flaws in Stress Relieved Structures

The procedure recommended for modification or removal of pits, gouges, or other flaws includes spray cool wet-grinding to "dish-out" an area of approximately 4 inches diameter followed by grit blasting to finish the ground surface.

Wet Grind

- Coarse No. 24 stone wheel, air-driven tool.
- Oxyacetylene torch nozzle with compressed air and cold water feed lines attached.

Adjust the spray to provide an atomized water flow with water accumulation kept at low amounts. Apply spray continually to the surface being ground. Contain the water (puddle) and occasionally wipe-up. Wipe dry when grinding is complete.

Feather the grinding toward the outer regions of the 4-inch area.

Finishing

- GL40 steel grit, R_c 45-55.

Apply a Class I finish in the center of the ground area and feather the grit blast beyond the 4-inch area. The Almen intensity in the center should be 4+ to 6 using "C"-type test strips.

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