CONTROL OF STRESS CORROSION CRACKING BY SHOT PEENING

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ABSTRACT

Studies were carried out in order to elucidate the protective effects of shot peening against Stress Corrosion Cracking(SCC) of austenitic stainless steel. SCC susceptibility of shot peened specimens was evaluated by using a constant load type SCC test apparatus in 3 kinds of corrodents. Beneficial effects and some problems encountered in shot peening for the prevention of SCC were discussed.

KEYWORDS

Shot peening; stress corrosion cracking; pitting corrosion; preferential dissolution; rusting; austenitic stainless steel; butt-welded specimen; weld slugs; cast steel shot; residual stress; transformed martensite.

INTRODUCTION

It is generally believed that shot peening is an effective method for protecting metals against SCC. The published works (Togano(1960), Suss(1962), Fisk(1979), Povich(1978)) relating to the effect of shot peening on SCC is, however, contradictory This is because the factors concerened in this phenomena are so numerous that the relating of parameters is very difficult to solve. Therefore, there seems to be some further studies necessary to elucidate the quantitative relationship between SCC susceptibility and shot peening intensity.

In the application of shot peening for protection against environmental assisted cracking such as SCC, considerations should be given to the following factors as well as the beneficial effect by residual compressive stresses, i.e., roughness of peened surface, hardened surface layer with a high density of lattice defects, phase transformation, imbedding of a piece of broken shot in the metal surface and change of residual stresses across the boundary between shot peened and unpeened area. This is because these factors, under some circumstances, will have an effect opposite to that of preventing SCC.

The principal purpose of this study is to evaluate the protective effects of shot peening against chloride-SCC of welded austenitic stainless steel. For this purpose, SCC susceptibility of butt-welded specimens which were subsequently shot peened under various peening conditions was investigated in boiling 42 wt.% $MgCl_2$ solution. The second purpose of this study is to elucidate the environmental effects on the SCC susceptibility of shot peened specimens. 2 kinds of corrodents, one of which causes pitting corrosion and subsequent SCC from corrosion pits (PC+SCC), and the other which causes SCC under general corrosion (GC+SCC) were used for this purpose. Beneficial effects and some problems encountered in shot peening for the prevention of SCC were discussed on these test results.

TEST SPECIMEN AND TEST METHOD

Austenitic stainless steel AISI304(18.7Cr-8.7Ni-0.06C) was tested. Cold rolled plate (140 mm length x 165 mm width x 3 mm thickness) with a root face:1 mm, groove angle:70° were 1-layer butt-welded by Shieled Metal Arc Welding(SMAW). Specimens were cut from a butt-welded plate(280 mm length x 164 mm width) into the shape as shown in Fig. 1. Shot peening was performed on both surfaces of specimen so that the reverse side of welded specimen could be shot peened finally. Uncoated area of 13 mm width and 35 mm length on the reverse side of specimen was exposed to SCC test solution. Cylindrical specimens of AISI 304TP (18.4Cr-8.3Ni-0.07C) shown in Fig. 1 were also used for the SCC test which was intended to elucidate the environmental effect on the SCC susceptibility of shot peened specimens.
Air blast type peening was adopted. Roughly spherical cast steel shot with average diameters of 0.3, 0.4, 0.5 and 0.6 mm were blasted by compressed air with blast pressure of 3.5, 5.5 and 6.5 kg/cm^2 . Shots were blasted normal to the surface of specimen, as shown in Fig. 2, at an injection rate of 4.7~5.0 kg/min. Two types of specimens, plate and cylindrical, were shot peened by attaching them to the turntable and to the rotating shaft respectively which were located 150 mm away from the fixed shot nozzle. Total rotating number of specimen was decided so that the coverage should be about 120 %. Peening intensity was expressed by Almen arc height of A-type strip (SAE Standard J442) which was shot peened under the same conditions as for the test specimen.
Table 1 is the list of plate-type specimens with their physical properties and the results of SCC test. Specimens with capital letters: A, B, C, D, E and F are the ones which were shot peened under various peening conditions. Specimen:H is as welded one. Specimens:I, J and K were Post Weld Heat Treated (PWHT) at 600, 900 and 1050°C respectively. These specimens were also SCC tested in order to compare their SCC susceptibility with those of shot peened ones. Specimen:L is shot peened after being ground.
Figure 3 shows the distribution of both surface residual stresses and Vickers hardness of

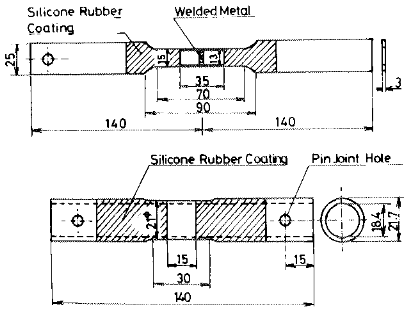


Fig. 1. Test specimen

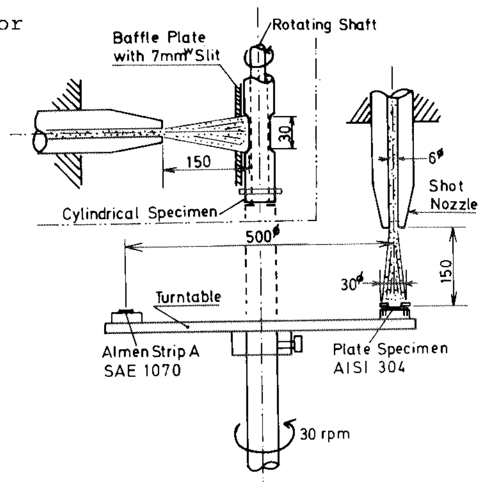


Fig. 2. Arrangement of shot peening

Table 1 List of Test Specimens

	shot dia.	pressure	arc height	hardness	$\sigma_{residual}$	σ_{th} SCC
A	300	6.5	0.2	370	-37	19.6
B		3.5	0.14	360	-51	18.3
C	400	5.5	0.17	320	-46	22.2
D		6.5	0.18	330	-38	19.5
E	500	3.5	0.17	340	-47	19.3
F		5.5	0.23	355	-60	19.4
G	600	5.5	0.25	400	-50	19.3
H	As Welded			190	+35	5.5
I	PWHT 600°C			180	+33	7.5
J	PWHT 900°C			160	+ 8	11.0
K	PWHT 1050°C			155	+ 4	13.0
L	400 5.5 S.P. after Grinding		0.16	340	-43	21.5
	μφ	Kg/cm²	mm	Hv	kg/mm²	kg/mm²

as-welded specimen:H and shot peened one:D. Residual stresses were calculated by $\sin^2\psi$ method using diffraction profiles of CrKβ from (311) planes. A carbon monoclometer was specially attached to the X-ray apparatus as the former was indispensable for the stress measurement of shot peened austenitic stainless steel because of the strain-induced α-phase martensite. It is apparent that shot peening changes to beneficial compressive stresses the residual tensile stresses that welding imposes in a metal surface. Residual compressive stresses induced by shot peening reaches to about -40~-60 kg/mm^2. Figure 4 shows the transverse distribution of Vickers hardness, residual stresses and X-ray diffraction peak height due to α-phase martensite. Capital letters have the same meaning as described in Table 1. Hardened surface layer reaches to about 300 µm thickness below the surface which corresponds to the thickness in which both residual compressive stresses and transformed martensite are observed. Magnetic ferrite meter showed that the amount of transformed martensite was less than 7 %.

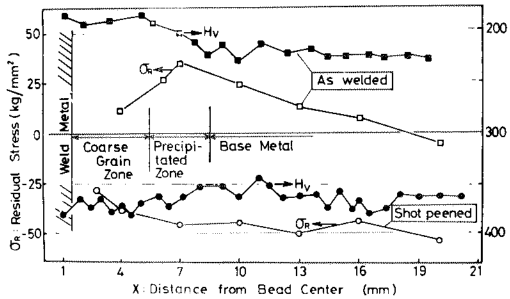


Fig. 3. Distribution of residual stress and Vickers hardness

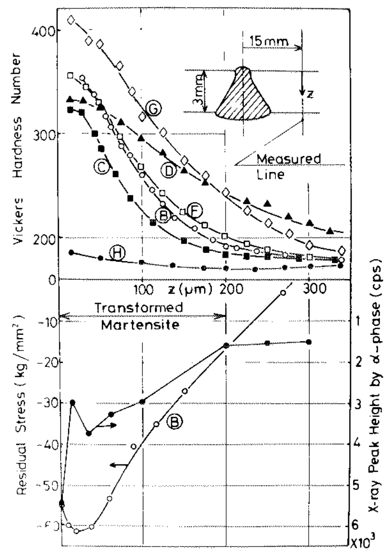


Fig 4 . Transverse distribution of hardness, residual stress and transformed martensite

CONTROL OF CHLORIDE-SCC OF AISI 304 STAINLESS STEEL BY SHOT PEENING

Specimens listed in Table 1 were SCC tested in boiling 42 wt.% $MgCl_2$ solution using a constant load type SCC apparatus. Results are shown in Fig. 5. Among all the specimens tested, as-welded specimen:H has extremely high SCC susceptibility because of their higher residual tensile stresses. Their threshold stress for SCC is as low as 6 kg/mm^2. Post weld heat treated specimens at relatively higher temperature have higher resistance than the as-welded specimens. It should be, however, recognized that PWHT at 600°C has no effect on preventing SCC of austenitic stainless steel. On the other hand, shot peened specimens have superior resistance to SCC. They have threshold stresses higher than 18 kg/mm^2. Threshold stresses for SCC are represented in Fig. 6 as a function of the peening intensity and the residual stresses. There seems to be no distinct correlations among these factors. For example, specimen:B, which has higher residual compressive stresses than specimens:A and D, has lower threshold stresses than specimens:A and D. Specimen:C which shows the highest resistance to SCC seems to be an

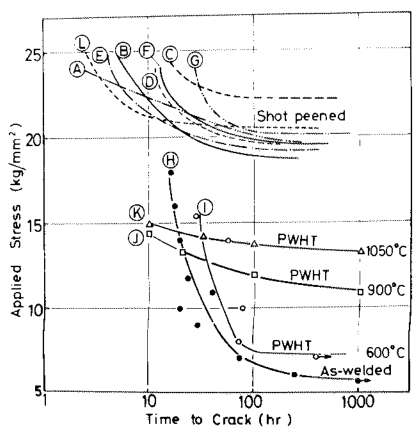


Fig. 5. Time to crack curves

Table 2 Location of Crack Initiation

Applied Stress (kg/mm^2)	WEL 308	AISI 304			
	Weld Metal	Bond	Coarse Grain Zone	Precipitated Zone	Base Metal
25	◒	Ⓔ Ⓖ			
24		Ⓒ Ⓕ Ⓐ Ⓓ	Ⓑ		
23	◒	Ⓔ Ⓖ	Ⓒ		
22	◒	Ⓑ Ⓕ Ⓓ	Ⓑ		
21	◒	Ⓕ Ⓖ	Ⓐ		
20		Ⓕ Ⓓ Ⓐ	Ⓔ		
19.5		Ⓑ			
18		●			
16		●			
14			● ◑		
12			◑		●
10			◑		●
8			◑		●
6					●

Key	Remark
●	As welded
○	Shot Peened
◑	PWHT at 600°C
◒	SP after Grinding

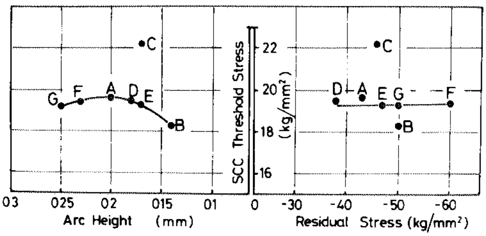


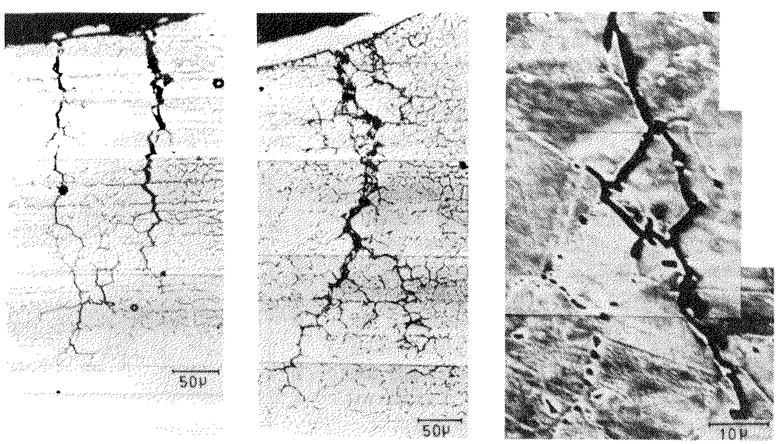
Fig. 6. Relationship between SCC thresh-hold stress, residual stress and arc height of shot peened specimens

exceptional one. These results suggest that the shot peening conditions, i.e., shot size, blast pressure and injection rate of shot can be selected optionally as required, provided that the arc height and a coverage are higher than 0.17mm and 100% respectively. Table 2 shows the location of crack initiation. Depending on the pre-treatment of specimens, cracks are observed in a limited zone. That is to say, 1) Cracks of PWHT specimens initiated from the coarse grain zone. 2) Cracks of shot peened specimens initiated from the bond and the coarse grain zone. But most of the cracks classified into the coarse grain zone were also observed near the bond. 3) Shot peened specimens after being ground have their cracks on the weld metal. 4) Cracks of as-welded specimens are distributed over the Heat Affected Zone(HAZ) and the base metal.

By the way, specimen:B which has the highest SCC susceptibility among 6 kinds of shot peened specimens has weld slugs on its surface. Cracks were observed under the weld slugs. This is the only case in which the intensity of shot peening is not sufficient to remove the weld slugs on reverse surface. Some examples of the transverse microphotographs of cracked specimens are shown in Fig. 7. It is apparent that the cracks initiate at the bond (specimen G) and/or near the bond (specimen F) and then propagate along the grain boundary where δ-ferrite is precipitated (specimen D).

The reasons why the cracks are concentrated on the bond are assumed as follows;

1) Weld slugs deposited on the reverse side is so strongly adhesive that they cannot



σ = 20 kg/mm^2 Specimen: F

σ = 21 kg/mm^2 Specimen: G

σ = 20 kg/mm^2 Specimen: D (E.M.X.)

Fig. 7. Transverse microphotographs of cracked specimens

be removed by shot peening when peening intensity is not strong enough. The surface of specimen under the weld slugs was not shot peened and therefore there exists both lower hardness and smaller residual compressive stresses. Residual compressive stresses of specimen under the slugs are smaller than $-15\ kg/mm^2$.

2) If weld slugs are removed by shot peening, peening intensity under the removed slugs is not enough to prevent SCC because most of the early peening are used for the removal of weld slugs.
3) Even in specimens without weld slugs, there exists a geometrical discontinuity between the base metal and the reinforcement of weld. Peening intensity is not enough to prevent SCC at the toe of weld, especially if large shots were blasted

As mentioned in the INTRODUCTION, the important problem to be well considered is the phenomena experienced in the practical application of shot peening to the equipment in service.

Specimen L, in Fig. 5, which was shot peened after being ground, was SCC tested in assuming the situation of the repair of a cracked member by welding where grinding was often used. The fact that specimen:L shows a superior resistance to SCC means that shot peening becomes an effective measure to protect the weldment against SCC in spite of whatever condition to which a specimen has been subjected. This conclusion is correct provided that all the surface of a specimen is shot peened so that coverage is more than 100 %. Conversely speaking, some trouble is feared when a minimum of 100 percent coverage is not obtained.

Subsequent studies were also carried out on this aspect. Results are shown in Figs. 8 and 9. A square specimen of 100 mm length and 10 mm thickness was ground and then shot peened whithout a baffle plate. A minimum of 100 percent coverage is assured within a circle of 13 mm radius which is expressed as an apparent boundary at x=0 in Fig. 8. Coverage decreases as distance increases from the boundary just along the distribution curve expressed by an error function. There exists high compressive and tensile stresses at the surface of specimens shot peened and ground respectively. Residual stresses change from compressive to tensile at x=-20 mm where the coverage is 18 %. This specimen was immersed in the corrodent for 50 hr without applied stress. SCC is observed, as shown in Fig. 9 , only at the surface 27 mm away from the apparent boundary where the coverage is less than a few percent.

ENVIRONMENTAL EFFECT ON THE AVAILABILITY OF SHOT PEENING

From the results of our studies on the chloride-SCC of austenitic stainless steel,

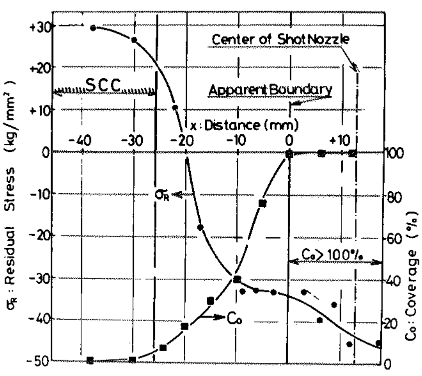


Fig. 8. Distribution of residual stresses and coverage of the specimen shot peened after being ground

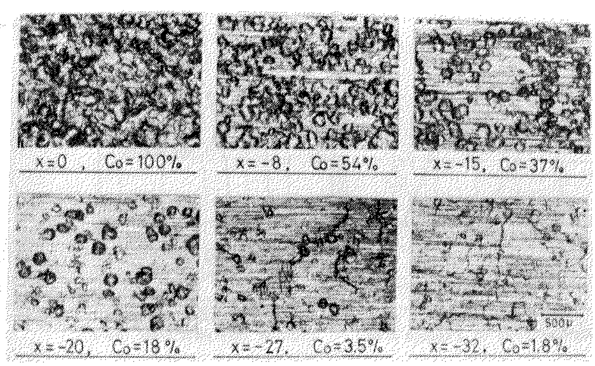


Fig. 9. Appearance of shot peened and stress corrosion cracked specimen (specimen was ground before shot peening)

it is recognized that shot peening is an effective measure against SCC. This is because stress is an important cntrolling factor and the metallurgical changes induced by shot peening seems to play no important role in this type of SCC. However, in the SCC by other types of corrodent, both the environmental and the metallurgical factors also should be taken into account as well as the residual compressive stresses.
Two kinds of corrodents which causes a different type of SCC, i.e., 20 wt.% NaCl + 1% $Na_2Cr_2O_7$ and 4N-H_2SO_4 + 0.4N-NaCl solution, were adopted for this purpose. The former solution causes pitting corrosion which in turn causes SCC from corrosion pits(PC+SCC), and the latter causes general corrosion which in turn causes SCC (GC+SCC). Cylindrical specimens, which were shot peened under the same condition as performed on the plate-type specimen:C (Table 2), were SCC tested by using a constant load type test apparatus.
Results obtained are as follows;

1. PC + SCC in Boiling 20 wt.% NaCl + 1 wt.% $Na_2Cr_2O_7$ Solution.
The observation of the initiation of cracks from corrosion pits is impossible because the solution is opaque due to the addition of a trace of oxidant:$Na_2Cr_2O_7$. Therefore, SCC susceptibility was evaluated by measuring the maximum crack depth and the number of corrosion pits after 50 hour duration from the start of test at each applied stress point.
Figure 10 shows the results obtained in this solution. The number of corrosion pits on shot peened specimen is higher than the one not peened, but the crack depth of not peened specimen reaches to a depth of about twice of the shot peened. The surface and transverse cracks are shown in Fig. 11. Straight shallow cracks are observed on shot peened specimen whose surface is attacked slightly. On the other hand, multibranched cracks with hair cracks are on the not peened specimen. The crack morphology and the propagation rate are apparently affected by the metallurgical and stress factors.
Rusting due to the formation of iron-oxide were observed on both specimens but bigger rusting were on the shot peened one. In this test solution, caution should be taken for the pitting corrosion and the rusting. Physical and metallurgical changes such as hardened surface, transformed martensite and imbedding of a piece of broken cast steel shot in metal surface are the probable causes of rusting and pitting corrosion.

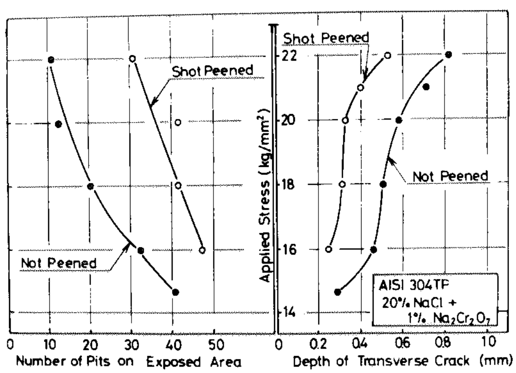


Fig. 10 . Number of corrosion pits and crack depth of shot peened and not peened specimens. (duration of test: 50 hour)

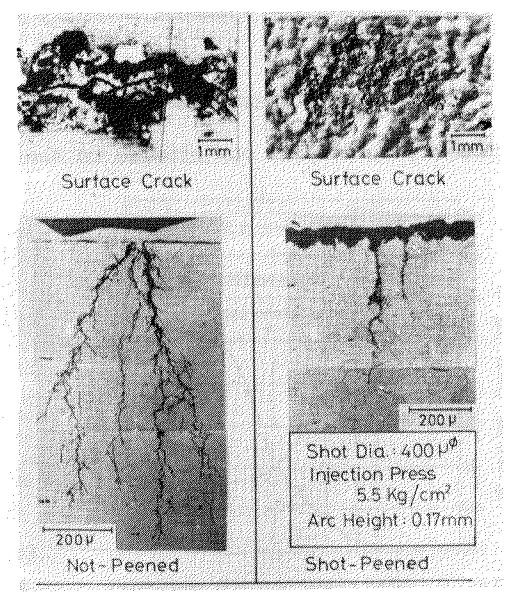


Fig. 11. Comparison of crack pattern of peened and not peened specimens in 20 wt.% NaCl solution

Heavy peening, as needed in the improving of fatigue life, is not necessary for SCC prevention. Therefore, shot peening by glass beads or some inorganic particles is a method for avoiding rusting.

11. GC + SCC in $4N-H_2SO_4$+ 0.4N-NaCl Solution

This solution has very low pH and therefore causes severe general corrosion. Results are shown in Fig. 12. Shot peened specimen has a slightly lower threshold stress than the not peened one. Preferential attack along the martensite are apparent in Fig. 13. The surface layer with residual compressive stresses does not play an important role in controling of SCC but also accelerates the SCC because of the preferential dissolution of martensite. This is a case in which shot peening has no beneficial effect, but rather an unfavorable effect on the prevention of SCC.

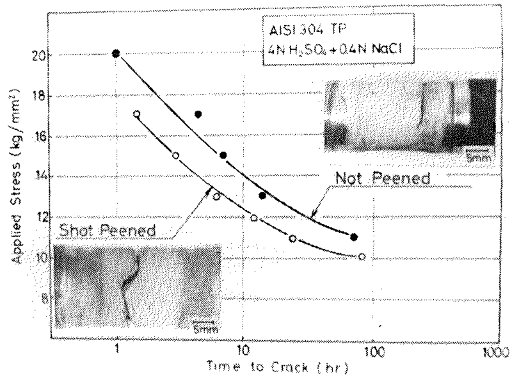


Fig. 12 . Time to crack curves with their cracked specimens

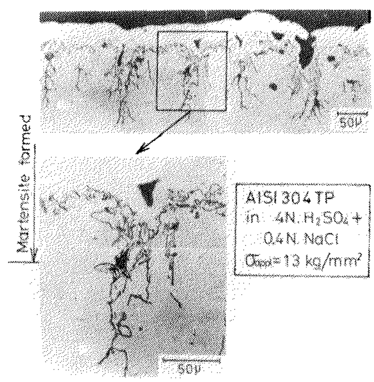


Fig. 13. Transverse microphotographs of cracked speciren (shot peened)

CONCLUSION

The present study shows that both the beneficial and the unfavorable effects were observed in using shot peening for the protection of stainless steel against SCC. It should be well recognized that mechanical, physical and metallurgical changes induced by shot peening each have great influence on SCC, depending on the corrodent in which stainless steel is attacked. The effects which are induced by shot peening and have influence on SCC are evaluated as follows;

1) Residual compressive stresses....advantageous in the protection of AISI 304 against SCC in $MgCl_2$ solution. But for SCC which is caused by prior pitting corrosion, much beneficial effect may not be expected.
2) Imbedding of a piece of broken shot in the base metal.....Bimetallic shot, such as the cast steel shot to stainless steel, has the probability of causing both rusting and pitting corrosion. Thus inorganic shot or shot made of base metal should be used.
3) Lattice defects and phase transformation.....danger especially in acidified solution where preferential dissolution is accelerated by metallurgical changes.
4) Change of residual stresses across the boundary between the shot peened and unpeened surface.....not much worry in case residual tensile stresses are the trigger of SCC.

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