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Surface Pre-Stressing to reduce the incidence of Stress Corrosion Cracking and Corrosion Fatigue of Welded Joints.

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SUMMARY

Controlled Surface Prestressing is a technique applied to many machined or fabricated surfaces to reduce the incidence of Stress Corrosion Cracking and Corrosion Fatigue. The benefit is gained by the removal of any surface residual tensile stresses, which can be considerable, and substituting residual compressive stresses whose magnitude can be 80% of the materials yield strength and depth 1,2 or 3mm, depending on the parameters selected.

The critical factor of any material where S.C.C. is concerned is the threshold level of tensile stress. This can be exceeded if applied or residual tensile stresses, eccentuated by any stress intensity feature, e.g. weld laps or geometry, result. Not only does controlled surface prestressing remove any residual surface tensile stresses, it effectively reduces the applied load witnessed on the surface and can negate the stress intensity problem.

The above aspects have been noted worldwide in recent years and that is why many countries, U.K., France, Germany, U.S.A. and Canada, have used the technique on welded structures. Success has been achieved on Wood Pulp Digesters, Deaerators, L.P.G's., M.E.A. Tanks, Ammonia Spheres, Nuclear Power Plant on Steam Generator Tubes, Bridges and Offshore Structures.

Applying this technique is no different to other processes and the success achieved is governed by the controls of its application and above all correct selection of Shot-Peening perameters.

INTRODUCTION.

Controlled Surface Prestressing (C.S.P.) is a technique whereby a surface is subject to an applied force resulting in the metal yielding, negating present residual stresses, and leaving a residual compressive stress. This can be achieved by a variety of different methods including, cold rolling, autofrettage, peenage, mechanical prestressing (torsion members/ springs) and Controlled Shot-Peening.

This paper relates to controlled shot-peening because it is more suited to the problems presented here and is often used in conjunction with the other prestressing methods stated. For instance, cold rolling of threads is often followed by Controlled Shot-Peening to improve the fatigue characteristics in transition areas. Autofrettage is the application of fluid pressure to pressure vessels or cylinders to increase ultimate strength.

This pressure is sufficient to deform the walls beyond the yield strength but insufficient to cause fracture. The effect is that after the pressure is relieved a residual compressive stress of low magnitude but great depth is retained. Where internal geometry or surfaces are such that areas of high stress concentrations result in those areas yielding first, it is feasible that microscopic fractures can result. Peenage is Controlled Shot-Peening followed by Autofrettage to overcome that fracture problem.

Controlled Shot-Peening is the cold working of a metal by bombarding its surface with shot. The result is that the surface yields but the core resists stretching and a residual compressive stress is induced. The magnitude and depth of this compressive stress (1) varies with materials but generally a level of 80% of Yield Strength of the base metal is achieved and the depth varying from 0.1 to 3.0 mm. See Figures 1 & 2. Shot used to achieve this level of cold work can be steel, glass, ceramics or stainless steel and these vary in size from 50 micron up to 3mm. Each of these sizes and types are used for specific reasons.

Welds and welded structures where fatigue, corrosion fatigue and stress corrosion cracking may occur respond well to Controlled Shot-Peening. Each of these failure problems is linked to stress and the greater the tensile stress the greater the problem. The reverse being the case with compressive stresses.

Stress and Welds.

The life of a weld, provided it is sound, is greatly affected by tensile stresses at the Heat Affected Zone. Applied stress and component life it is acknowledged are directly related with a lower component life achieved with higher applied loads. What is often dismissed is the effect residual stress has on that life. The load that a surface experiences is the algebraic sum of the residual and applied stress. See Figures no. 3 (1). Consequently the H.A.Z. of a weld with tensile stresses close to, and in some cases, above yield will fail at very small applied loads.

Reversing the residual stressed stated by C.S.P. will require higher applied loads and or greater cycle times before failure may occur. It is for this reason that C.S.P. is preferred in many instances to thermal stress relief because with stress relief, a) as soon as a stress is applied the surface will experience tension and b) it is recognised that not all residual tensile stresses will be removed.

To demonstrate the link of fatigue and stress examine Figures no. 4. This work (2) was conducted on 50 Rockwell 'C' by grinding and the variations in residual stress were plotted against failure strength. Not only does this graph emphasise the relationship, it shows how grinding or dressing surfaces after welding must be carefully controlled or these themselves can cause problems. See Figure No. 5. This graph indicates the high levels of tensile stress resulting from different levels of grinding in a mechanised manner. Hand dressing or grinding which results in surface discolouration can be worse with residual tensile stresses at the weld close to or above yield, hence surface cracking which occasionally occurs.

Weld Fatigue and Surface Prestressing.

It is clear from research work in recent years that to improve the fatigue strength of a sound weld residual stress and its profile must be improved.

Residual stress has been mentioned above in detail and it will be quantified here but profile must also be considered for the greatest improvement. Peening onto a weld will show benefit, but not as much as peening onto a dressed weld, because the stress concentration areas have been removed. Figure no. 6 indicates the stress intensity factors (3) at the toe of welds after different post weld fatigue improvement methods. This data, when read in conjunction with Figure no. 7, attempts to quantify the benefits each technique has (3). In this particular case toe grinding followed by Shot-Peening gave the greatest benefit because three things were achieved:-

a) reduced stress concentration factor.
b) removal of slag intrusions.
c) generation of residual compressive stresses.

It would be wrong to advise that the improvements in fatigue strength quoted are standard and would be repeated on all welds. What is shown is the manner in which improvements can be achieved but each case must be assessed against the component, weld, load and environment. Experience has indicated that the Shot-Peening variables have to change with different situations to ensure optimum results are achieved.

Work has been done to reduce the cost of changing weld profile and inducing high levels of compressive stress. This entailed Shot-Blasting the surface first to "abrasive machine" the profile and produce a smoother finish followed by Controlled Shot-Peening. These tests which were conducted quickly to indicate if further work may be worthwhile, were successful, but a detailed study must be done to qualify and quantify the benefits.

Stress Corrosion Cracking and Surface Prestressing.

Stress Corrosion Cracking in the Process Industries is a major problem and is caused by one of four conditions. Residual and or Applied Tensile Stress, Corrosive Environments, Susceptible Alloys, and Time (4). To eliminate one of these conditions eliminates the problem. In welded structures it is generally the H.A.Z. that causes concern because of the high residual tensile stresses. The critical factor being to ensure that the threshold level of tensile stress is not exceeded by the residual or the applied stress. The applied load coming from pressurization, temperature, dead weight of contents, bolting, wind or wave action. These loads can be low in magnitude but in combination with a residual tensile stress from welding the threshold level can be reached. Figure no. 8 gives an indication how that critical stress varies with time (5).

In applications where the critical stress levels are known and thermal stress relief is adequate even though 15-20% of the H.A.Z. stress can still be present after treatment, then surface prestressing can often be preferential on economic grounds only. In other words the technique can be used as a stress relieving operating where the residual compressive stress induced is a bonus but not essential. Local Controlled Shot-Peening has shown to be considerably cheaper on many structures than thermal stress relief.

An additional benefit of the treatment is that it is sometimes difficult on structures which exhibit cracking to determine whether the problem is surface related or the material or weld has a major sub-surface defect. On a structure where cracking is experienced and some sub-surface defects are suspected but environment problems are belived to also exist it would be feasible to grind out all cracks and re-weld but this would be time consuming and expensive. An alternative would be to Shot-Peen during a maintenance period and re-examine at a subsequent down time. Those cracks which are environment related would be eliminated and those caused by sub-surface welds flaws of a major nature may re-appear. Effort can then be expended only on these, i.e. grinding out/welding, considerably reducing the re-work.

It would then be necessary to re-Shot-Peen to remove the tensile stresses from the welding and grinding.

Intergranular Corrosion of Welds.

Intergranular Corrosion of 304 S.S. in the sensitized Heat Affected Zones is a problem when this material is used in corrosive environments. Controlled Shot-Peening is an accepted technique for resisting attack because of the breaking up of grain boundaries and creation of slip planes as sites for carbide precipitations. The surface will no longer have a continuous chromium depleted grain boundary that is susceptible to intergranular corrosion. However care must be taken to ensure the cold work is done prior to sensitization and if the welded structure is to be used in the sensitizing temperature range then a secondary shot-peening operation must be conducted (6).

How to Specify Controlled Shot-Peening.

The object of Controlled Shot-Peening is to induce a compressive stress of predictable magnitude and depth. The magnitude is dependant on the yield strength of the base metal and provided uniform cold work is achieved that level will not vary. Depth is important and the shot-peening perameters are chosen to suit the problem. For instance should the environment not be excessively corrosive or suffer erosion and be reasonably smooth or defect free, then a shallow compressive layer is adequate. However excessive corrosion, erosion or surface defects requires maximum depths of cold work otherwise limited benefit will be noted.

The process has a number of variables that effect the depth of residual compressive stress. Control of those variables is important otherwise repeatability and confidence in the technique will suffer. The variables include: shot (size, shape, hardness, alloy), velocity, coverage, angle of incidence, nozzle distance, substrate hardness and substrate roughness. Having discussed the problem with the Corrosion/ Structures Engineer to note the depth of compressive stress required which will be based on the surface removal rate/annum, if any, the surface roughness, is checked. Weld laps or weld toes of tight radius effects the shot size selected. However the smaller the shot size the less the depth of compression and less "Corrosive/erosion" resistance. Sometimes if the alloy hardness allows it is better to severely cold work the surface, changing its geometry, obliterating the small radius/fillet effect.

Both techniques have been applied with success but knowledge of the problem is essential. Once the process has been complete, checking that it has been performed correctly in terms of uniform coverage or obliteration is important.

The technique used to achieve this, which was seconded from the Aerospace Industry is Peenscan/Dyescan. This is a type of flourescent dye which is used in the following manner. The Corrosion/Structures Engineer decides which areas are critical (H.A.Z./formed ends etc.) and the dye is sprayed or brushed on. Thorough coating of these critcal ideas is checked with an Ultra Violet (U.V.) light and the contractor cleared to proceed with C.S.P. Once complete the surface is re-examined with the U.V. light and areas not adequately cold worked stand out as white on black. Bearing in mind that most parts that will be shot-peened can be large, (storage tanks/pressure vessels/bridges/oil rigs) then visual inspection becomes impractical. Should the weld not quite meet the specified condition and have areas of tight radius in laps or toes then the flourescent dye will not be removed. The subsequent approach is then to either use a secondary shot-peening process with a smaller media (bear in mind the lower depth of compression) or dress the area and re-peen. Certainly in cases where corrosion fatigue is a problem then dressing is preferred because the stress concentration factor (K t) will be reduced and fatigue strength improved 25 to 50%. Concerning corrosion fatigue problems, which tend to be erratic as most forms of fatigue, this flourescent dye technique plus shot-peening does highlight critical stress concentration areas that will adversely effect the structures life. Therefore it could be considered as a technique in its own right as a quality control check of weld conditions. The specification of C.S.P. must therefore include the shot size; intensity of peening; method of coverage determination (Peenscan) and advise on overall quality standard i.e. Military Specification 13165B, is a good basis.

Conclusions.

Controlled Shot-Peening to produce compressive stresses has proved to be a reliable technique for improving the life of sound welds. Sufficient care of its application must be conducted to achieve the right magnitude and depth of compressive stress. The American Society of Mechanical Engineers advise shot-peening is a permissable or acceptable procedure under the A.S.M.E. Boiler and Pressure Vessel Code.

Therefore in situations where fatigue, corrosion fatigue and stress corrosion cracking cause problems it is an economic and therefore technical proven process to use on structures or vessels in the Process Industries.

Acknowledgements.

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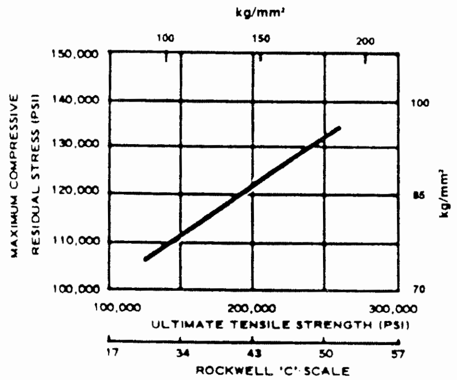
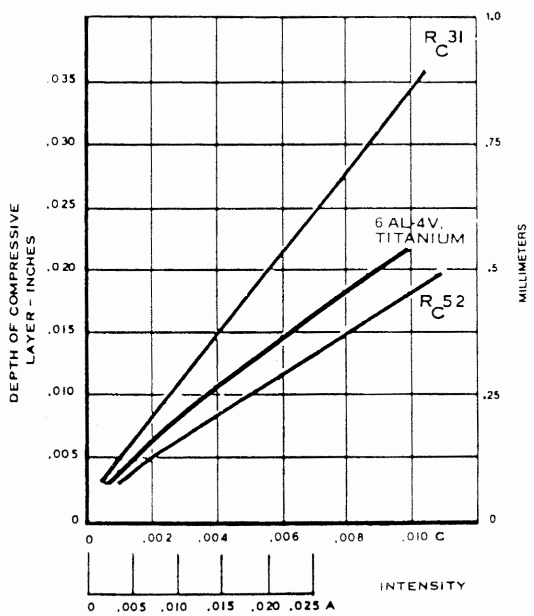


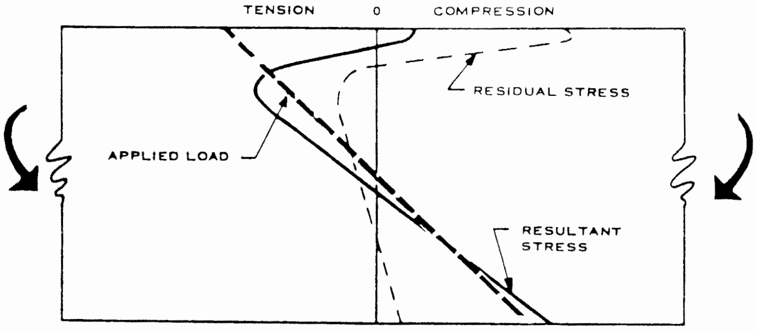
RESIDUAL STRESS PRODUCED BY SHOT-PEENING
VS TENSILE STRENGTH OF STEEL

Figure No. 1.



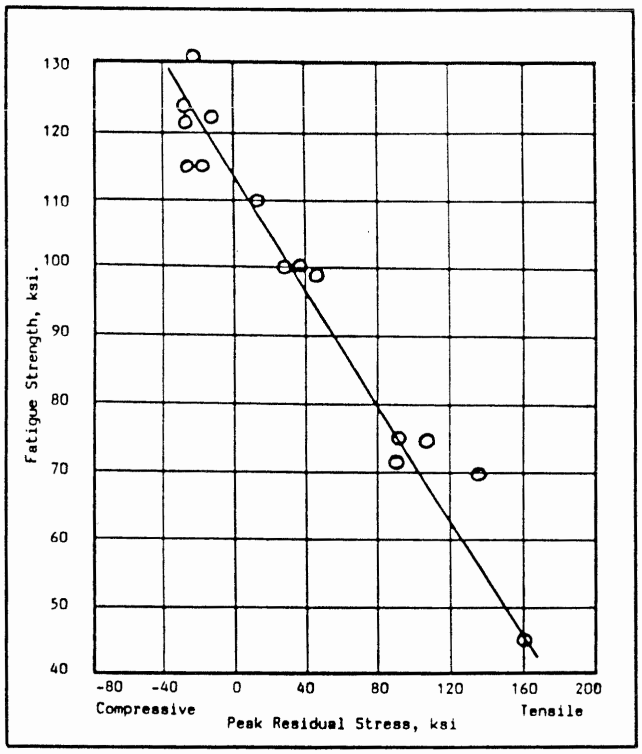
DEPTH OF COMPRESSIVE STRESS VS
ALMEN INTENSITY FOR STEEL & TITANIUM

Figure No. 2



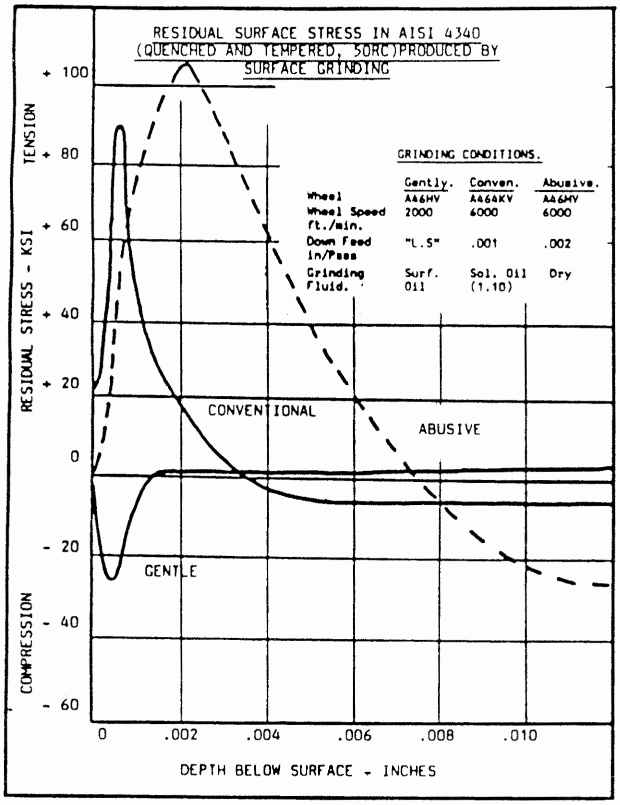
RESULTANT DISTRIBUTION OF STRESS
IN A SHOT-PEENED BEAM WITH EXTERNAL
LOAD APPLIED. SOLID LINE IS THE RESULTANT

Figure No. 3



FATIGUE STRENGTH vs PEAK RESIDUAL SURFACE STRESS IN
GROUND 50 RC STEEL

Figure No. 4



RESIDUAL STRESS IN 50 RC AFTER SURFACE GRINDING

Figure No. 5

WELD TOE PROFILE DATA

Condition of weld	Mean toe radius (mm)	Mean toe angle (deg)	K_t
As welded	1.4	53.	2.92
Improved profile	1.4	42.	2.85 (2.19)*
Toe ground	5.4	66.	1.93
TIG dressed	6.4	54.	1.82
Shot peened	1.4	53.	2.92
Toe ground/shot peened	5.4	66.	1.93
As welded, 100 mm plate **	1.4	53.	4.32
As welded, 100 mm plate **	4.7	53.	2.92

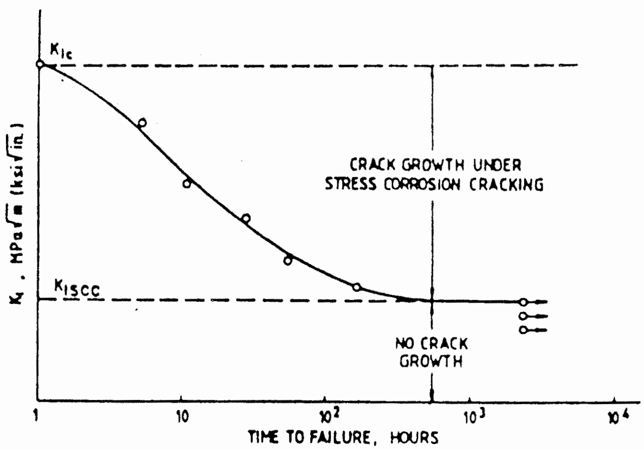
* corrected to fit test data
** assumed values for prediction of thickness effect

Figure No. 6

COMPARISON OF PREDICTED AND EXPERIMENTALLY DETERMINED FATIGUE STRENGTHS AT 2. 10^6 CYCLES

Condition of weld	S_{test} (MPa)	% improvement over the as-welded fatigue strength from test	S_{pred} (MPa)
Class F, mean line (t= 22 mm)	95		
As welded, T= 30 mm	102		112
As welded, T=100 mm			75
As welded, T=100 mm, scaled r			95
Improved profile	130	27	129
Toe ground, T=30 mm	153	50	147
TIG dressed	147	44	147
Shot peened	161	58	165
Toe ground and shot peened	261	156	250
Base material	290		

Figure No. 7



CRITICAL STRESS INTENSITY.

Figure No. 8