

**NPL REPORT
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**Integrity of Shot-Peened High
Strength Steel Components in
the Context of Residual Stress
Relaxation and Hydrogen
Uptake – A Critique**

A TURNBULL

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**Integrity of Shot-Peened High Strength Steel
Components in the Context of Residual Stress
Relaxation and Hydrogen Uptake – A Critique.**

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ABSTRACT

A short overview is given of the effect of applied static and cyclic stress on residual stress relaxation of shot-peened high strength steels. In the context of possible failure by hydrogen embrittlement, the impact of shot-peening on hydrogen uptake and diffusivity is considered also.

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1 INTRODUCTION

High strength low alloy steels are used in a wide range of applications where strength to weight ratio is critical; e.g. tension wires, fasteners and in many structural components. However, the steels can be susceptible to hydrogen embrittlement¹, with the potential for failure in service. In addition to processing of the alloys to optimise resistance of the microstructure, reduction in the risk of cracking is achieved by limiting hydrogen entry (application of coatings and well controlled cathodic/galvanic protection) and by minimising tensile stress. In some applications, control of the stress is achieved by inducing large compressive residual stresses in the near-surface region by shot-peening. The latter has had considerable success and has been used in the power, aerospace and nuclear industries to enhance structural integrity. However, relaxation of the beneficial compressive residual stress in response to service loading is a possibility, especially where fluctuating loads are important.

Residual stress relaxation in response to mechanical loading is not a new phenomenon and, indeed, has been exploited as a means of reducing undesired tensile residual stress in components². There has been a number of research investigations³⁻¹⁶ based on experimental measurement and modelling, though these have yet to evolve into guidelines for testing and evaluation of residual stress relaxation in service. In these studies of residual stress relaxation, parallel assessment of the impact on hydrogen uptake has been limited and thus an integrated assessment of the implications for structural integrity in the context of high strength steels is inherently constrained. Coatings would generally be applied to control corrosion, in some cases sacrificial coatings as such as cadmium, but coating damage has to be assumed and hydrogen generation from local corrosion or protection tolerated. Hydrogen uptake may be affected by the compressive stress at the surface and by the cold work associated with the introduction of the surface compressive stresses.

The objectives of this review are to highlight existing knowledge on residual stress relaxation in response to applied stress, static and dynamic, and to evaluate the literature on the impact of surface residual stress and cold work on hydrogen uptake and diffusion. In both cases, the focus will be on shot-peened surfaces. Nevertheless, this is not intended as an exhaustive review, rather a short overview as a framework for undertaking experimental investigation and interpreting the results.

2 RELAXATION OF RESIDUAL STRESS

In service, structures and components may be subject to quasi-static loading, impact loading, low amplitude cyclic loading and occasional large amplitude cycles with often a complex load spectrum and history. These external stresses may then activate microscopic or, if severe, macroscopic plastic flow leading to relaxation of residual stress. This is important in systems for which induced compressive stress is a key factor in sustained structural integrity and also for welded structures where relaxation of undesired residual tensile stress may have a beneficial effect, albeit one that cannot be relied on at the design stage.

There has been a diverse number of studies of residual stress relaxation in shot-peened materials. The more relevant of these has been assessed and the key features are now summarised.

2.1 EVALUATION OF PUBLISHED DATA

James³ reviewed the literature up to 1987 and this has since been updated following the review by Lohe and Vohringer¹².

2.1.1 External static load

In relation to quasi-static applied loads, the observation was made by James³ that stresses approaching yield must be attained before relaxation of compressive stresses induced by shot peening could occur. An example for a 7075-T6 Al alloy is shown in Figure 1. The applied stress at which relaxation occurred under applied tensile stress is close to that of the tensile yield stress for the unpeened material.

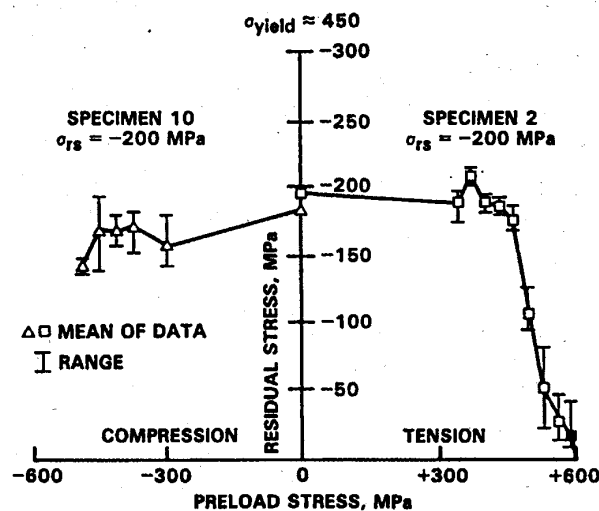


Figure 1. The effect of static load stress on the surface residual stress level of 7075-T6 Al (after James³ and reprinted from Potter and Millard in that reference).

In studying shot-peened En15R steel, the conclusion from more recent work by Smith et al¹¹ was similar in one respect insofar as the applied stress at which relaxation occurred was not affected by the magnitude of the residual stress (Figure 2).

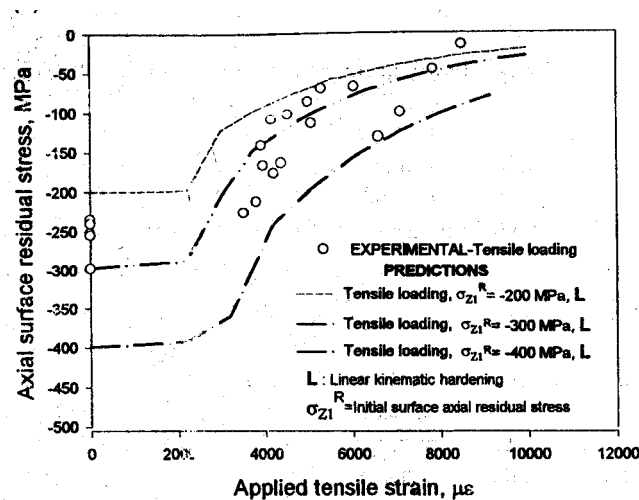


Figure 2. Experimental results and FE simulations of residual stress relaxation of EN15R steel after tensile loading using kinematic hardening model (after Smith et al¹¹).

However, the major difference was the observation that relaxation was initiated at an applied tensile strain significantly below that corresponding to yield of the unpeened material. With an initial yield stress before peening of 800 MPa, the expected applied strain to cause yielding (accounting for the negative compressive stress) would be 5200 $\mu\epsilon$. Clearly, relaxation was occurring well below that value, which the authors attribute to the non-linear dependence of residual stress relaxation on the surface strain. The authors invoke the Bauschinger effect* in which the compressive yield stress is reduced if the material is initially subjected to an applied tensile strain above yield. In this case, they do not explain clearly how this applies to shot-peened surfaces that are initially in biaxial compression and subject to tensile loading, nor why relaxation is initiated at the same applied microstrain for different levels of initial residual compressive stress.

* The physical basis of the Bauschinger effect was associated initially with simple ideas based on residual stress following prestrain but is now better explained by modern dislocation theory. There is a degree of overlap as, depending on the alloy, the latter can give rise to internal back stresses but also the possibility of microstructural modification allowing greater ease of deformation; i.e. a lowering of the yield point of the material as distinct from an additive stress concept. The origin of the early residual stress model is differential deformation in the material, with some regions deforming plastically and other elastically. After unloading, the regions that have deformed plastically have associated compressive residual stress and the elastically deformed regions have balancing residual tensile stress. Upon compressive loading yielding will occur at a lower applied stress because of the local regions of residual compressive stress. The plastically deformed regions could be slip bands or some “softer” phase or component and could arise in polycrystalline and it is argued in single crystalline metals (C. Zener, *Elasticity and Anelasticity of Metals*, Univ. of Chicago Press, 1948). The dislocation theory is perhaps considered more apt but more complex with several variations on the theme, the simplest being to consider dislocation piling up at obstacles of one kind or other producing back stresses that assist reverse plastic flow. Other perspectives envisage dislocation lines bowing out between obstacles and then rebounding when the load is reduced generating plastic deformation in the opposite direction. Also, annihilation of dislocations of opposite sign will reduce strain hardening and the yield point of the material upon reverse loading (the thesis of J Yan, ‘Study of Bauschinger effect in various spring steels’, Univ. of Toronto, 1998 provides a useful web-accessible overview of this complex subject.)

It is a complex issue as there will be gradients of cold work, and hence yield strength, in the material, biaxial stress states, as well as a transition from near-surface compressive stress to tensile stress. Superimposed on this will be the applied static stress. There will also be a material sensitivity to the prior treatment and the response to applied stress. This may explain why the results reported in the review by Lohe and Vohringer¹², appear to differ quite considerably from that of Smith et al. In this case (Figure 3) the residual stress in shot-peened specimens relaxes under applied tensile stress at a stress corresponding to 95% of the yield stress (1180 MPa) of the unpeened material, similar in response to that observed for 7075-T6 Al quoted in the review by James³.

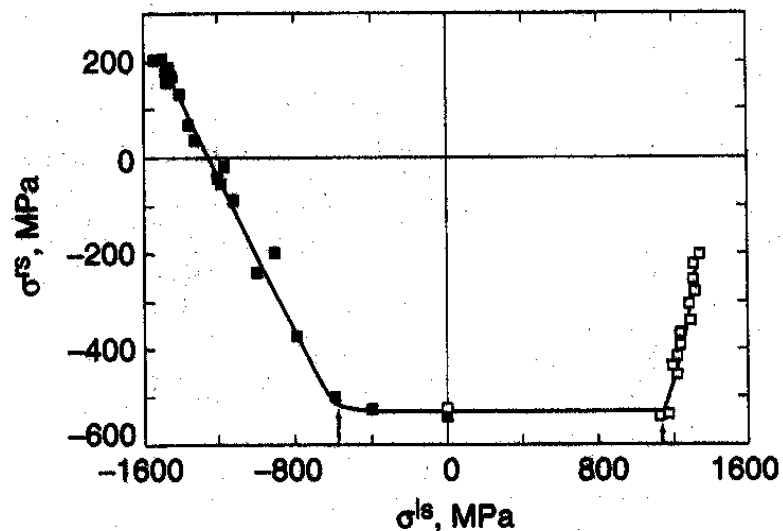


Figure 3. Macro residual stress at the surface versus loading stress under tension and compression, respectively, of shot-peened AISI 4140 in a quenched and tempered condition (after Lohe and Vohringer¹²).

There would appear to be no observation of the markedly reduced applied tensile stress required for relaxation measured by Smith et al. When the applied stress was compressive, residual stress relaxation set in (Figure 3) at about 45% of the compressive yield strength of the unpeened material (1300 MPa) suggesting that the relaxation is induced by the combined residual and applied compressive stress. The relaxation occurs more slowly with increasing compressive stress and is complete just below the yield strength of the unpeened surface before going net tensile. Under tensile loading, the relaxation is faster but incomplete.

Lohe and Vohringer describe the critical stress for the onset of plastic deformation, and thus residual stress relaxation initially for the core as the summation of the applied tensile and tensile residual stresses. In the surface zone, a similar summation is made of the compressive residual stress and the applied stress but the authors recognise that with a multi-axial residual stress state, typical of that with shot peening, the yield stress will be modified and indeed may be somewhat smaller. However, this effect depends on the material characteristics: for a normalised AISI 4140 steel the surface work hardens to give a higher yield strength but for the quench and tempered steel, work softening

occurs. The latter is attributed to a strong Bauschinger effect in the quench and tempered steel. In essence, the yield strength is increased if the peening-induced work-hardening is stronger than the Bauschinger effect and vice versa.

It is still hard to reconcile the observations of Lohe and Vohringer with the observation of Smith et al of a relatively low tensile stress for stress relaxation in their EN15R steel. The apparent independence of residual stress in the latter may reflect the limited variation in tensile stress in the core, on the assumption that under tensile applied stress it is the core that deforms and relaxes the surface residual stress. This is indirect in one sense insofar as relaxation of the core residual tensile stress due to yielding must be associated with a balancing change in surface compressive stress. This balance is presumably achieved on unloading as the core is elongated more than the surface and the compatibility of stresses tends to drive the core under compression and the surface under tension¹³.

However, it is still difficult to explain the apparent reduction in yield strength in the core of the specimens that is under tension implicit in the work of Smith et al. Despite this, their model predictions do conform well to the experimental data, though the model does not appear to account for multi-axial stress state. It should be emphasised that the residual stress is measured after unloading and reversed plasticity would possible cause microscopic yielding. This may have a minor influence but there may be some merit in measuring the actual near-surface stress in self-loaded specimens and inferring the residual stress.

2.1.2 Fatigue loading

Zhuang and Halford¹⁰ suggest that relaxation under cyclic loading is affected mainly by: (1) initial magnitude and gradient of the residual stress field and degree of cold working; (2) fatigue stress amplitude, mean stress and number of cycles; (3) material cyclic stress-strain response and degree of cyclic work hardening/softening. The cyclic directed dislocation movement/generation converts the elastic strain associated with the macro residual stress into micro plastic strain.

A range of studies of residual stress relaxation under cyclic loading has been conducted and all show a consistent pattern in the response of the near surface residual stress. Where the stress amplitude or range is sufficient to induce relaxation then there is a relatively large degree of relaxation in the first cycle and then a more progressive relaxation with subsequent number of applied load cycles.

Smith et al predicted the residual stress relaxation for shot-peened tensile specimens of EN15R steel under fully reversed loading (stress ratio -1) with the first half cycle in tension. The results are presented in Figures 4 and 5 where the response to different magnitudes of the strain range is shown. Here, $2200\ \mu\epsilon$ would correspond to about $0.65\ \sigma_y$. The relaxation is modest at this stress range and indeed is all achieved during the first cycle. Only with the higher stress range is there more progressive relaxation with numbers of cycles. Interestingly, the transition depth between compressive and tensile stress seems not to be affected, though this needs experimental confirmation. This is important when considering hydrogen ingress.

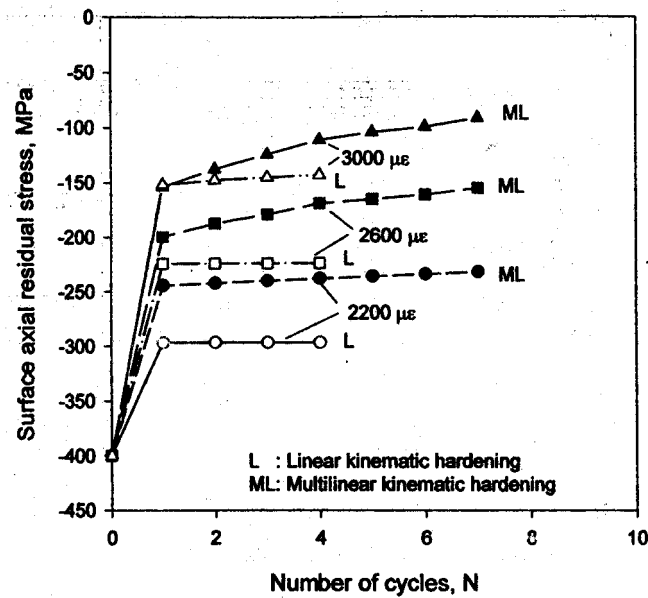


Figure 4. Finite element prediction of axial residual stress relaxation with varied cyclic strain range using linear and multi-linear kinematic hardening assumptions with an initial surface axial residual stress of -400 MPa (after Smith et al¹¹).

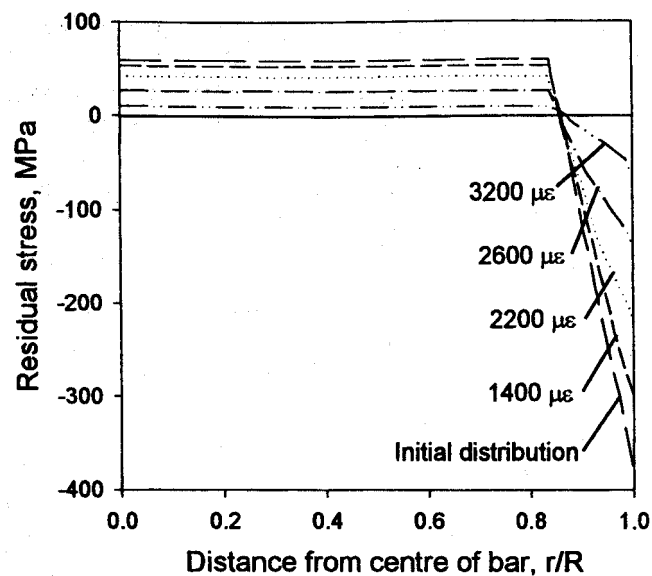


Figure 5. Predicted redistribution of axial residual stress after the first fatigue cycle (after Smith et al¹¹).

Lohe and Vohringer¹² reported measurements on a quenched and tempered AISI 4140 steel that showed a broadly similar behaviour to the predictions of Smith et al, as shown in Figure 6. A significant degree of relaxation occurs in the first cycle but thereafter relaxation depends on the magnitude of the stress amplitude and can be described by a logarithmic creep law similar to that previously derived by Kodama²:

$$\sigma^{rs} = A(\sigma_a) + m(\sigma_a) \cdot \log N \quad (1)$$

where σ^{rs} is the shot-peened induced macro residual stress at the surface, A and m are functions of applied stress amplitude (σ_a) and are obtained from the linear section of the curves in Figure 6b and N is the number of cycles. At the end of the fatigue life, departure from this relationship can occur which in this case was attributed to cyclic work softening (Figure 5a) but in other circumstances could also be induced by crack development.

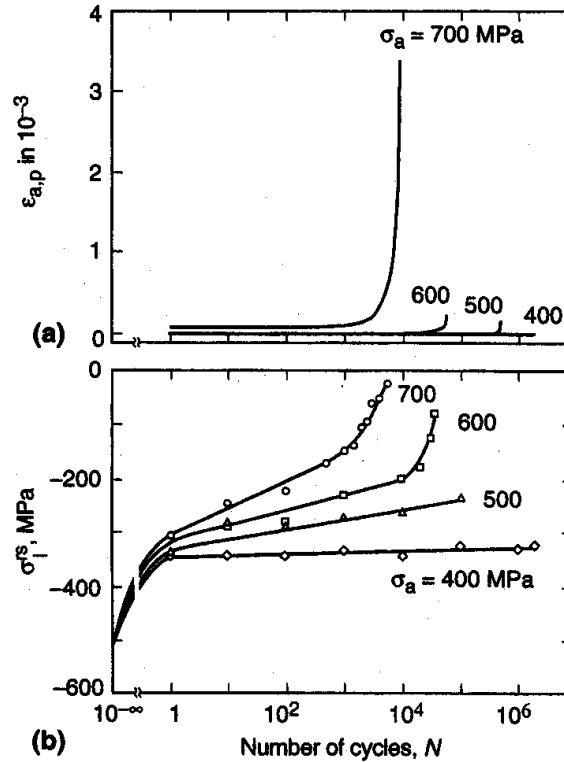


Figure 6. Plastic strain amplitude and longitudinal macro residual stress versus number of cycles during strain-controlled push-pull tests with different stress amplitudes of shot-peened AISI 4140 in a quenched and tempered condition: 600 °C for 2h (after Lohe and Vohringer¹²).

In these tests, the specimens were subjected to axial loading. Under alternating bending, the relaxation is less complete as shown in Figure 7. Here the topside was initially loaded in compression in the first half cycle. Relaxation responded to the compressive cycle with little relaxation on the bottom side, which would be loaded in tension during the first cycle. On reversing the load, the residual stress on the bottom then relaxes. Overall, the degree of relaxation is much less than in axial loading.

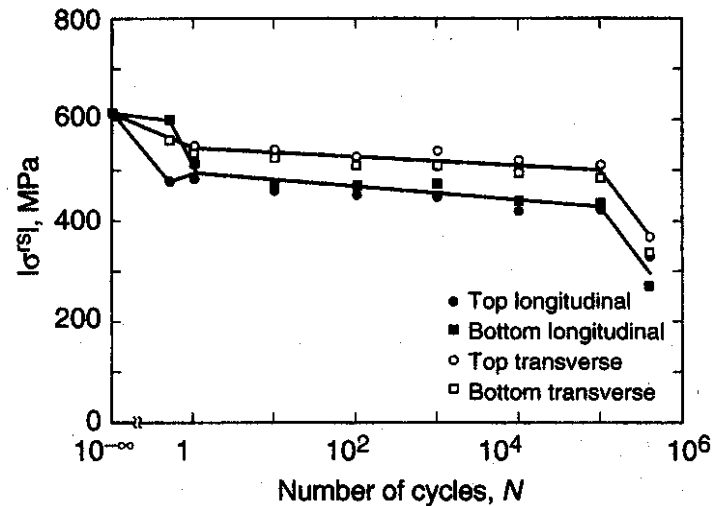


Figure 7. Absolute values of macro residual stress at the surface versus number of cycles during alternating bending testing of shot-peened AISI in a quench and tempered condition (450 °C for 2h0 for a surface stress amplitude of 700 MPa. The sharp decrease at large number of cycles reflects crack development (after Lohe and Vohringer¹²)

Focusing on Inconel 718, Zhaung and Halford¹⁰ developed an analytical model that generates the same trends in behaviour to that of Smith et al and of Vohringer in terms of residual stress relaxation with increasing numbers of fatigue cycles. As shown in Figure 8, there is an initial relatively large decrease in the first cycle and a more progressive decrease with increasing number of cycles, depending on the stress amplitude.

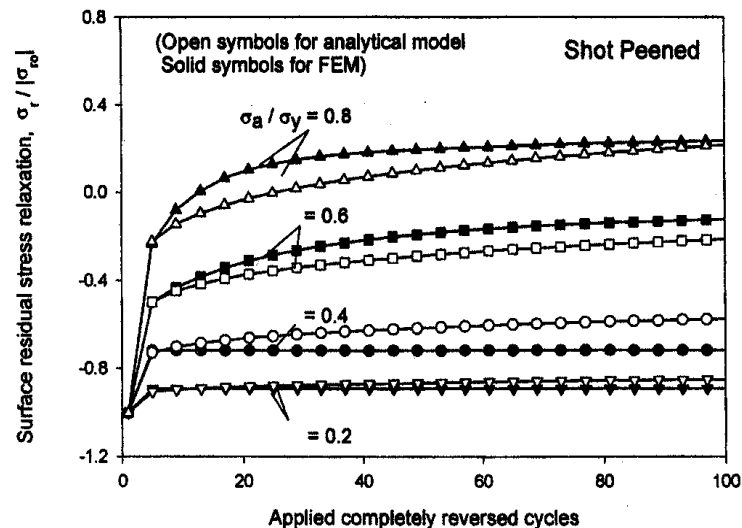


Figure 8. Comparison of analytical and FE predictions of the effect of load amplitude on residual stress relaxation in Inconel 718 (after Zhaung and Halford¹⁰).

The analytical model accounts for stress ratio, R , and the degree of cold work:

$$\frac{\sigma_N^{\text{re}}}{\sigma_0^{\text{re}}} = A \left(\frac{2\sigma_a^2}{(1-R)(C_W \sigma_Y)} \right)^m (N-1)^B - 1 \quad (2)$$

where the first term represents the ratio of the residual stress after N cycles to the initial value (absolute value), A is a material constant, B controls the relaxation rate versus loading cycles, m is a material constant that depends on cyclic stress and strain response and C_W is a parameter that accounts for the degree of cold work. The analytical model appears to predict the relaxation behaviour well (albeit FE calculated) and can also account for the source of the residual stress (Figure 9); shot-peening, laser shot-peening and low plasticity burnishing. However, these are all theoretical predictions and the authors acknowledge the need for experimental validation.

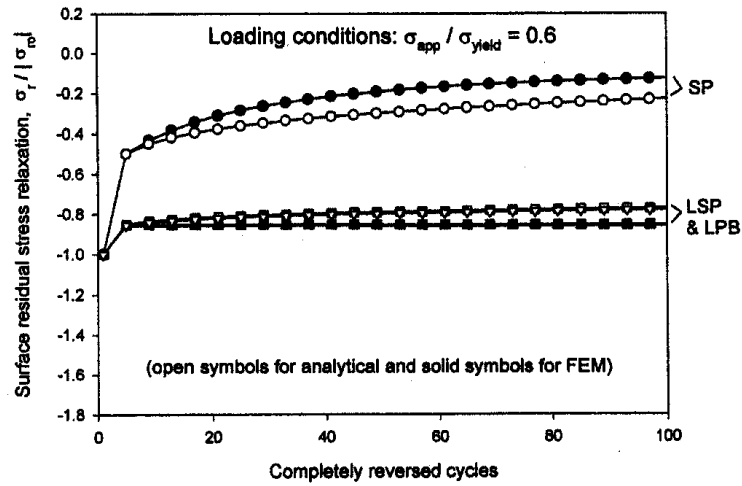


Figure 9. Predicted variation of surface residual stress with loading cycles for different surface treatments (after Zhaung and Halford¹⁰)

The important point to note is that relaxation does not require macroscopic yield but responds to cyclic loading induced microplasticity. The model of Zhuang and Halford predicts an increase in stress relaxation with increase in stress ratio. A detailed study of the effect of stress ratio on residual stress relaxation at constant stress amplitude has been difficult to locate.

2.2 DISCUSSION

The lack of consistency in results for the effect of applied static stress on residual stress relaxation makes it difficult to draw together the key features of this literature in a fully coherent way. Relaxation is contingent upon some degree of microscopic or macroscopic plastic deformation. On that basis, the expected behaviour under tensile applied stress would be for an applied stress at relaxation to be just smaller than the yield stress. This reflects the influence of the small net tensile residual stress in the bulk of the tensile specimen. There would be a core layer above yield and a surface layer in net tension but below yield. The assumption is that once deformation of the core occurs this induces relaxation of the residual tensile stress in the core and a balanced reduction

in the compressive stress must occur. Further clarification is required to resolve the unexpected results of Smith et al but there is a general issue of whether the unloading process affects the measured compressive stress.

There is a high degree of consistency with respect to the impact of cyclic loading with a relatively large degree of relaxation occurring in the first cycle and a progressive decrease with increasing cycles, the magnitude dependent on the applied stress amplitude. The latter would simply reflect the higher degree of plastic deformation with increasing load amplitude but implies the minimum requirement for the stress amplitude to continue to induce microplasticity. At low stress amplitudes, no cyclic plastic deformation occurs after the first cycle.

There will also be a Bauschinger effect. Shot peening acts as a tensile pre-load, which results in a decrease of compressive yield strength as soon as the material is loaded under compression¹⁴.

These studies seemed to focus on constant amplitude loading with little evidence of systematic investigation of the effect of variable amplitude loading and limited assessment of the effect of stress ratio.

3 IMPACT OF RESIDUAL COMPRESSIVE STRESS ON HYDROGEN UPTAKE

There is a risk that coating damage will occur in service leading to hydrogen generation and the possibility of hydrogen uptake. Two factors are important: the extent of coating damage, which is important in determining the active source area for hydrogen and thence the degree of absorbed hydrogen delocalisation, and the impact of the compressive stress and cold work on hydrogen uptake and diffusion. The emphasis will be on the latter but the issue of source area will be considered in the discussion.

3.1 EVALUATION OF PUBLISHED DATA

In shot peening a surface, there are several factors that may potentially impinge on hydrogen uptake and permeation: the surface area is increased, the hydrogen discharge and recombination reactions may be affected, compressive residual stress is introduced and may affect hydrogen solubility in the lattice, and the surface is heavily cold worked with a high dislocation density leading to local trapping. There have been a number of studies to resolve the relative contribution of these factors.

From thermodynamic considerations, a reduction in hydrogen solubility with compressive stress is to be expected and relatively large values were proposed for pure iron¹⁷ but for low alloy steels¹⁸ the effect was considered to be less significant because of the lower partial molar volume of hydrogen in the low alloy steels. In other words, the hydrogen atom, or more accurately the proton, in the interstitial site doesn't take up too much of the space and so will be less affected by elastic compression of the adjacent lattice. Indeed, a decrease in permeation flux of only 17%, at relatively high compressive stresses, was reported by Bockris and Subramanyan¹⁸. The diffusivity was found to be unaffected by elastic compressive stress^{17,18}.

Measurements of hydrogen permeation on shot-peened specimens are more difficult to interpret because of the range of factors affected. Brass et al²¹ reported a 20% decrease in permeation flux for shot-peened specimens of a low carbon steel, with no change in diffusivity. Two levels of shot peening had been undertaken to induce different depths of cold work but with no difference in permeation current. Chattoraj and Wilde²⁰ reported a factor of up to two decrease in permeation current density for a AISI 4130 steel but also no impact on diffusivity. In both cases, shot peening was applied to the charging surface only in a standard Devanathan-Stachurski double cell electrochemical permeation test.

When shot peening was applied to the oxidation surface there was a significant decrease in the diffusivity. The interpretation of this observation varied, with Wilde and Chattoraj²² using this as evidence for a role of compressive stress in reducing permeation. This is a questionable deduction and Brass et al²¹ offer a more enlightened perspective based on the influence of trapping on hydrogen diffusion. In essence, there are two layers in these membrane tests, a thin surface layer with varying levels of cold work with an increased trap concentration and a much thicker (typically > 10:1) layer of the original material. Diffusion will always be slower through the high trap region but the impact of overall diffusivity will depend on the thickness ratio and the relative diffusivities in the two regions. When the cold work layer is at the charging surface the higher concentration of hydrogen associated with the charging surface causes the traps to be more readily occupied. The effective diffusivity in this region will increase because there are less available empty traps, diminishing the impact on the average diffusivity through the steel membrane. When the layer of high trap concentration is on the exit (oxidation) side, the lattice concentration is inherently low. Correspondingly, the trap occupancy will be low and there is a high probability of diffusing lattice hydrogen being trapped. The low diffusivity in this layer will be sustained and this will reduce the average diffusivity through the steel membrane.

An explanation for the decrease in the steady permeation current when the shot-peened layer is on the charging side is still required. At steady-state, the flux can be expressed as $J = DC_0/a$ where D is the lattice diffusivity, C_0 is the sub-surface lattice concentration on the charging side and a is the thickness of the membrane. Trapping does not play a role at steady state since lattice and trapped hydrogen concentration are at equilibrium. Since the lattice diffusivity has been shown not to be affected by shot-peening, the decrease in flux must be associated with a decrease in sub-surface concentration. There is a modest effect of compressive stress on lattice solubility, which can account for almost 20% of the decrease, enough to explain the results of Brass et al²¹ but not those of Wilde and Chattoraj²².

The latter authors then proposed an effect of shot peening on the surface coverage, recognising that the sub-surface concentration will be in equilibrium with the absorbed hydrogen atoms in these experiments. They invoked a concept of the stress redistributing the surface electrons, thereby reducing the effectiveness of hydrogen charging, which depends on the supply of electrons. This seems a very tenuous explanation since the charging current was maintained constant in these tests. An effect on the surface area or on the recombination reaction would be more pertinent. For constant current to nominally unit area, a rougher surface should mean that the hydrogen atoms are likely to be more spaced out assuming a simple proportional increase in the number of active sites. That is more likely to encourage hydrogen entry,

since recombination is more difficult as more surface diffusion is required to find a neighbour to recombine with. In practice, polarisation experiments indicated no difference between shot-peened and untreated specimens, suggesting no corresponding increase in surface sites. Hence, surface roughness in simple terms would not seem to be a factor, one way or the other. A more efficient recombination is implied, thus generating a lower surface coverage, albeit without any physical explanation.

3.2 DISCUSSION

The results have to be considered in the context of a steel surface that has been shot-peened and then coated. The key requirement for sustaining structural integrity is to prevent build up of hydrogen in the tensile sub-surface region as little hydrogen is required for high strength steels to fail in tension¹. There is clear evidence of a reduced hydrogen content and steady-state flux with conventional shot-peening. However, the effect is modest and as low as 20%. This is scarcely the kind of reduction that would inspire confidence in the effectiveness of shot-peening in mitigating failure by its effect on hydrogen uptake. Whilst there will be surface compressive stress that will reduce susceptibility where the hydrogen content is highest, the hydrogen would in principle diffuse to the tensile region and induce failure. Indeed the permeation measurements indicated a timescale of hours to achieve such penetration.

To understand why failure does not readily occur (albeit problems in military aircraft exposed regularly to seawater are more common), it is necessary to move away from the concept of sustained and uniform hydrogen charging as adopted in permeation tests and many laboratory mechanical tests. The latter would be relevant for a coating that had failed catastrophically with a large area of steel corroding, or had been subjected to cathodic polarisation in a sustained manner. In practice, coating failure would usually be highly localised and the exposure transient and these factors are of key importance. Hydrogen entering the steel from a local source will undergo multi-dimensional diffusion with the character depending on the nature of the coating damage; e.g. scratch or local pore breakdown. This diffusion away from the source will cause significant delocalisation of the hydrogen atoms and will reduce significantly the available hydrogen concentration at regions relatively remote from the source. Clearly, the distance scale will be determined by the area of the source. This delocalisation has been demonstrated theoretically²³ and the beneficial effect confirmed in experimental measurement using partially coated tensile specimens of a carbon steel exposed to an aggressive environment²⁴. The other factor is intermittent exposure. In the case of protection from cadmium coating for example, the dry period may result in hydrogen diffusing back out of the steel and of course diluting its local concentration by diffusion and delocalisation within the steel.

There will be a reduced diffusivity in the cold worked zone because of the high concentration of traps. This could be an advantage under intermittent exposure as it would limit the ingress of hydrogen during the exposure period.

The biggest concern would be pitting corrosion if this develops to a depth where the primary local source of hydrogen begins to approach the transition between the compressive and tensile residual stress zones.

In conclusion, there is a reduction in hydrogen entry in response to shot-peening of high strength steels but, while welcome, the effect would be considered rather modest and in itself would be insufficient to establish confidence in structural integrity. The extent of damage to the coating will be the biggest factor that will influence the hydrogen ingress and coating maintenance is the key to sustaining low hydrogen content in the steel.

4 CONCLUSIONS

- Stress relaxation of shot-peened surfaces is contingent upon the material yielding locally or macroscopically.
- Under applied static load, the weight of evidence suggests that this is achieved when the combined effect of residual stress and applied stress (allowing for biaxiality) exceeds the yield stress for the unpeened material but with one unusual result indicating relaxation considerably below the expected value.
- For cyclic loading, a relatively high degree of relaxation occurs in the first cycle with further relaxation dependent on the stress amplitude inducing sufficient microplasticity.
- After the first cycle, the dependence of stress relaxation on the number of cycles tends to obey a logarithmic creep law.
- The location of the transition from compressive residual to tensile residual stress seems not to be affected by stress relaxation according to predictions but this needs experimental validation.
- While stress amplitude is argued to be the most important parameter there seems limited investigation of the impact of stress ratio and of variable amplitude loading.
- Hydrogen diffusivity in steels is not affected by compressive stresses associated with shot peening and the solubility is reduced only by 17%. In itself, this would be insufficient to establish confidence in structural integrity.
- There will be a reduced diffusivity in the cold worked zone because of the high concentration of traps. This could be an advantage under intermittent exposure as it would limit the ingress of hydrogen during the exposure period.
- A combination of hydrogen delocalisation from the source and the intermittent nature of exposure may explain why failures have not been more prevalent
- However, if combined with significant stress relaxation such a benefit may not accrue.
- Pitting corrosion is a concern if this develops to a depth where the primary local source of hydrogen begins to approach the transition between the compressive and tensile residual stress zones.

- The extent of damage to the coating will be the biggest factor that will influence the hydrogen ingress, and coating maintenance is the key to sustaining low hydrogen content in the steel.

5 RECOMMENDATIONS

- The extent of residual stress relaxation in response to both static and cyclic stress will be material sensitive and it is necessary to develop data specific to the material and application.
- In the latter case, this should account for the complex variable loading that will be experienced in service, including occasional overloads, either compressive or tensile.
- The effect of stress ratio is apparently not so well characterised experimentally and a more systematic evaluation would be of value.
- The rate of stress relaxation in response to such variable loading needs to be determined and any load interaction effects considered when applying simple summation laws.
- Residual stress profiling with high-resolution measurement techniques is essential but should be coupled with detailed microstructural evaluation.
- There seems less need for direct measurement of hydrogen permeation as the existing data are reasonably clear but there is a more fundamental issue of trying to track the hydrogen profile under intermittent exposure. A capability for predicting pit size development under service conditions would be pertinent for local failure of non-sacrificial coatings.

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