Effects of Plastic Straining on Residual Stresses induced by shot-peening

D.Kirk, School of Materials, Coventry Lanchester Polytechnic, Coventry, UK.

Introduction

The 'skin' of residual compressive stress induced by shot-peening is of primary practical importance. It is this skin of compressive stress, which offsets applied tensile stress, that gives rise to improved service performance in fatigue, corrosion-fatigue and stress-corrosion situations. Any factor which affects surface stress level is therefore very significant.

It is well-known that elevated temperature treatments can reduce the level of residual stress in a component (1,2). Harmful tensile surface stresses are usefully reduced by 'stress-relief-annealing'. Beneficial compressive surface stresses are also relieved by elevated temperature treatments and are therefore proscribed in standard specifications for shot-peened components (3). It is less well-known that small plastic strains can drastically affect the residual stress distribution in shot-peened components and therefore should be proscribed. Vohringer (1) has pointed out that, for a shot-peened aluminium alloy (AlCu5Mg2) both tensile and compressive plastic strains will change the surface stress level. A small applied tensile plastic strain can replace the original compressive surface residual stress with a tensile surface residual stress. Compressive plastic strains, on the other hand, only reduced the level of surface compressive residual stress without reversing its sign.

This work is concerned with extending our knowledge of the effects of plastic strain applied to shot-peened material. Only applied tensile strains have been considered since they are known to have a more serious effect than applied compressive strains. Two simple pure materials, copper and nickel were chosen together with three steels - a mild steel (American Flat B), a plain-carbon steel (BS EN8) and a low-alloy steel (BS EN30B). Sub-surface residual stress distribution changes were to be examined for the two pure materials. All of the work was to be carried out on flat tensile test pieces shot-peened on both major surfaces using the same grade of shot.

Experimental Details

The materials used for this investigation were copper (O.F.H.C., 99.99%Cu), nickel ('O' grade, 99.92%Ni), a mild steel (American Flat B, 0.05%C), a plain-carbon steel (BS EN8, 0.4%C, 0.8%Mn) and a low-alloy steel (BS EN30B, 0.3%C, 0.5%Mn, 4.1%Ni, 1.25%Cr, 0.3%Mo).

The samples used were in the form of flat tensile test specimens. These specimens were 150mm long overall with a central region 13.0mm wide by 3.0mm thick for the copper and nickel and 2.2mm thick for the three steels. All of the specimens were stress-relief-annealed prior to shot-peening. The copper and nickel specimens were peened to 5N using SAE 70 shot. All of steel specimens were peened to 8A2 using SAE 110 shot.

Tensile plastic strains were applied using an electronic tensile test machine with an extensometer clipped to each specimen in turn. Different plastic strains were applied within a separate series of specimens for each material. These strains were estimated from the load/extension curve obtained for each specimen. Accurate plastic strain readings were deduced from the change in the separation of small diamond-shaped indentions monitored using a travelling microscope.

Sub-surface residual stress measurements on the copper and nickel specimens required the uniform removal of successive layers of materials. This was effected by chemical polishing using appropriate solutions. Layers were removed from one major face only and stress measurements were corrected for the effects of layer removal.

Experiments and Results

The results of an investigation into the effects of applied plastic elongation on surface residual stress level are presented in Figs.1 to 5. The surface stress level was measured for every tensile test specimen both before and after tensile stretching. A significant scatter in the as-peened stress level was obtained for all five materials studied. Most of this scatter can be attributed to shot-peening variability. This is because the precision of residual stress measurement itself was established as less than one-quarter of the observed scatter. The shapes of all five stress/plastic strain curves are very similar. A common feature is that the surface stress level falls rapidly to zero with increasing applied plastic strain. The plastic strain at which this stress becomes zero may be termed the "critical strain". Estimated critical strain values are 0.30, 0.275, 1.1, 1.25 and 0.30% for copper, nickel, American Flat B, BS EN8 and BS EN30B respectively. A second common feature is that further plastic extension beyond the critical strain induces surface tensile residual stress. It appears that there is a maximum value for this induced tensile stress beyond which further extension tends to lower the stress level. These maximum values are estimated as being +160, +185, +375, +300 and +260MPa for copper, nickel, American Flat B, BS EN8 and BS EN30B respectively.

In-depth residual stress surveys, involving successive layer removal, were carried out on selected copper and nickel tensile test specimens. These surveys are illustrated in Figs.6 and 7. The surveys show several interesting features. In the as-peened condition the compressively-stressed 'skin' extends to a depth which is about 150µm for both copper and nickel. Beyond this depth balancing tensile residual stresses appear. On straining beyond the critical strains the stress system is reversed. A tensile-stressed surface layer appears with then a balancing compressively-stressed core. It can be inferred that the depth of the tensile-stressed surface layer increases with increasing post-critical strain. With an applied strain on copper only just beyond the critical strain (0.31 cf 0.30%) this depth is 50µm whereas, for nickel an applied strain of 1.31% (cf 0.275%) the depth is 100µm. A sub-critical strain of 0.25% applied to a copper specimen shows an intermediate stage of stress reversal. The compressively-stressed surface layer persists but with much lower levels of stress near to the surface.

Comprehensive metallographic studies and microhardness surveys were carried out on selected specimens before and after plastic straining. These confirmed (a) that the depth of the compressed layer in the as-peened condition was similar to that of the work-hardened layer and (b) that no significant changes in hardness were induced by plastic straining up to a 1.0% extension.

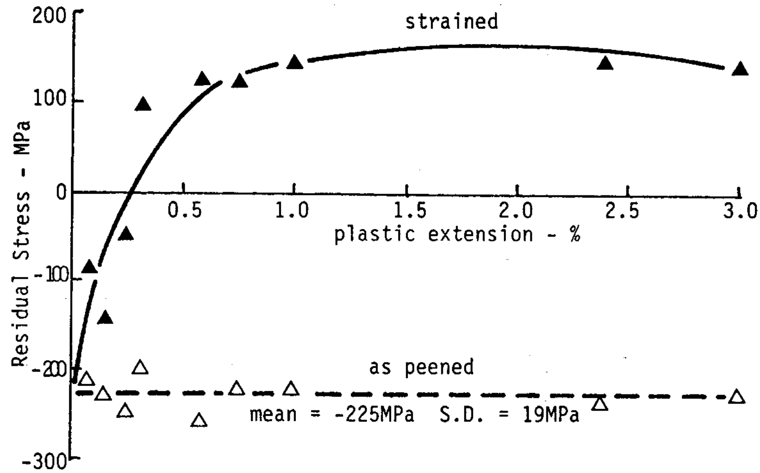

FIG.1: Residual Stress/Plastic Extension curve for shot-peened copper

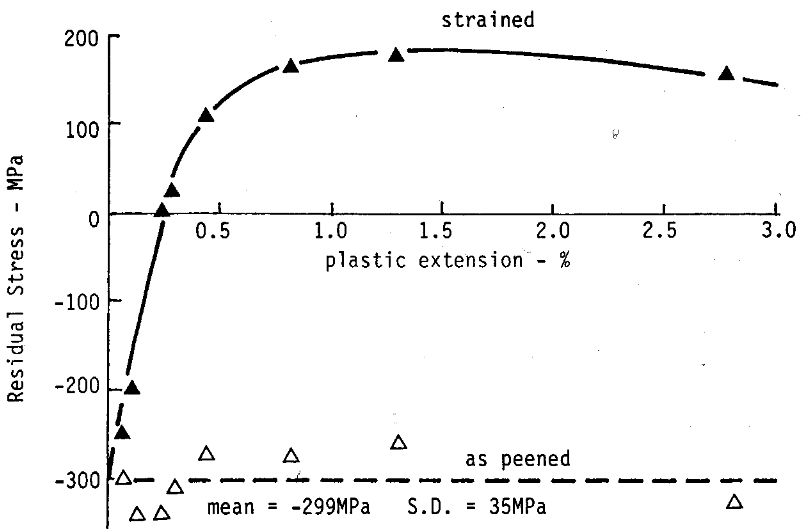

FIG.2: Residual Stress/Plastic Extension for shot-peened nickel

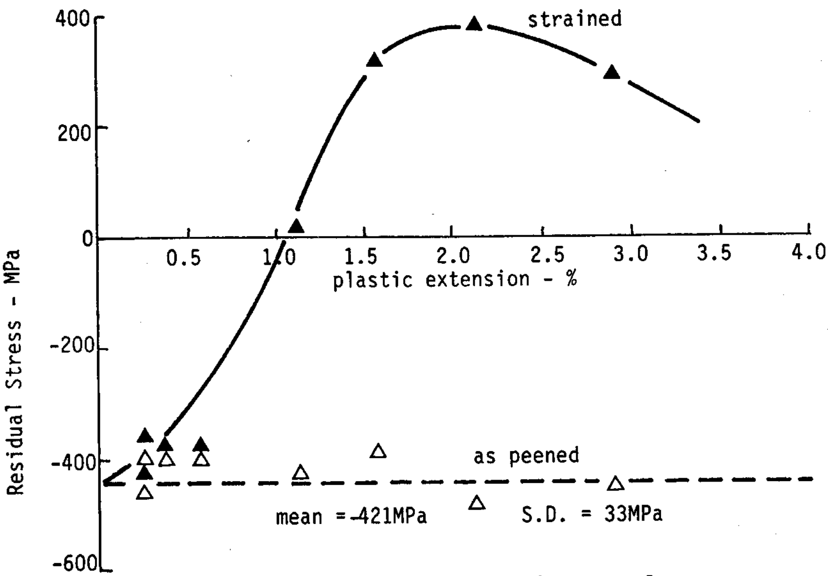

FIG.3: Residual Stress/Plastic Strain curve for shot-peened American Flat B steel

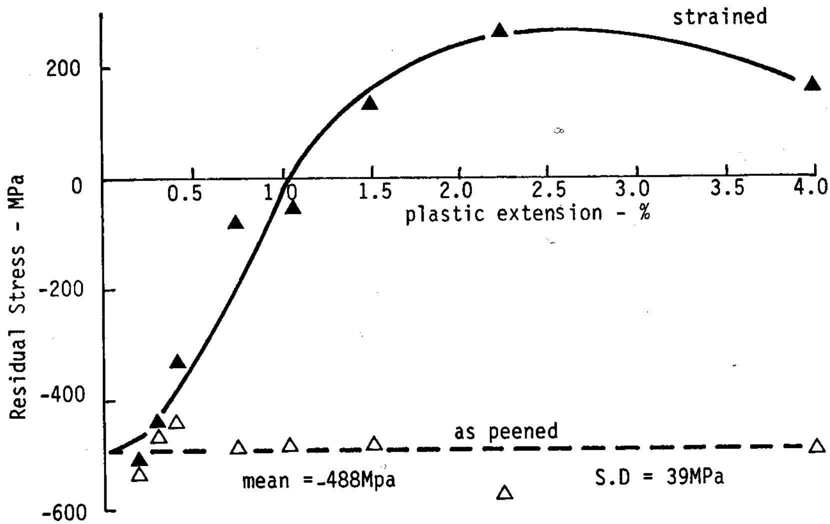

FIG.4: Residual Stress/Plastic Extension curve for shot-peened BS EN8 steel

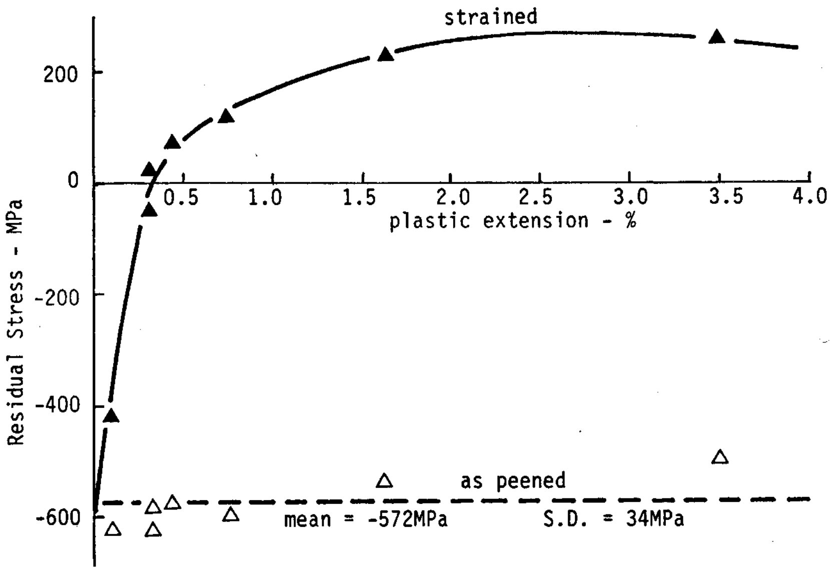

FIG.5: Residual Stress/Plastic Extension curve for BS EN30B steel

Discussion and Conclusions

The observed effects of tensile plastic strain on surface residual stress are very similar to those reported by Vohringer (1) based on work by Hirsch et al (2). It can therefore be concluded that surface stress reversal is to be expected if a critical tensile plastic strain is exceeded. This is very important since the advantages associated with having a surface compressive residual stress would be lost. Indeed we would have the disadvantages of a surface tensile residual stress. Service situations involving plastic straining of shot-peened components are not impossible. Accidental damage of components may occur and distorted components may be subject to straightening. These situations should therefore be avoided if at all possible. Re-peening could, however, be used to restore a compressively-stressed surface layer.

Elegant models to explain the mechanism of surface stress reversal have been presented by Vohringer. The present results can be explained using the same models.

It is apparent from the sub-surface residual stress surveys that stress reversal is not confined to the extreme surface. Induced tensile residual stress can extend to a depth similar to that of the original compressive stress.

The results obtained for sub-surface residual stress changes are too limited to justify a detailed, quantitative, model of behaviour. A simple mechanistic explanation is presented in Fig.8. The as-peened residual stress distribution, σ_R, is shown schematically together with the variation of yield stress, Y,

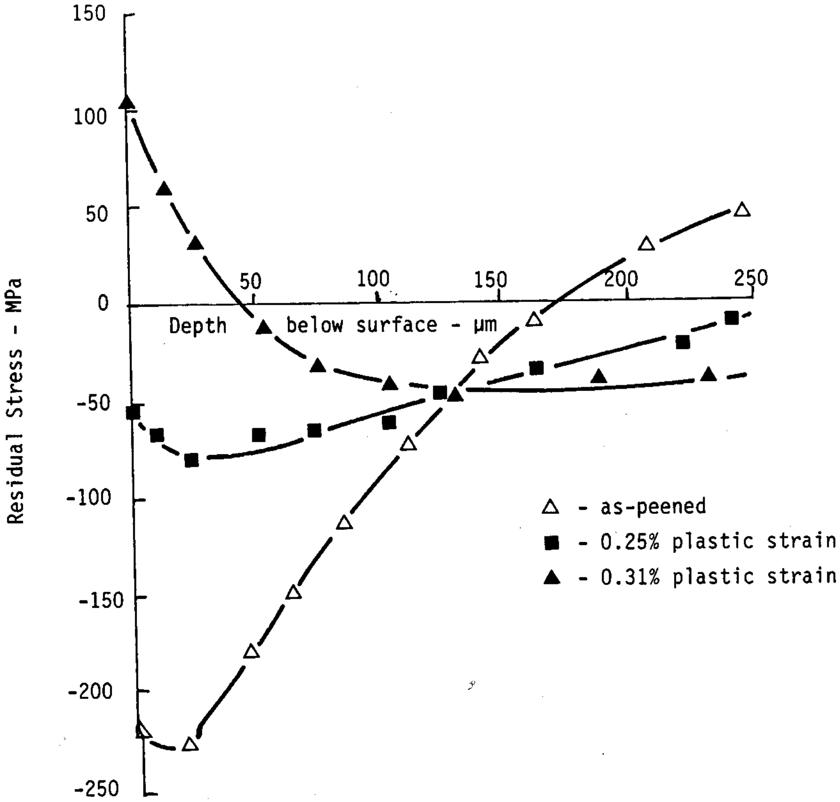

FIG.6: In Depth Residual Stress Surveys for as-peened and strained copper.

across the section. The yield stress is greater at the surface because of work -hardening induced by shot-peening. Any applied tensile stress, σ_A, will combine with σ_R to produce a combined stress distribution, σ_C. When σ_A reaches a critical value σ_C attains a value equal to the yield strength of the core. Permanent plastic extension of the core can therefore take place. The surface layers are, however, only loaded elastically at that stage. We then have the classic situation of homogeneous plastic deformation which is the basic mechanism for development of residual stress distributions. The core plastic extension is resisted by a tensile force in the surface layer. The greater the degree of core plastic extension the greater the balancing surface force has to be. This increased force is achieved by an increase in tensile stress level acting over increased depths.

In conclusion it should be pointed out that considerable scope exists for further studies of the effects of plastic straining on residual stress distributions in shot-peened materials.

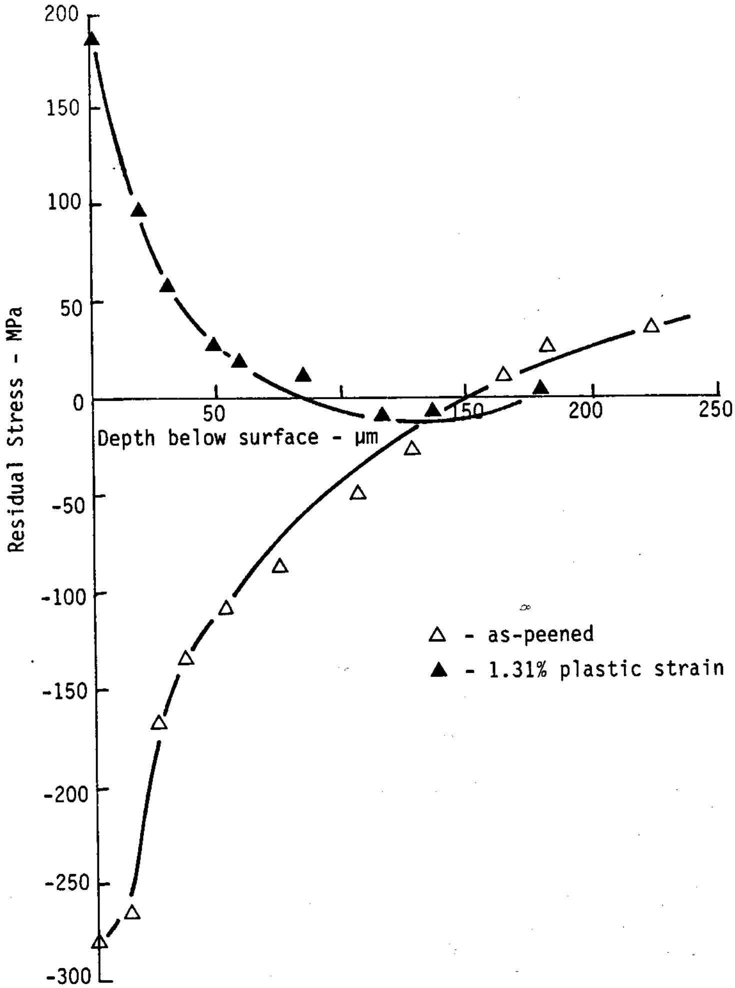

FIG.7: In Depth Residual Stress Surveys for as-peened and strained nickel.

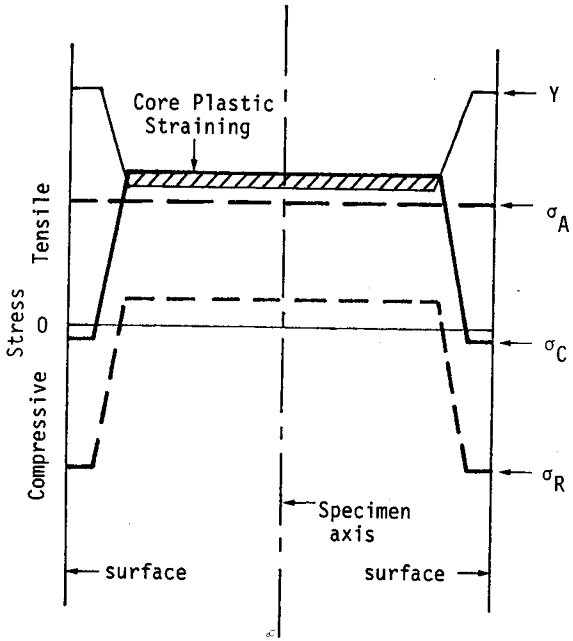

FIG.8: Schematic representation of stress superposition during tensile stretching of shot-peened specimen.

Acknowledgements

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References

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