APPLICATION OF SYNCHROTRON EDXRD STRAIN PROFILING IN SHOT PEENED MATERIALS

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ABSTRACT

We report the application of an energy dispersive X-ray diffraction (EDXRD) method to profile the depth variation of the strain in shot peened materials. The near surface compression, induced by shot peening, has made it a classic industrial technique to extend the loading limits and fatigue lives of materials. We have measured the detailed depth variation of the strain, in high carbon spring steel plackets of varying thickness, and peened with varying peening shot sizes. Our results directly elucidate a number of important issues: the magnitude and depth of the near surface compression; the detailed coupling of the peening-compression to the underlying plackets elastic strain with the resulting radius of placket curvature; and the correlation of the peening-compression depth with the peening shot size. A simple elastic/plastic model is used to quantitatively understand the peening effects and experimental results.

INTRODUCTION

Catastrophic failure of cyclic load-bearing components is, more often than not, near surface initiated. In particular, tensile surface strains/stresses, arising in the manufacture, processing or duty cycle of the component, greatly accelerate the surface-initiation and growth of cracks [1]. Since antiquity it has been empirically recognized that surface hardness/durability could be enhanced by impact-cold-working [2]. The systematic improvement of fatigue life by shot peening dates back to the early 1900's [2]. The high impact velocity of the peening shot causes a biaxial surface expansion and a near-surface plastic region, which is rendered in a state of compression by the coupling to the underlying bulk material. The characterization of the surface compression/toughening as a function of the peening intensity has been studied exhaustively over the years to optimize performance of a multitude of components varying from dental picks to airplane wings.

Characterization of the detailed magnitude and depth of the shot peening surface compression are crucial to the systematic improvement of this already highly successful surface toughening process. Such characterization rests on the same repertoire of techniques used in the more general field of residual strain/stress (RS/S) depth profiling [2-5]. Many of the most frequently used techniques in this area are explicitly destructive, and involve theoretical modeling of the strain fields accompanying material removal (e.g. hole drilling and layer removal) [3]. Conventional X-ray and neutron scattering have traditionally been the only direct (i.e. involving actual lattice parameter measurements), non-destructive methods for strain profiling as a function of depth into a material [2-5]. Unfortunately, the short penetration depth of the former (< 0.01 mm), and the large sampling volume (~1mm^3) of the latter make their applicability to shot peening studies quite demanding.

In recent years high intensity/energy synchrotron radiation has begun to be used for deeply penetrating X-ray diffraction strain profiling [5-9]. The high count rates, from small diffraction volumes, and simultaneous multi-line diffraction spectra achievable using

EDXRD has made it one of the prime techniques for such strain field depth profiling[5-7]. In this paper we discuss EDXRD strain profiling studies on shot peened test materials.

EXPERIMENTAL

The measurements were made using the high-energy/intensity "white beam" (20-150 KeV) "wiggler" source at X17-B1 at the Brookhaven National Synchrotron Light Source (NSLS)[5]. In EDXRD the incident/diffracted beam and sampling volume are fixed with the Bragg reflections being collected as a function of energy. The relation between the Miller indexed inter-atomic-plane spacing (d_{hkl}) and the corresponding Bragg reflection energy E_{hkl} is given by E_{hkl}(in KeV)= 6.199/[sin(θ) d_{hkl}(in Å)], where the scattering angle, 2θ ~ 12° was used in this work. A high-resolution, solid state Ge-detector was used in the data collection. The calibration of the detector energy scale and scattering angle were accomplished using multiple atomic fluorescence and cubic diffraction standards. A description of the detailed experimental setup can be found elsewhere [5-7].

In our EDXRD method the incident/diffracted beams are stationary and apertured to ~40 μm in height defining a small gauge volume. The diffraction profiling is accomplished by sample micro-positioning through the fixed gauge volume. The diffraction data analysis involved a several step procedure [7]. Background and flexible peak fitting functions were used to determine the Bragg lines centers of gravities. The average lattice parameter (a) was determined by least squares fitting over all lines, and was refined by a culling of lines with high a-value deviations and/or statistical error. The relative lattice parameter precision of this fitting process was between ±0.0001 and ±0.0003 Å (or better). It should be noted that evaluation of the strain from $\Delta a/a_o$, using each Bragg line individually, always tracked (with larger error bars) the results of the higher statistics method.

The stress-free reference lattice parameter (a_o), used in the strain $\varepsilon = \Delta a/a_o$ calculation, was determined by the equilibrium condition that the integrated stress (σ) across the material must be zero [10-11]. In fact for correct strain determination, appropriate determination of a_o is essential, but usually exceptionally elusive, due to the intrinsic difficulty of creating a truly equivalent unstrained lattice [16]. Our procedure automatically yields a precise a_o value. Here it should be noted that potential variations between the test plackets make the simple use of the a_o value of the unpeened samples in principle an unknown approximation. In fact the principle results would be very little changed if the unpeened a_o values were used. Detailed measurements by our group have shown that the stress in these peened samples is biaxially symmetric. In this biaxial case the strain is related to the stress by $\sigma = \varepsilon E/(1-\nu)$, with Young's modulus E = 200 Gpa and Poisson ration ν= 0.3. [See footnote 12 regarding stress versus strain].

RESULTS AND DISCUSSION

This shot peenning study was conducted on standard 1070 cold rolled spring steel plackets heat-treated to 46-48 Rc hardness, and initially having 0.0005 arc flatness. As we will see, these standard steel plackets are also residual "strain-free" to the limit of our resolving power. The shot-peened samples were prepared with the invaluable collaboration of the Metal Improvement Company. In the shot peening industry the evaluation of peening intensity is calibrated by the simultaneous peening of spring steel test plackets (Almen-strips). The placket's radius of curvature, R, (measured with an Almen Gauge [2]) is then used to quantify the peening-induced stress via the bending-moment response. A schematic of a peened placket, with exaggerated curvature, is shown in Figure 1b.

To motivate both the shot peening effect and our strain/stress profile results we will consider a simple elastic-plastic model [13,14] (similar to that used for differential thermal expansion in bi-metallic strips). The peened specimen (see Figure 1a) is divided into two parts; the peened-plastic-surface region (1) of thickness h_1, and the underlying steel (region 2) of thickness h_2 (note that $h_1 + h_2 = h$, is the the placket thickness). The peened-region undergoes a plastic deformation that, in the absence of a coupling to the underlying steel, would be a dilatation of magnitude ε_p. The coupling to region-2 introduces an accommodation, compressive stress P_1

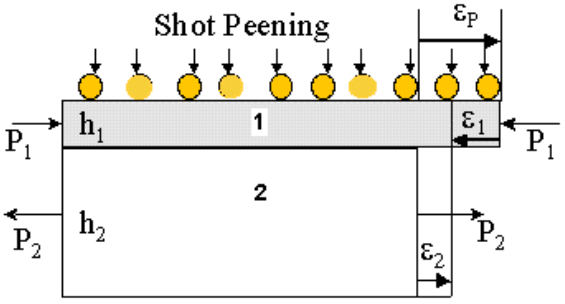

Figure 1a. Schematic of model for shot peening strains/stresses (see text).

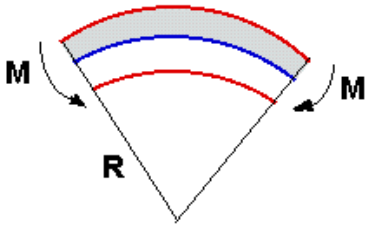

Figure 1b. Schematic for bending moment and radius of curvature for peened material (see text).

(and elastic strain ε_1) on the peened layer. In reaction, the underlying steel is also elastically strained, with a tensile stress P_2 (and the strain ε_2 as noted above), to accommodate to the peened-plastic-surface. The matching of the strain at the region-1/2 interface requires $\varepsilon_p = \varepsilon_1 - \varepsilon_2$ and stress (force) equilibrium mandates that $P_1=P_2=P$. The compressive/tensile force couple (P_1, P_2) introduces a bending moment (M) to the specimen given by $M = P(h_1+h_2)/2 = Ph/2$ [14]. In response to this bending moment there is linear strain/stress (σ/ε) variation across the placket given by $\sigma = E' \varepsilon = [M/I]\, y$ or $\varepsilon = [M/(E\, I)]\, y = y/R$. Here: y is the depth coordinate into the placket, referenced to the null-strain point in the interior; $I = bh^3/12$ is the second moment of the beams cross sectional area; E' is the appropriate elastic modulus (E/[1-ν] here); and R is the radius of curvature of the placket.

In the above analysis it should be noted: that 1.) the bending moment and compressive force on the peened layer both follow from the placket curvature; but 2.) that the absolutely crucial absolute compressive (negative) stress in the peened layer can only be evaluated with a knowledge of the peened layer thickness h_1 by $\sigma_1 = P/(h_1\, b) = E'\varepsilon_1$. It is, of course, the negative value of σ_1 that produces the enhanced surface-tensile load capacity in shot peend materials as illustrated by the relation $\sigma_1 + \sigma_{\text{tensile-load}} < \sigma_{\text{tensile-yield}}$. Although a body of empirical and theoretical work has allowed the industry to successfully estimate σ_1 for various materials and peening conditions using only the Almen curvature, a direct measurement of h_1 is important for deeper understanding of the shot peening process. Thus the nondestructive measurement of both h_1 and ε_1 (or calculated σ_1), via our depth-profiling measurements, provide crucial information regarding the fundamentals of the shot peening process.

With this simple model in mind, we show in Figure 2a the lattice-parameter/stress profile of a 3.85 mm thick spring steel placket, intensly peened, with 550 (1.4 mm diameter) hard shot, to a curvature radius of R_A=1650 mm (as measured in collaboration with the Metal Improvement Corporation, by an Almen Gauge). Figure 2b shows a microscope picture of the indentations

on the peened surface with an approximate distance scale. This specimen was an Almen gauge calibration standard, and was substantially thicker than the thickest Almen strip used in shot peening intensity monitoring. The lattice paramater profile (see Figure 2a), of the peened
steel placket manifests dramatic internal strains. Two points should be noted here: our technique measures the atomic inter-planar distances parallel to peened surface (i.e. along the most important direction in this problem); and our measurements are of elastic strain only, with plastic-deformation-stress effects being evidenced by the concomitant strain response. The peening-induced plastic compressive strain extends to a depth of about 1 mm (region 1). As expected from the simple model, the underlying steel (region 2) responds to the peened layer elastically, with the bending moment creating a linear elastic strain vs. position in region

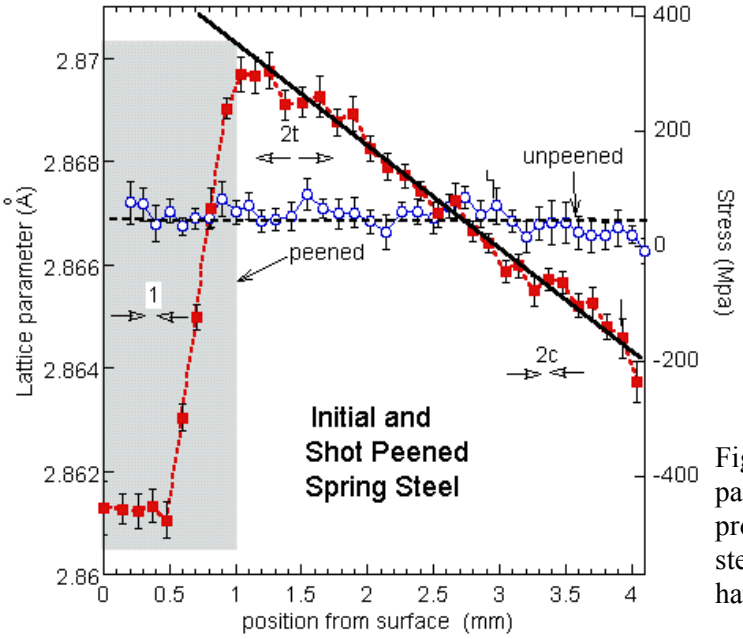

Figure 2a. Measured lattice parameter and calculated stress profile for a 3.85mm thick spring steel placket peened with 1.4mm hard steel shot.

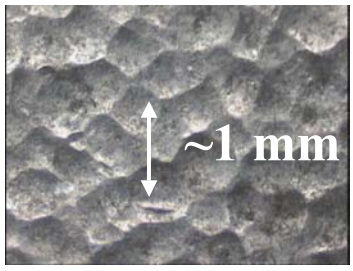

Figure 2b. A photomicrograph of the peened surface of the 3.85 mm thick specimine.

2 given by $a = a_0 (1- y/R)$. Least squares fitting the linear portion of the region 2 data yields a microscopically-determined curvature of R= 1530 mm, in quite good agreement with the macroscopic Almen Gauge curvature (R_A=1650 mm).
Qualitatively in region 2, an equilibrium-required balancing interior tensile strain extends over a wide depth range (region 2t). The linear elastic response overshoots the null-strain to yield a compressive elastic strain near the unpeened surface also (region 2c). Such a compressive elastic stress is to be expected at this concave surface. In terms of our simple model, the "strain free" equilibrium lattice parameter a_0 = 2.8664 Å, and the strains ε_1= -0.00214 and ε_2= .000667 were determined. In Figure 2a, the right-scale shows the value of the stress versus position in the specimen. The stress in the plastic region is ~-480 MPa, indicating substantial strain hardening in this layer. Thus, our strain profiling method provides a direct and clear quantitative method of characterizing the detailed internal strain distribution in such important peening modified materials.
It should be noted that Figure 2a also shows the lattice parameter profile of a "virgin" 3.85 mm thick spring steel blank. Importantly, our results indicate that this "virgin" steel blank provides an excellent, essentially strain-free standard. Moreover, the constancy of the lattice parameter across this standard experimentally sets of the maximal extent of systematic instrumental effects in our data. Additional experiments on powdered Ge and Si "zero-strain-

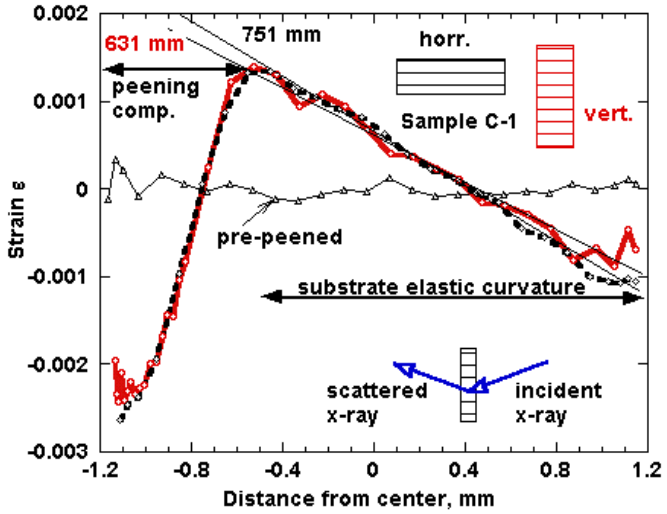

Figure 3. Strain profile for a 2.4 mm thick C-Almen strip peened with hard steel shot of diameter 0.84mm.

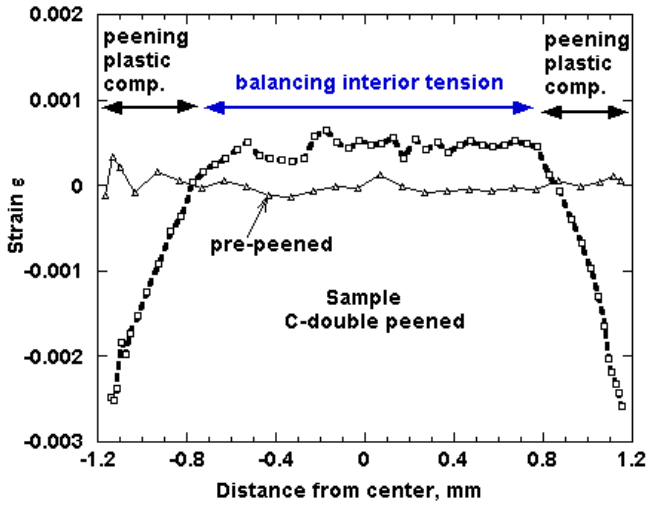

Figure 4. Strain profile for a C-Almen strip peened on both surfaces with hard steel shot of diameter 0.58 mm.

standards" and detailed simulations have directly confirmed this small greatest upper bound of systematic instrumental effects in our technique [5-7].

In Figure 3, we show the strain profiles for an Almen-C spring steel strip, peened with 330 hard steel shot (0.84 mm). In this case, the strain between the atomic planes along both the long and short directions of the strip were measured utilizing two sample orientations with 90° relative rotation. The peened region extent and the microscopic elastic curvatures in the two directions are quite similar. The upturn in the strain very near the peened surface is present in many of the strain profiles we have studied and is common in shot peening literature.

In Figure 4 we show the strain profile for another Almen-C strip peened on both surfaces with 230 hard steel shot (0.58 mm). Such "double peening" exploits the balancing of the peening on the two surfaces to yield surface toughening of a thin component without the elastic curvature that would result from a single pened surface. Indeed, referring to Figure 4, one can see that nearly constant interior tensile strain evidences only a slight slope (curvature).

Comparison of the depth of the compressed region in Figures 2-4, suggests a direct correlation with the peening shot size. As a first step toward checking this correlation, we show in Figure 5 the calculated stress profiles for our all of the peened samples discussed here, plotted versus their distance from the peened surface. The linear elastic contributions to each curve, indicated in the figure, obscure decisive comparison of the peening depth. Accordingly, we have subtracted this linear component from these results and present in Figure 6 resulting elastic-

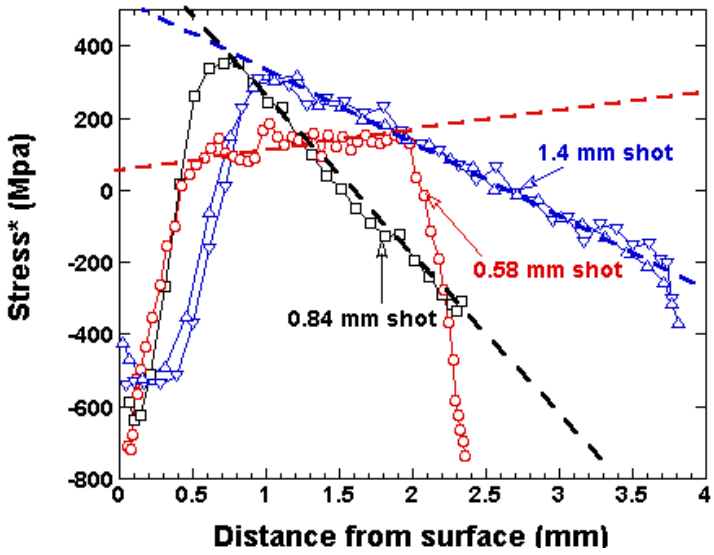

Figure 5. A comparison of the stress profiles for the samples discussed above. The solid lines indicate the linear elastic components.

subtracted stress profiles. To provide a notion of the detailed variability in the peening process, the double peened sample data is included twice (once for each surface) and stress profiles in two directions for the 0.84 mm-shot-pened sample are also included.

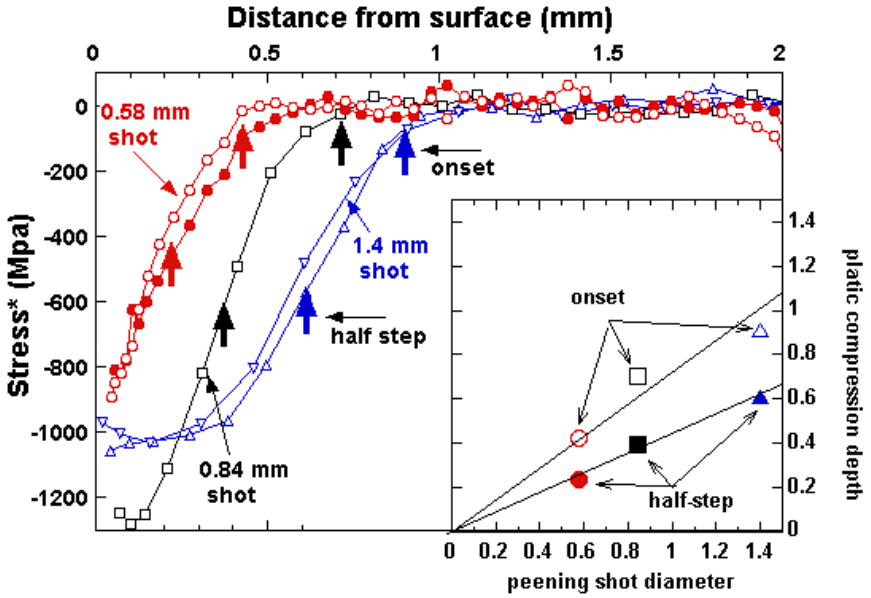

Figure 6. The stress profiles for the samples in the previous figure with the linear elastic components subtracted. Note that results for both surfaces of the double peened sample are included.. The arrows mark the compression onset and half-step depths. Inset: a plot of the onset and half-step compression depths plotted versus peening shot size.

The larger-shot-size/deeper-plastic-layer correlation is dramatically apparent in Figure 6. Two compression depth indicators are labled by arrows in the figure; the depth of first onset of the compressional deviation; and the compression half step depth. These depths are plotted in the inset of Figure 6 versus the peening shot size and their correlation is abundantly clear. With only three points, the linear lines are meant to be guides to the eye, however linearity is clearly suggested.

Some time ago, Al-Hassani [15]used an analytical treatment to derived an exprssion for the depth (h_1) of the plastically compressed shot peened layer, which can be paraphrased as $h_1/r = [c]^{1/2}[\rho^2 P_g/ P_y]^{1/4}$. Here r is the radius of the shot, P_g is the gas pressure of the peening nozzle, P_y is the dynamic-yield-strength of the peened martial and ρ is the mass density of the peening shot. The constant "c" can also involve contributions from the details of the nozzle and shot size. However, the impression of his work is that, to first order, a linear plastic-depth vs. shot-size correlation is not unreasonable, for a given peening setup as employed here. The correlation we observe between the shot-size and plastic-peened-layer depth therefore appears consistent with these model calculations.

CONCLUSION

In summary, our implementation of the EDXRD is well suited to directly and nondestructively studying the key details in the depth dependent strain/stress fields induced by shot peening. Specifically, the depth and magnitude of the near surface-plastic-compression zone and the elastic bending of the underlying material can be probed precisely. The correlation between peening shot size and the depth of the plastic-compression zone in our results is quite suggestive. Interestingly, our technique is amenable not only to static residual strain measurements, but also to in-situ load experiments. Thus, the interaction of the residual and impressed-load stresses, which are at the basis of the benefits of shot peening technology, should be accessible to study.

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