Shot Peening Effects on Residual Stress in Heat Treated Steel for High Pressure Diesel Fuel Injection Systems

PURDUE MATERIALS ENGINEERING

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Abstract: Cummins Fuel Systems shot peens components to introduce surface compressive residual stress (CRS), which increases the fatigue life. This study investigated shot peening effects on residual stress (RS) in austempered (AT), carbide reduction (CR), low pressure carburized (LPC), and plasma nitrided steel coupons. 52100-AT and 52100-CR both had a tensile RS at the surface before shot peening, but exhibited a maximum CRS of 1300 MPa and 1100 MPa, respectively, after shot peening. 8620-LPC had a slight compressive surface RS before shot peening, and a maximum CRS of 1400 MPa after shot peening. M2-Nitrided exhibited maximum CRS ranging from 615-745 MPa at depths near 250 µm, with shot peening exhibiting little influence due to the high hardness of the white layer. Finite element modeling was used to predict the RS in 52100-CR from parameters determined by comparison to 52100-AT.

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Project Background

Cummins Fuel Systems (CFS) designs and manufactures high pressure diesel fuel injection systems that need to survive high cyclic pressures during operation. Shot peening is used as a surface strengthening technique on pressure bearing surfaces of fuel system components where fatigue failure is likely to occur. Shot peening is a process in which the surface of a part is bombarded with small spherical media called shot (see right image). Shot peening induces subsurface compressive residual stresses (CRS) that impede crack growth and increase fatigue life (see left image). CFS uses a variety of steel alloys that have been heat treated to obtain the desired properties. The main objective of this study is to investigate shot peening effects on residual stress in heat treated steel and provide CFS a tool to predict the depth and magnitude of residual stresses in their fuel system components.

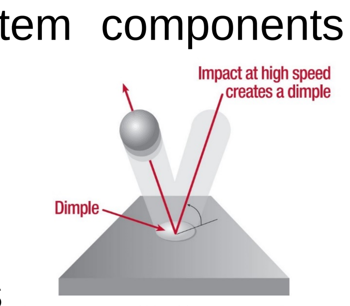
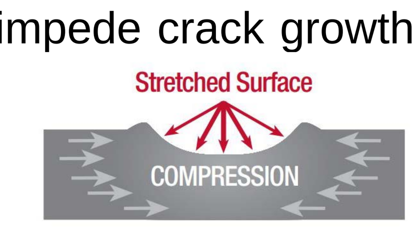


Image courtesy of Metal Improvement Company.



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Experimental Procedure

Each batch of twelve steel alloy coupons (76.1mm x 18.95mm x 6.35mm) were subjected to one of four heat treatments: Q/T Carbide Reduction (52100 - CR), austempering (52100 - AT), Low Pressure Carburizing (8620 - LPC), and Plasma Nitriding (M2 - Nit.). The coupons were subsequently shot peened using an air nozzle machine at 100% coverage for a given shot type and air pressure (see table below). Three coupons were produced per condition.

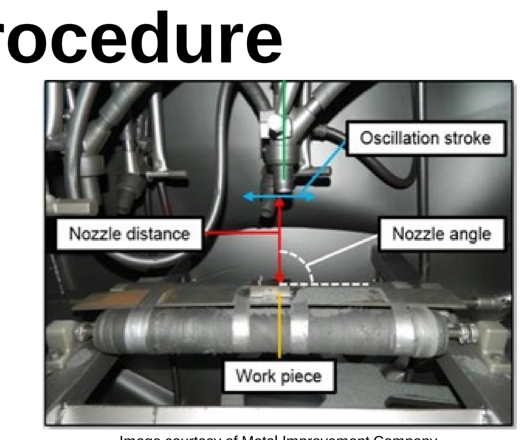
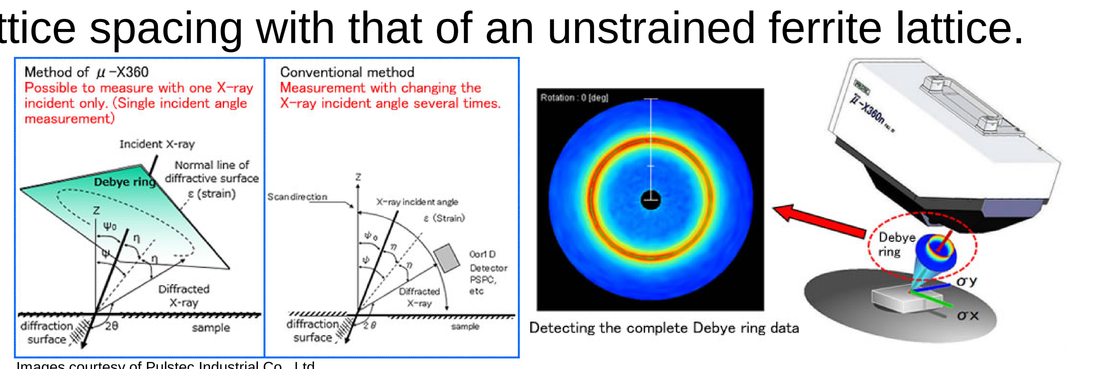


Image courtesy of Metal Improvement Company.

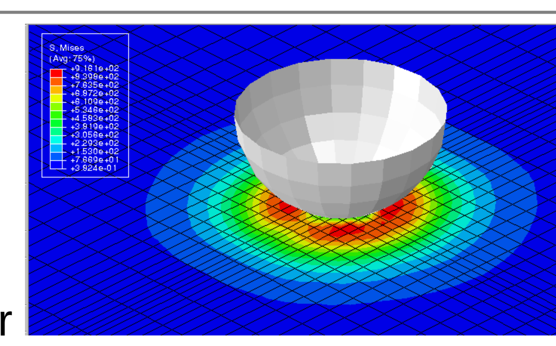
Number of Coupons	3	3	3	3
Shot Material (Per AMS2431)	S70H		S110H	
Air Pressure	30 PSI	75 PSI	30 PSI	75 PSI
Almen Intensity @ T1 (in.)	0.0075 A	0.0107 A	0.0082 A	0.0126 A

Macro hardness measurements were collected on the surface of the coupons. Micro hardness measurements were collected on the coupons that were cross sectioned perpendicular to the long edge. Hardness vs. load curves and hardness vs. depth curves were constructed to determine bulk hardness, and depth of shot peening effects. Coupons were subsequently electropolished in 45-150 second increments at 0.5 A in a 20%, by weight, NaCl electrolyte solution. The electropolished area was measured using X-ray diffraction (XRD) and a two-dimensional X-ray detector with a molybdenum source (Pulstec μ-X360 Portable X-ray Residual Stress Analyzer). Three XRD measurements were collected per electropolishing step. The Pulstec utilizes Bragg's Law to calculate residual stress. The incident angle, theta, is set to angle of 35º ± 0.1, which is characteristic of a ferritic microstructure. The lattice spacing, d, can be calculated as all other parameters are known. The lattice spacing depends on the strain in the X-Y plane. The software returns a residual stress after comparing the calculated lattice spacing with that of an unstrained ferrite lattice.



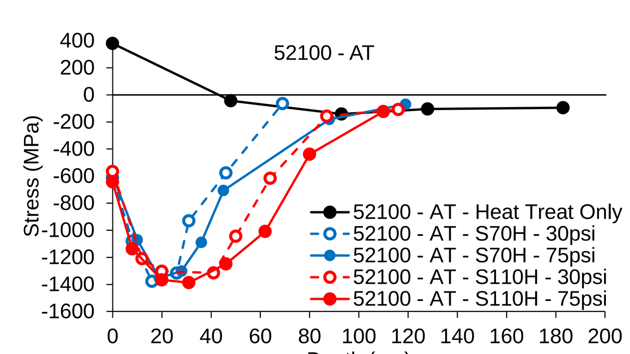
Images courtesy of Pulstec Industrial Co., Ltd.

Simulations were conducted using ABAQUS finite element analysis software. The model uses material properties, such as elastic modulus, yield stress, and strain hardening behavior, in conjunction with shot peening parameters, such as shot size (50 μm) and shot velocity.

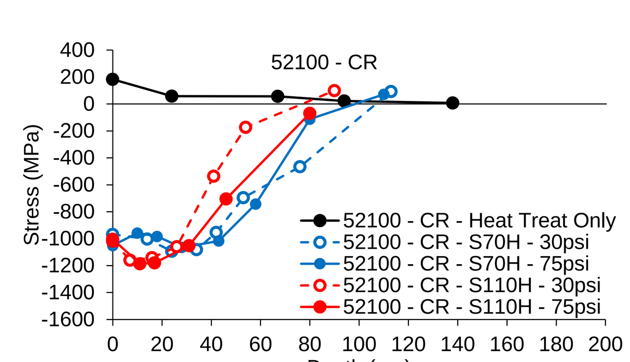


The properties are used to generate residual stress profiles. The elastic modulus was obtained from literature values, while yield stress and strain hardening behavior were calculated using 52100 steel tensile test data provided by CFS. Velocity was varied to fit the model, while literature values were used for other shot parameters. The model assumes the shot is a non-deformable object, and is impacting a homogenous substrate.

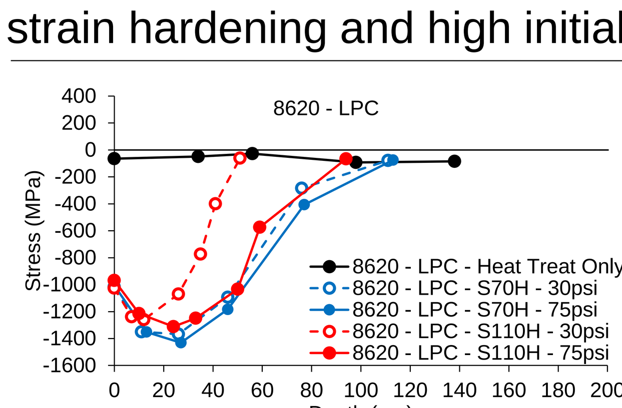
Results & Discussion



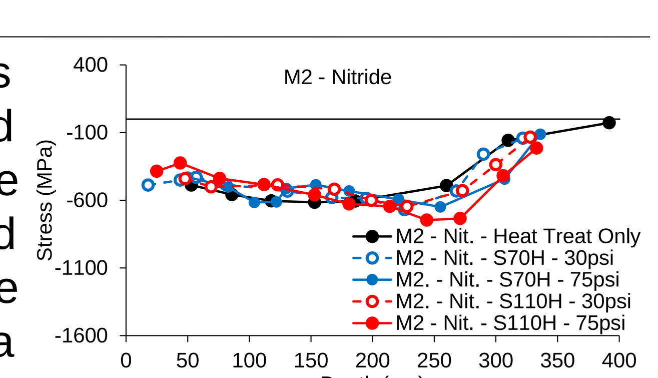
The 52100-AT coupons had a surface CRS between 566 and 643 MPa. The coupons reached a maximum CRS of 1301 to 1387 MPa that was observed between 28 and 31 μm. The heat treat only condition had a tensile RS of 380 MPa. All coupons reached a maximum CRS near 20 μm. The S70H profiles were shallower overall, and the effect of reducing the pressure was similar but less significant. The RS profiles had a more substantial increase from surface to maximum unlike the 52100-CR, resulting from increase in initial surface RS and strain hardening for the 52100-AT.



The 52100-CR coupons had a surface CRS between 968 and 1019 MPa. The coupons reached a maximum CRS of 1093 to 1186 MPa that was observed between 11 and 24 μm. The heat treat only condition had a surface tensile RS of 183 MPa. All coupons reached a maximum CRS near 20 μm. The S70H shot resulted in a slightly lower maximum RS with an overall greater compressive zone. The 52100-CR profile was flatter than the other heat treatments (0-30 μm), resulting from its low strain hardening and high initial hardness than 52100-AT.

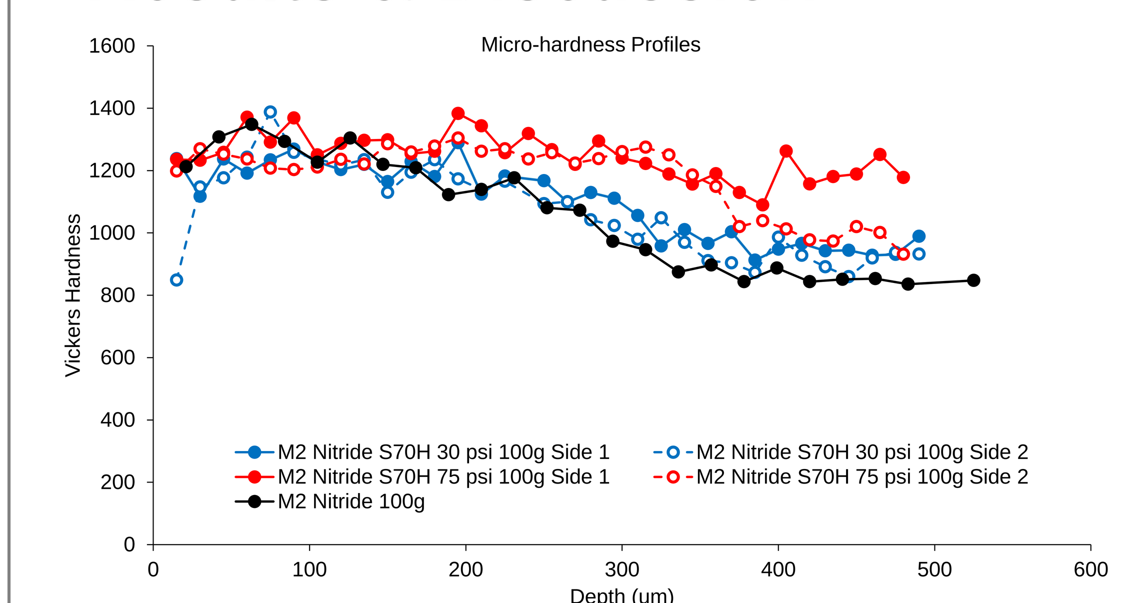


The 8620-LPC coupons had a surface CRS between 968 and 1026 Mpa. The coupons reached a maximum CRS of 1260 to 1431 MPa that was observed between 11 and 27 μm. The heat treat only condition had a compressive residual stress of 65 Mpa. All coupons reached a maximum CRS near 20 μm. The coupons processed under S70H had the greatest magnitudes of residual stress. Reducing the pressure from 75 PSI to 30 PSI resulted in a much shallower profile for the S110H shot.

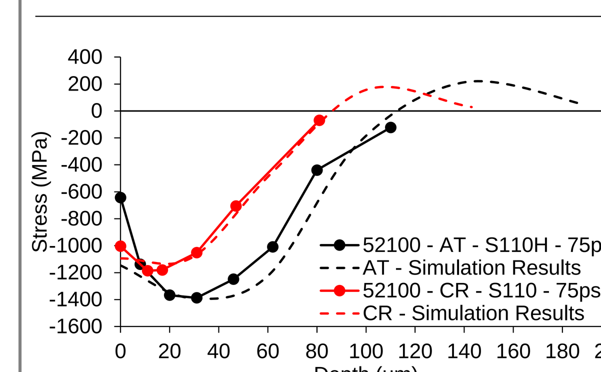


The M2-Nitrided coupons could not be measured for RS at the surface due to the white layer imposed from nitriding. The coupons reached a maximum CRS of 649 to 745 MPa that was observed between 200 and 300 μm, which were only slightly larger than the heat treat only condition, which had a maximum CRS of 615 MPa for depths greater than 50 μm. No significant effect on CRS from shot peening was observed.

Results & Discussion



The M2-Nitrided S70H coupons hardness showed no significant deviation from the heat treated only (black) until 200 μm. There was also no significant deviation in hardness values from side 1 to side 2 (shot peened surface), except the surface for 30 PSI, and from 400-600 μm for 75 PSI. The heat treated only coupon is comparable to the 30 psi coupon. No significant decrease in hardness was detected until about 250 μm in all coupons. This trend is also seen in the residual stress profiles for shot peened coupons, albeit less so. This indicates that shot peening does not remove the white layer, but the white layer absorbs most of the impact of the shot. In both S70H samples, a significant decrease in hardness begins at the maximum case depth, which is not seen in the S110H coupons, requiring further investigation.



Simulations were conducted over a range of shot velocities since shot velocity was not known. The substrate conditions were set to match the mechanical properties of 52100-AT steel. A shot velocity of 50 m/s produced the closest RS profile to the experimental results (black). The mechanical properties in the simulation were then changed to reflect the properties of the 52100-CR, and the simulation was completed using a 50 m/s shot velocity that was identified in the 52100-AT simulation. The modeled RS profile closely matches the experimental RS profile for the 52100-CR (red).

Conclusions

Under the experimental shot peening conditions and simulations, only slight changes in residual stress were observed between a shot type of S70H and S110H, and pressures of 30 psi and 75 psi. CRS maximums are normally observed within 40 μm of the surface. Shot peening the M2-Nit. had no observed effect on residual stress because of the white layer and case depth. In addition, more aggressive shot peening of the M2-Nit. is needed to remove the white layer. The simulation produced a close match for the 52100 samples impacted by S110H shot at 75 PSI. Additional simulations altering shot size should be investigated to improve the understanding of the S70H shot. Simulations of 8620 steel would be helpful in understanding why increasing shot size leads to a higher maximum CRS in the 8620 but lower maximum CRs in the 52100

Acknowledgement

A special thanks to Metal Improvement Company (MIC), a division of Curtiss-Wright Corporation, for shot peening the coupons used in this study.