High-Pressure Fuel Injection Systems: Shot Peening and Its Effect on Residual Stress

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CUMMINS FUEL SYSTEMS designs and manufactures high-pressure diesel fuel systems that must survive high-cyclic pressures during operation. Shot peening is employed as a surface strengthening technique on pressure-bearing surfaces of fuel system components where fatigue failure, due to alternating pressure, is most likely to occur.

Cummins Fuel Systems has been a long-standing supporter of Purdue Senior Design Projects and they sponsor a project almost every year. Precision shot peening and the measurement of the resulting properties are topics of special interest to the company.

The following is a reprint of the students' research poster.

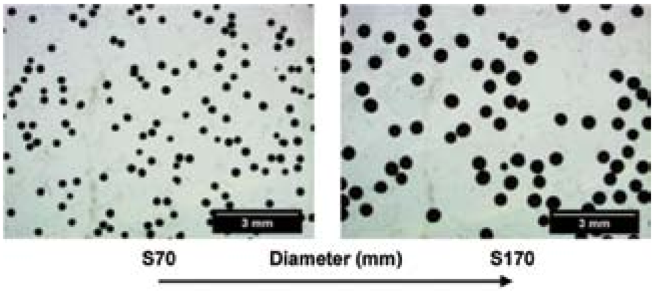
Project Background

Almen Intensity and residual stress were characterized by varying shot peening parameters and measured by X-ray diffraction (XRD). Hardness, surface roughness, and residual stress (RS) depth profiles were conducted on 4140 and 52100 steels as well as Almen strips to analyze the effects of variation in shot media size, shot pressure, and shot type. Hardness variation was seen to be the most influential variable in roughness and RS.

XRD techniques are capable of directly measuring crystallographic lattice strain which can be translated to stress by the $\sin^2\psi$ method. However, because XRD cannot be performed on small inner diameters such as that of fuel system components, Almen Intensity is instead used to monitor the shot peening process. The main objective of this study is to correlate the stresses measured with XRD to the Almen Intensity and determine the effects of altering shot peening parameters.

Experimental Procedure

Steel coupons (76.1 mm x 18.95 mm x 6.35 mm) of 4140 (40-45 HRC and 50-55 HRC) and 52100 (58-62 HRC) were shot peened by Metal Improvement Company. Peening was performed using a ⅜" nozzle set perpendicular to the coupon and at 7" spacing. Nozzle oscillation speed across the coupon was 24 in/min for metallic shot and 12 in/min for ceramic shot until 100% coverage was achieved (3-8 passes). Single and dual shot media sequences were studied. S170-H and S70-H cast steel shot were utilized in single peening; dual peening experiments used S110-H and S70-H cast steel shots sequentially or S170-H cast steel shot and Z150 ceramic shot sequentially. S170-H and S70-H were chosen for comparison to the incumbent process; dual peening and ceramic shot were chosen for investigative data gathering.



The increased diameter size increased the potential to input more force into the surface of the sample, with residual stress.

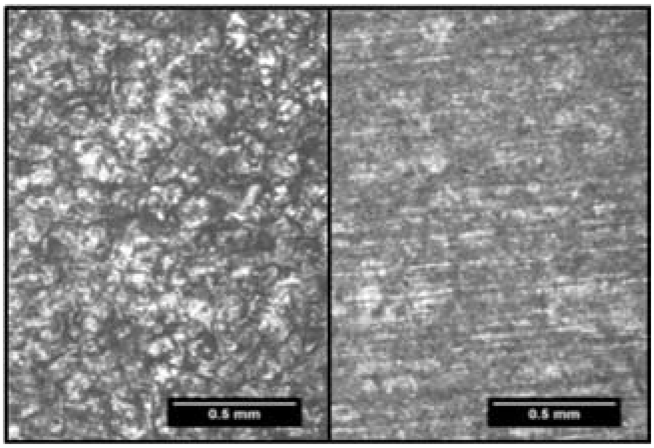
Samples were then examined via optical microscopy, profilometry, hardness, and XRD. XRD was performed using a chromium x-ray tube with vanadium filter, set to 25kV and 0.8mA. SaraTEC Analysis Manager v1.3.37 software calculated RS values using 4340 50 HRC for the material constant. This software also compiled RS depth profiles using XRD measurements obtained after incrementally electropolishing into the coupons. Three-dimensional optical profilometry (ZeScopeTM) gathered five surface roughness measurements across each sample.

Almen Intensity is the arc height measurement of thin, standardized, steel strips. If a sample is sufficiently thin, the compressive RS imparted by peening creates concave bending of the sample which is measured by regulated gauges (SAE J443).

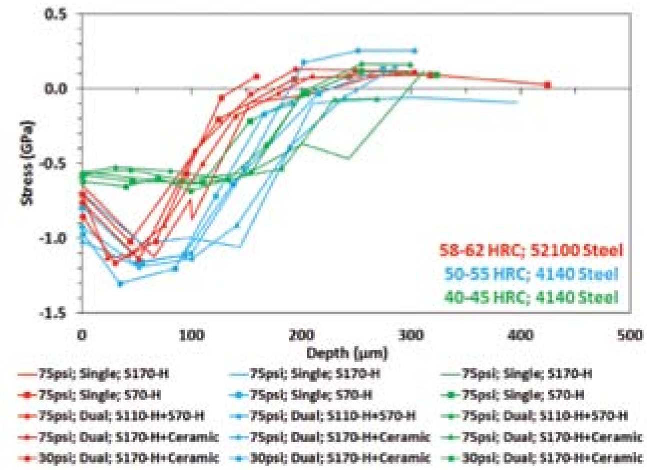
Results and Discussion

Roughness

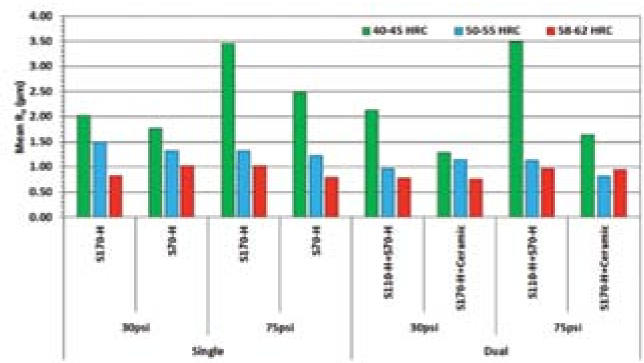
Hardness was the most influential variable to surface roughness as shown by the 40-45 HRC sample. Changes in air pressure showed only slight differences in roughness. From only changing the hardness, softer coupons displayed rougher surfaces after peening. However, the 75 psi, S170+Ceramic dual-peened sample with 58-62 HRC displayed a higher

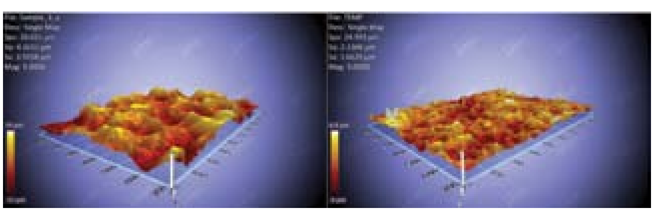


4140 40-45 HRC (left), 52100 58-62 HRC (right)

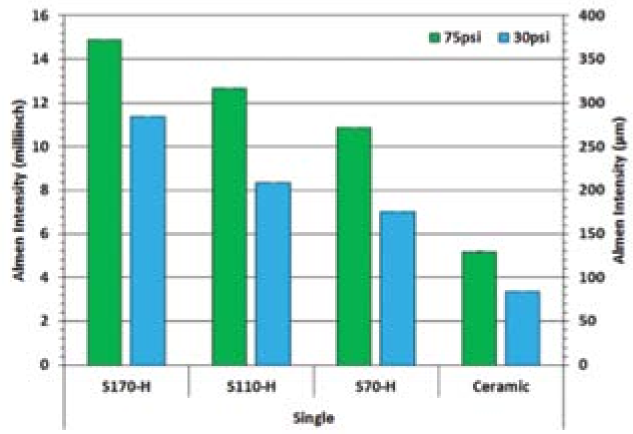


Almen Intensity values increased with pressure and media size. The ceramic shot was harder than the steel shot used, but due to mass decrease, the Almen Intensity was the lowest.

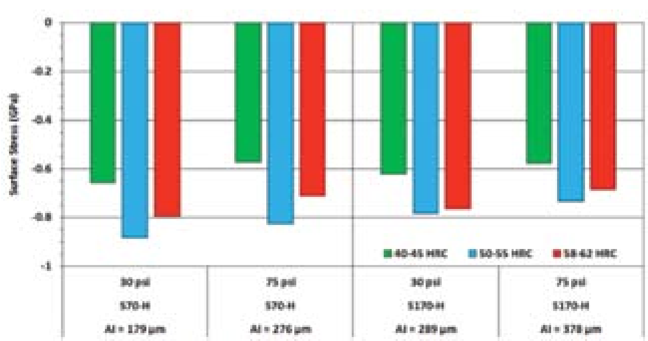




A S170-single peened (left) vs. a S170+Ceramic-dual peened (right) sample showed decreased roughness. The second, smaller ceramic deformed the surface more uniformly, resulting in a smoother surface.



Surface RS decreased as air pressure increased.

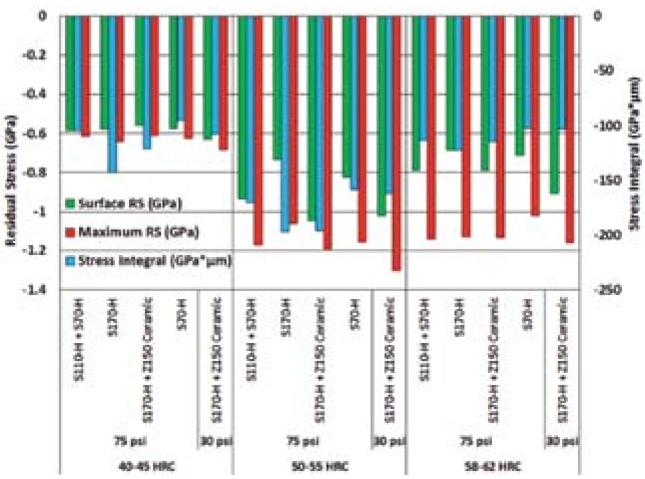


roughness value than expected. This was due to debris on the sample's surface increasing the distance between the highest and lowest measured points and thereby increasing the mean Ra value.

Residual Stress and Almen Intensity (AI)

The initial hypothesis was that harder materials would exhibit larger RS due to deformation resistance. Results showed that the 50-55 HRC samples exhibited the largest compressive RS as seen in the depth profile.

Stress integral was defined by the definite integral of the depth profile for compressive stresses beneath the x-axis. This integral increased with shot size and corresponded to an increase in Almen Intensity implying that Almen Intensity can be correlated to RS.



Conclusions and Future Work

- Coupon hardness was the most influential parameter regarding material response. The 40-45 HRC material was unable to retain induced stresses.
- 52100 (58-62 HRC) contains carbides that may act to impede dislocation motion. When compared to 4140 (50-55 HRC), 52100 (58-62 HRC) may require a higher intensity shot peening process to induce the same RS magnitude.
- Future work should include measuring RS after peening of reduced-carbide 52100 as well as 4140 and 52100 samples of the same hardness.
- Immediate future work should include creating RS depth profiles of coupons peened at 30 psi to relate air pressure to maximum compressive RS and area under the depth profile curve.

"In the past, shot peening has served as a solution to improve a component's robustness when challenged by manufacturing in global markets. Moving forward we are interested in creating a bridge between design and manufacturing. On one hand, our designers focus on compressive residual stress for modeling and, on the other, manufacturers are concerned with Almen Intensity for process control," said Andrew Armuth, Current Product Leader – Materials Science Engineering at Cummins Fuel Systems."The work completed by Purdue has given us a foundation on which we can correlate compressive residual stress to Almen intensity. The thorough analysis will serve as a design tool and drive our shot peening process parameters," he concluded.

Acknowledgement

Metal Improvement Company, a division of Curtiss-Wright Corporation, was critical in the development and execution of this project.

For More Information

Companies interested in utilizing the research capabilities of Purdue Materials Engineering should contact Dr. David Bahr at dfbahr@purdue.edu or (765) 494-4100.