2010 DOE Hydrogen Program and Vehicle Technologies Program AMR

Fatigue Enhancements by Shock Peening

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Overview

Timeline

Project start date:	October 2007
Project end date:	December 2010
Percent complete:	60%

Barriers

- Material limits
- Lack of investment in improving the traditional reciprocator platform
- Cost of advanced materials and their processing

Budget

Total project funding:
- DOE – $1,040 K
- Cost Share – 50%

Funding FY08: $350 K
Funding FY09: $340 K
Funding FY10: $223 K

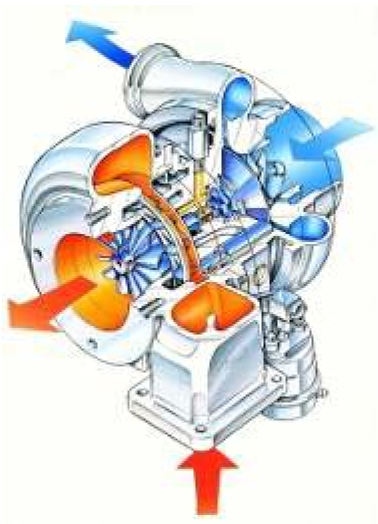
Partners

Industrial CRADA Participant:
Cummins Inc.
- Dr. Yong-Ching Chen
- Jeffrey Cooper

Supplier Development:
LSP Technologies – Laser Peening
Flow International – Waterjet Peening

Support:
South Dakota School of Mines – Friction Stir Processing

Objectives of Project



Enable improved engine efficiencies by increasing injection pressures and the overall durability of reciprocating parts

- Evaluate the capability for surface modification techniques to improve fatigue performance of steel, aluminum and cast iron engine components
  - Potentially enabling a lower cost material to meet or exceed the performance of higher cost materials
- Surface modification techniques, which are non-traditional for engine manufacturers, include Laser Shock Peening (LSP), Waterjet Peening (WJP), and Friction Stir Processing (FSP)
- Materials of interest are steel used in fuel systems and aluminum alloy and cast iron structural components

Deliverables

- Demonstrate fatigue enhancements achieved by LSP and WJP for steel and aluminum components, including a comparison to traditional shot peening approaches
- Demonstrate enhancements achieved by FSP for cast iron components
- Prototype a component enhanced by a promising surface modification technique for full scale evaluation

Technical Approach

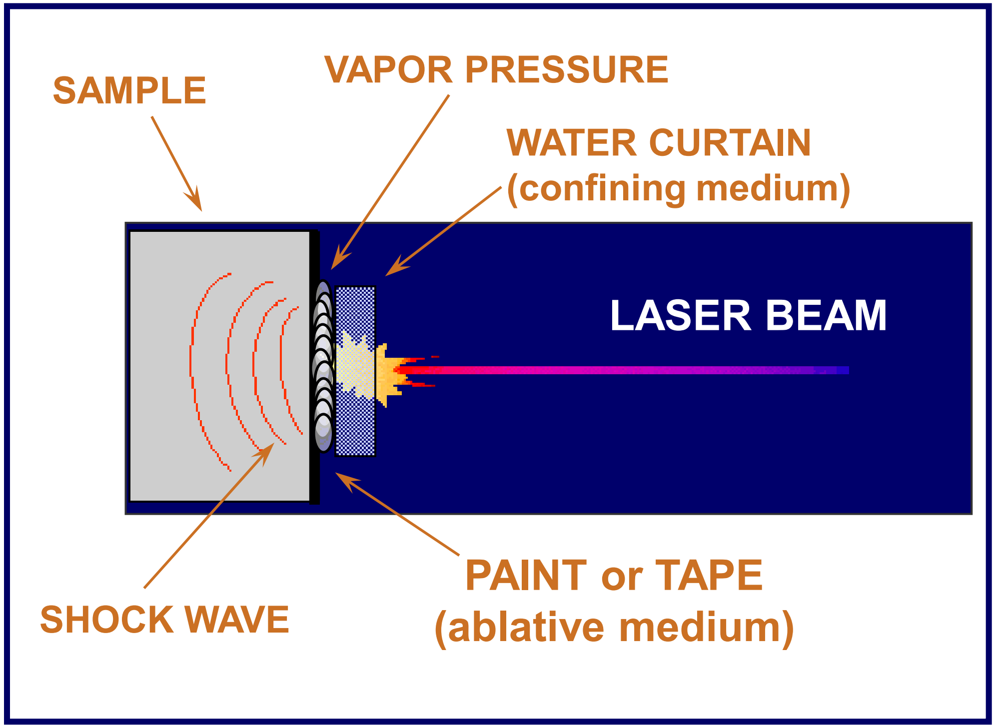
- **Technology Development**
  - **Fatigue Enhancements in Steel and Aluminum**
    - Demonstrate LSP and WJP produce **deep** compressive stresses in steel and aluminum test specimens
    - Characterize stress distributions and compare to control specimens
    - RBF testing of surface modified and control specimens
    - Perform thermal stability tests of surface modified specimens
    - Develop cost model for process deployment
  - **Friction Stir Process Development for Cast Iron**
    - Demonstrate FSP technique for processing of cast iron
    - Investigate new tool materials and designs for cast iron FSP
- **Technology Deployment**
  - Demonstrate LSP and WJP surface modification approach on full-scale steel and/or aluminum component
  - Develop a cost effective process sequence for LSP/WJP of a relative high volume production

Technical Progress

- The last year of the project was focused on:
  - Laser shock peening to enhance the Rolling Contact Fatigue of 52100 steel and Rotating Beam Fatigue life of 52100 steel and A354 cast aluminum
  - Parameter development for waterjet peening of A354 cast aluminum
  - Processing development for friction stir processing/joining of cast iron

Technical Progress - LSP

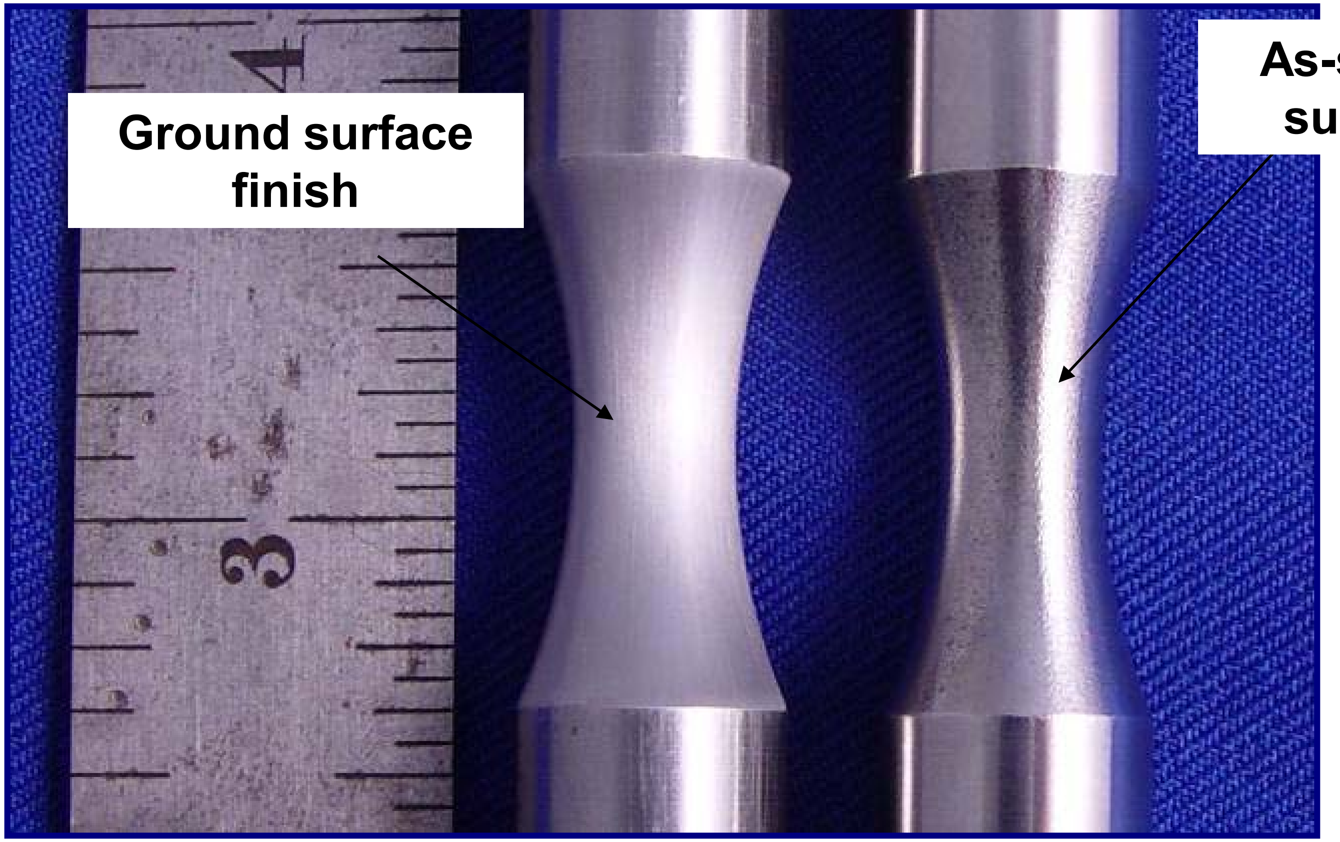
- Laser Shock Peening
  - Produces very deep compressive residual stresses
  - Large stand-off distances convenient for irregular geometry
  - Essentially not used in high strength steels prior to this project



Technical Progress - LSP

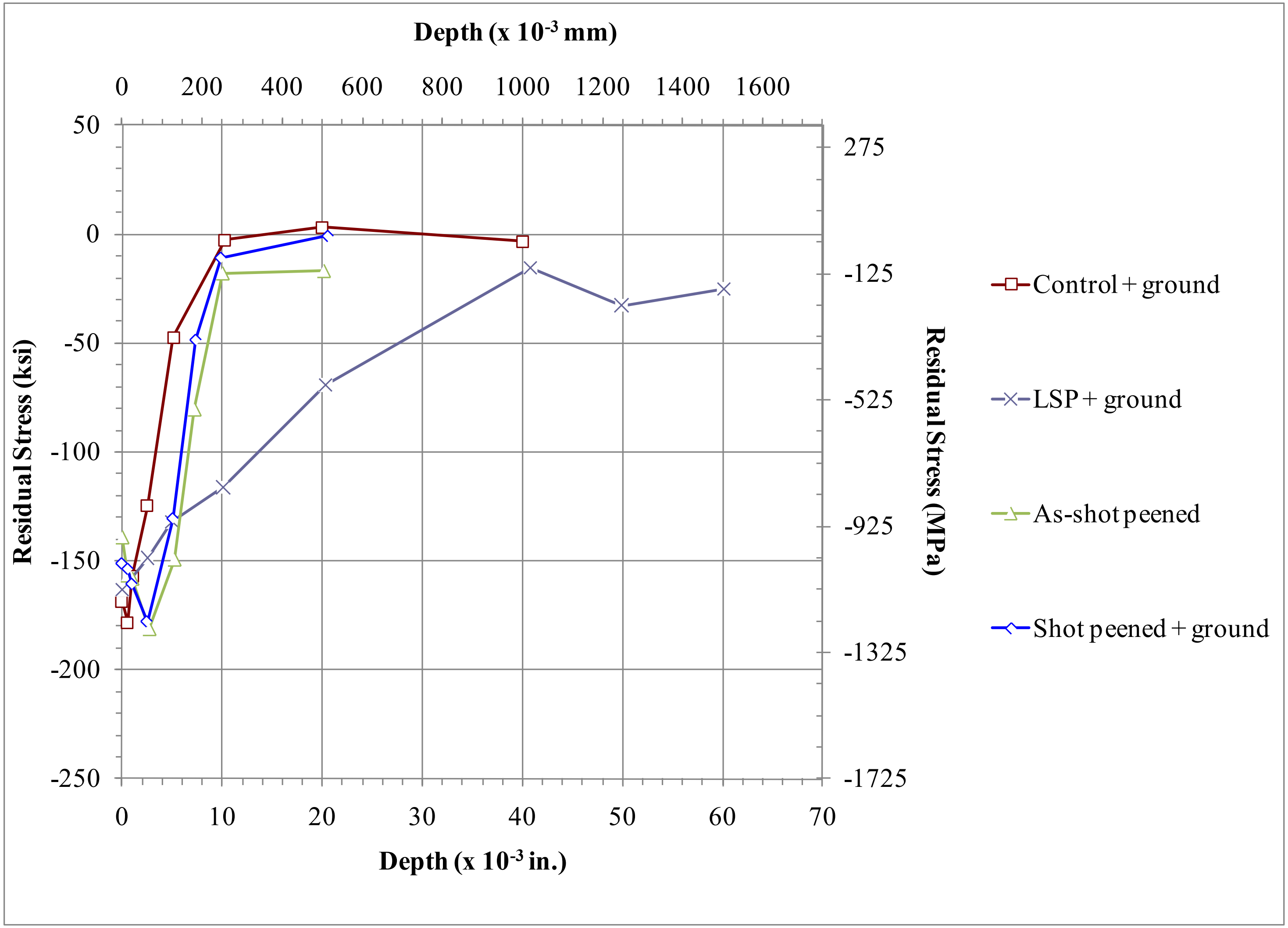
- LSP was expected to produce deep compressive stresses therefore unlike most surface peening methods post peening finishing can be used
- Rotating Beam Fatigue – tested at PNNL
  - 52100 Steel - 4 populations: 1) Control (ground), 2) LSP and ground, 3) as-Shot Peened, and 4) Shot peened and ground
    - Assumed that as-LSP roughness too high
  - A354 cast aluminum - three populations: 1) Control (ground), 2) as-LSP and 3) LSP and ground
    - Tested as-LSP to evaluate potential for peening areas that may not be accessible for post-peening finishing
    - Custom alloy prepared at PNNL
- Rolling Contact Fatigue – tested at Cummins Inc.
  - 52100 steel – tested 2 populations: 1) LSP and ground 2) Control (ground)

Alloy 52100 Steel Specimens Surface Finish Comparison

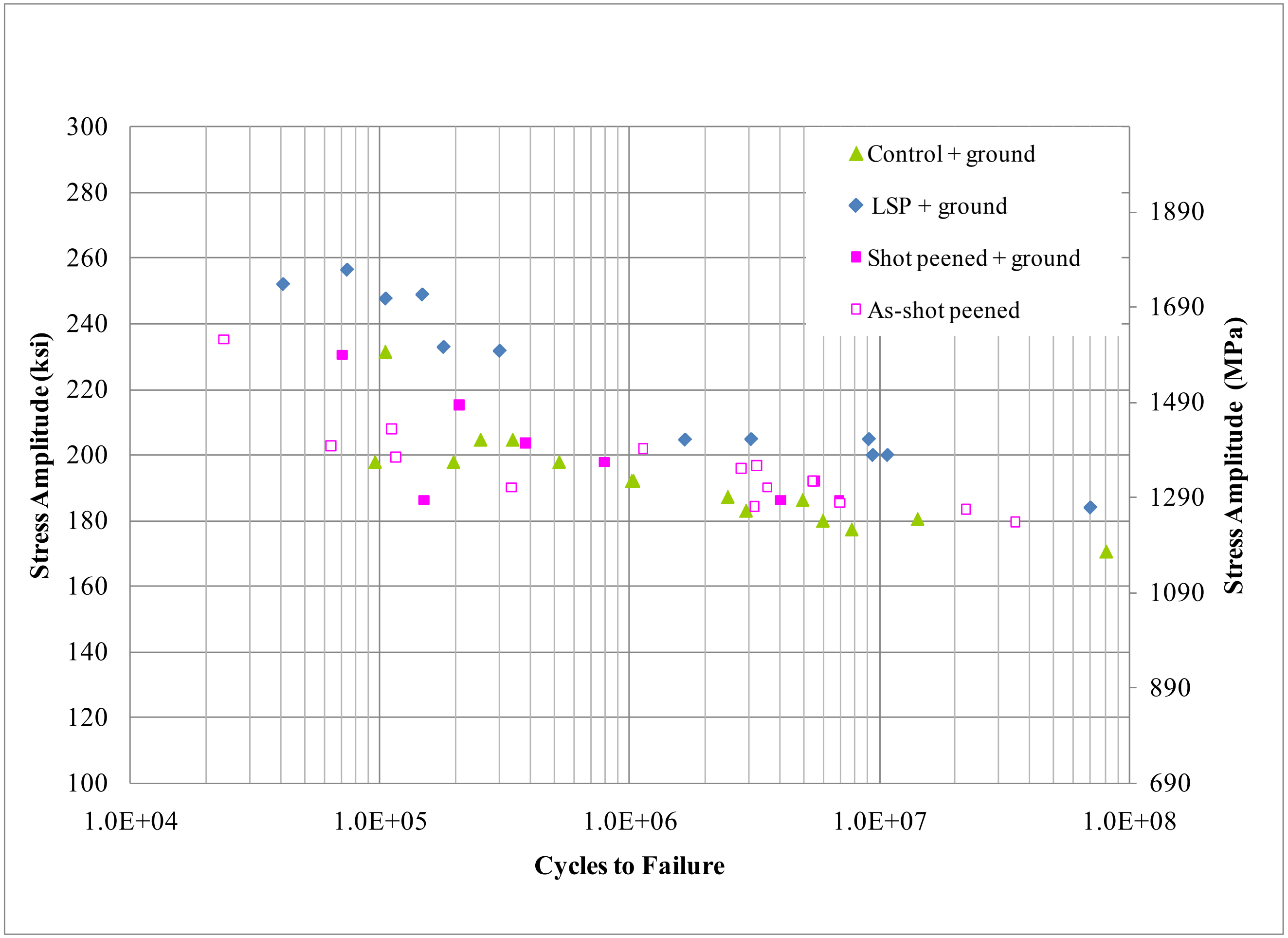


All samples ground after LSP have a ground finish similar to the as-ground sample on the left

Longitudinal Residual Stress Distributions of Alloy 52100 Steel Specimens



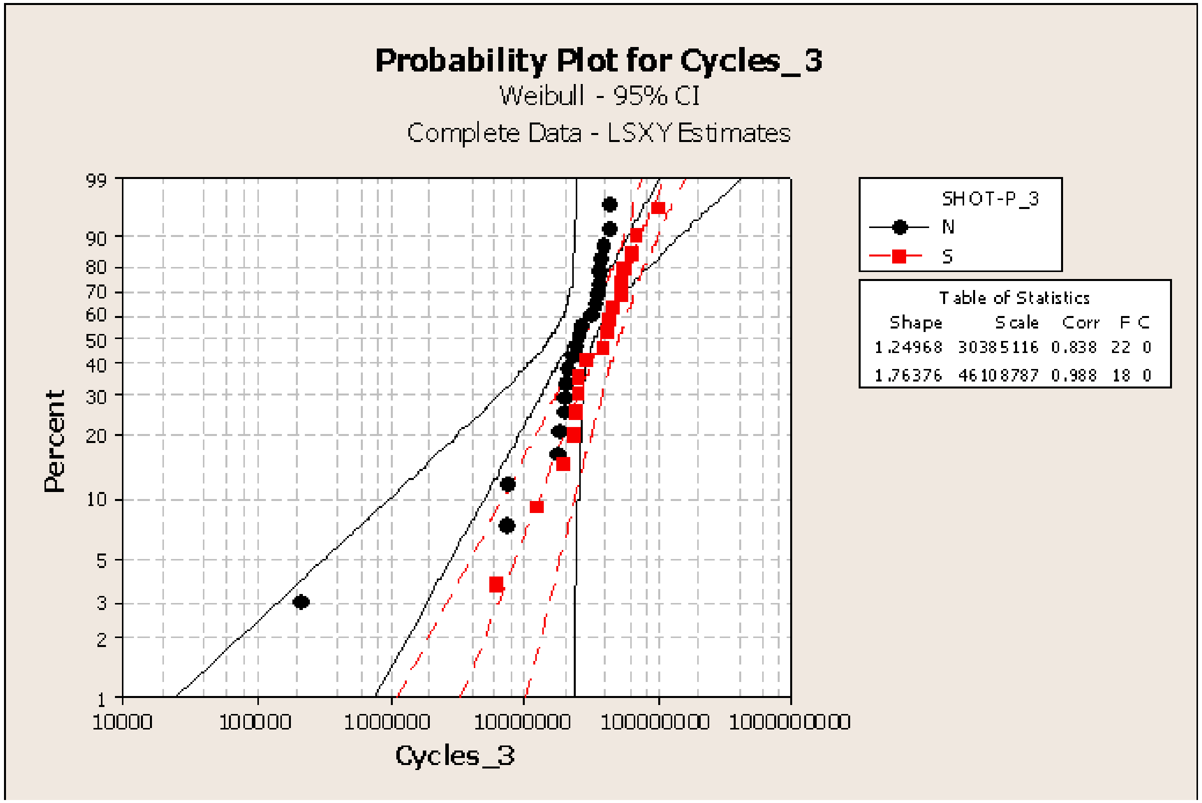
Fatigue Test Results of Alloy 52100 Steel Specimens



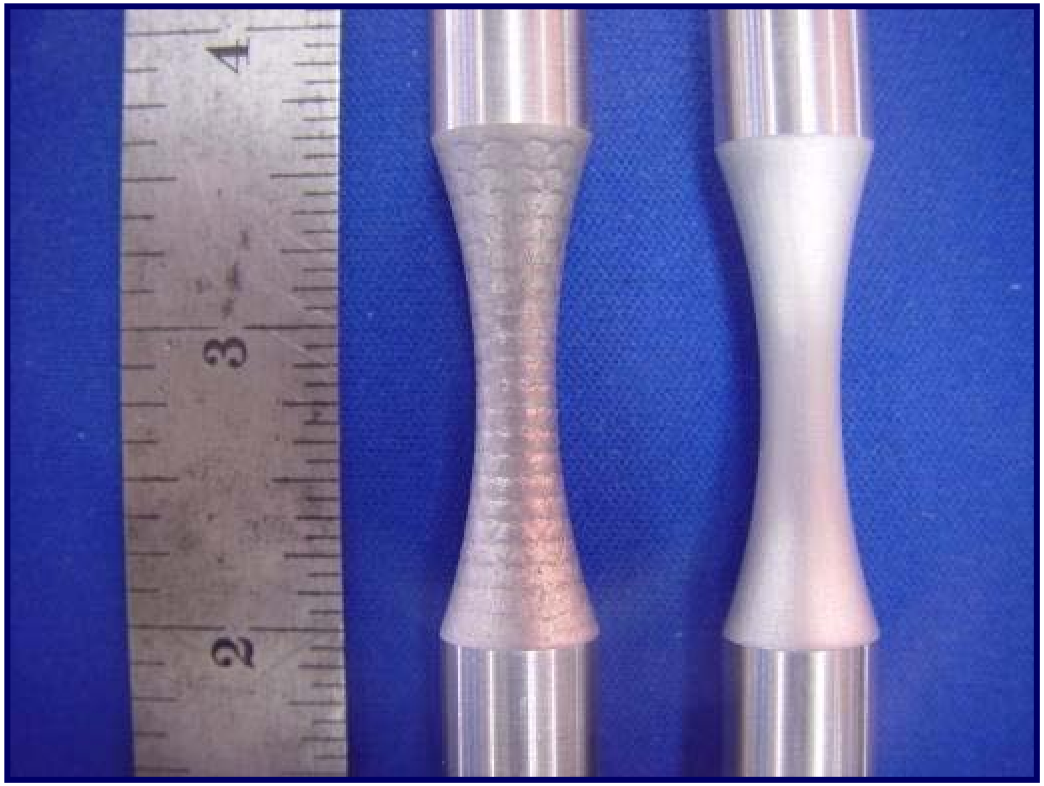
- Statistical analysis performed by Cummins indicated ~12% increase in high cycle fatigue between baseline (Control and ground) and LSP plus grind

Rolling Contact Fatigue Results

- Cummins observed ~50% improvement in rolling contact fatigue life in the LSP processed specimens with ground finish in comparison to the control



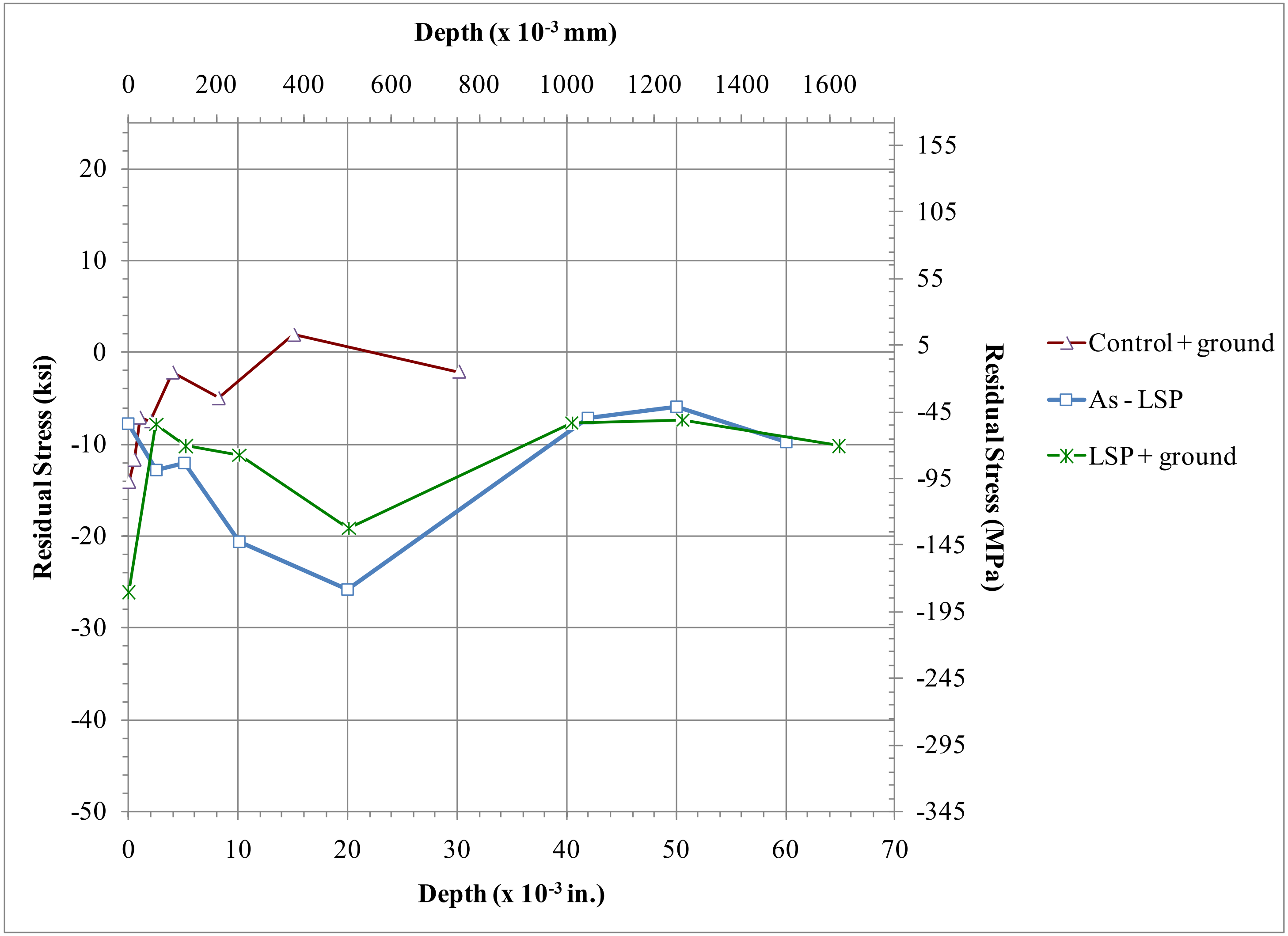
A354 Cast Aluminum Specimens Surface Finish Comparison



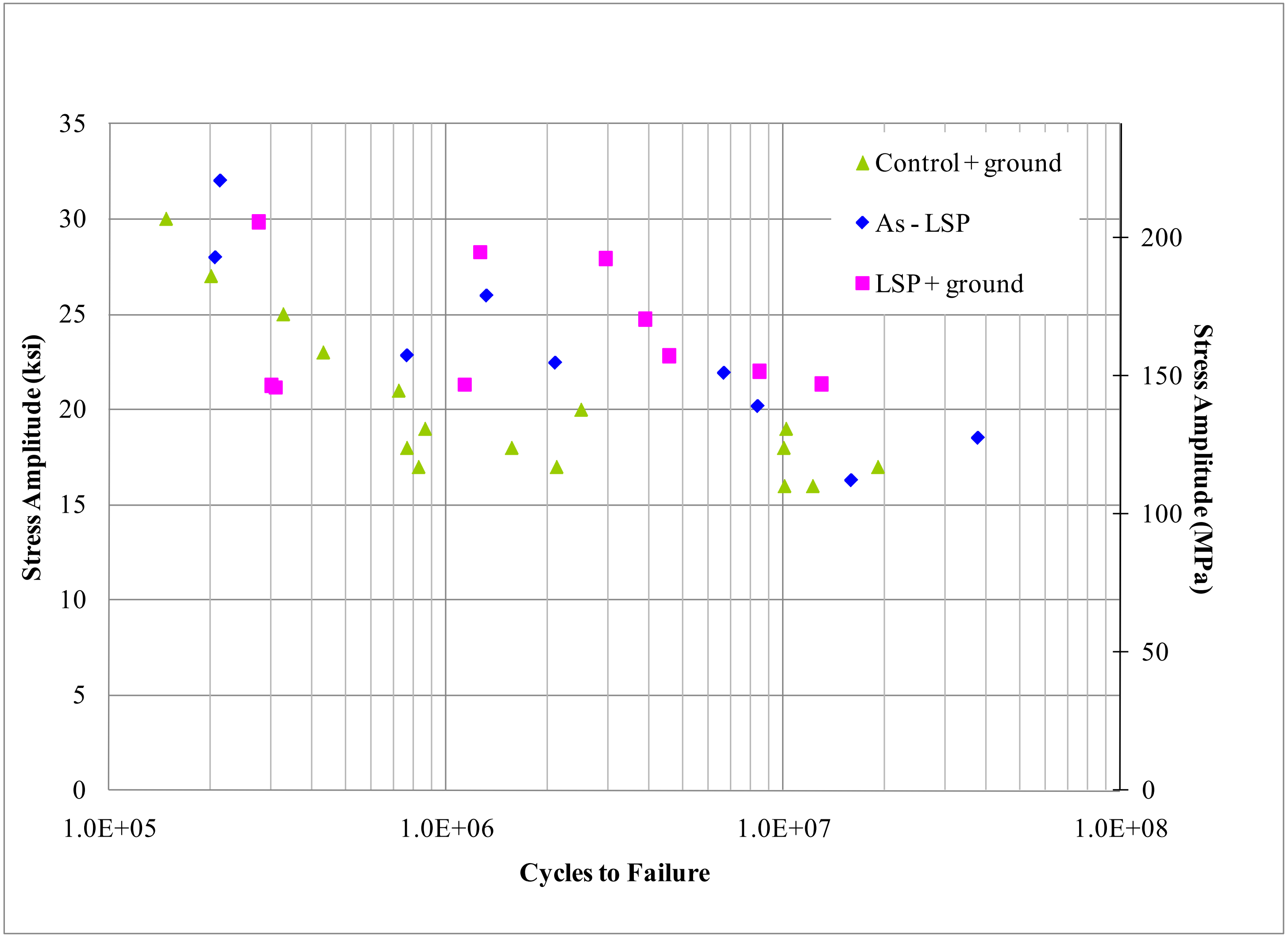
- Surface finish comparison of the as - laser shock peened (left) and the as-received ground (right) cast aluminum specimens
- Shock peened surface approximately 2.4 times rougher
  - 19 μin. vs. 8 μin

All samples ground after LSP have a ground finish similar to the control sample shown the right above

Longitudinal Residual Stress Distributions of A354 Cast Aluminum Specimens

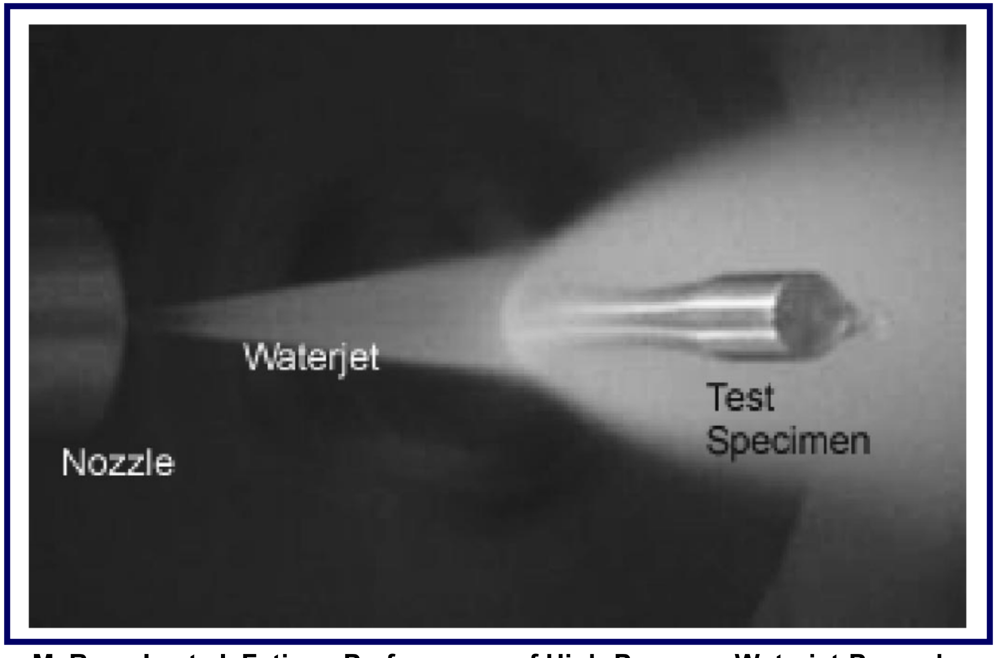


Preliminary Fatigue Test Results of A354 Cast Aluminum Specimens



Technical Progress - WJP

- Waterjet peening
  - Produces residual stress
  - Can improve finish
  - Large stand-off distances convenient for irregular geometry



M. Ramulu et al, Fatigue Performance of High-Pressure Waterjet-Peened Aluminum Alloy, J. of Pressure Vessel Tech. Vol. 124 pp.118-123, 2002

Waterjet Peening of A354 Cast Aluminum

- Approach focuses on the use of waterjet technology for peening the A354 cast alloy to enhance its fatgiue life
  - Pre-Screening of waterjet methods to determine the best method to produce a set of samples for evaluation – methods A, B, C
  - A parametric study to determine the most optimum processing parameters from the most promising methodology will be evaluated by RBF
    - Pressure
    - Stand-off distance (the distance between workpiece and nozzle)
    - Speed/feed rate per unit area

Technical Progress

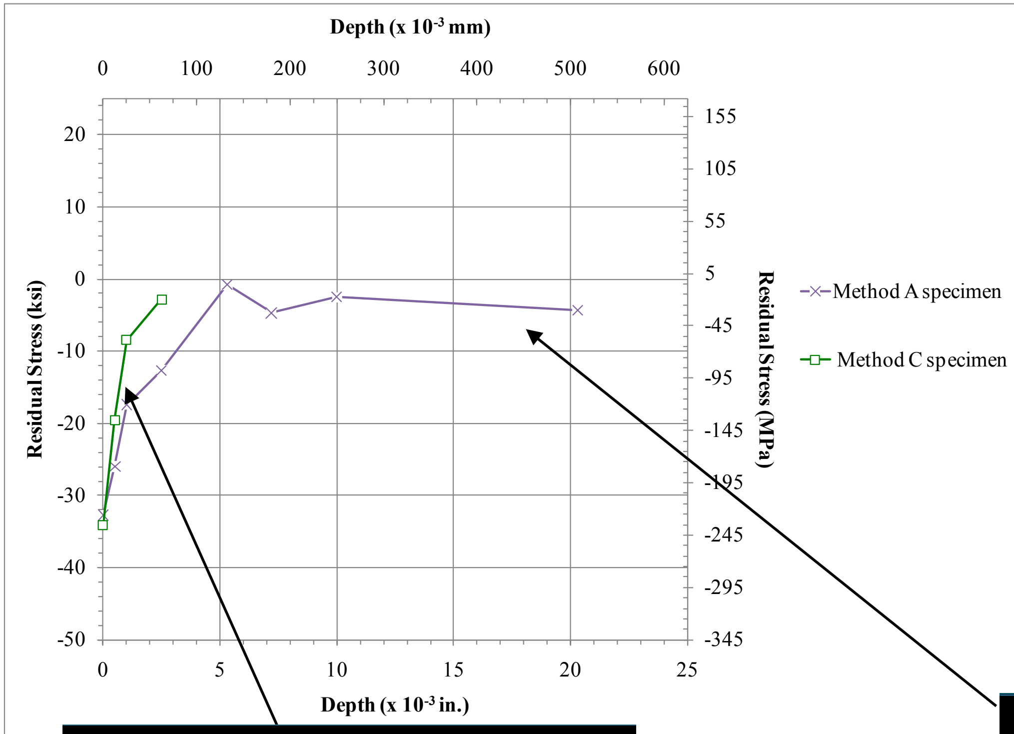
- From the pre-screening task, it was determined that further evaluations would continue on methods A & C
  - Peening method applied will affect depth of compressive stress and finish
- A quadratic model, DOE was applied, where the supply pressure (P), air pressure (P_A), stand-off distance, and traverse rate (u) was varied
- 26 runs were conducted; residual stress measurements and 3-d surface profilometry performed on each specimen processed

Table summary of process conditions evaluated.

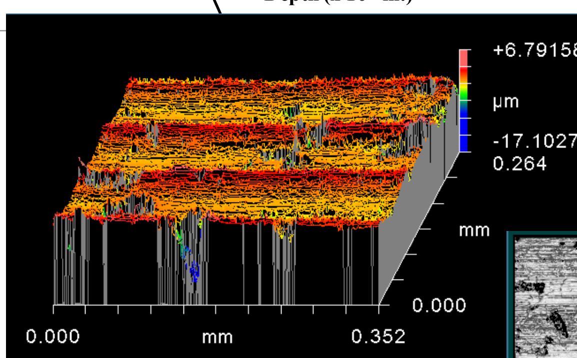
		P	SOD	u	Pa
Run No.	Sample #	*(ksi)*	*(in)*	*(in/min)*	*(psi)*
16	*F16*	10	1	25	0
23	*F25*	10	1	25	0
14	*F14*	10	2	2.5	0
22	*F24*	10	4	2.5	0
7	*F7*	10	4	25	0
2	*F2*	25	1	2.5	0
11	*F11*	25	1	25	0
21	*F23*	25	4	2.5	0
9	*F9*	25	4	25	0
19	*F19*	10	1	2.5	30
6	*F6*	10	4	25	30
25	*F27*	17.5	1	15	30
15	*F15*	17.5	2	15	30
17	*F17*	17.5	2	15	30
20	*F22*	25	2	25	30
26	*F28*	25	4	2.5	30
13	*F13*	10	1	2.5	60
10	*F10*	10	1	25	60
4	*F4*	10	2	15	60
8	*F8*	10	4	2.5	60
18	*F18*	17.5	2	2.5	60
5	*F5*	17.5	4	25	60
3	*F3*	25	1	2.5	60
12	*F12*	25	1	25	60
1	*F1*	25	4	15	60
24	*F26*	25	4	15	60

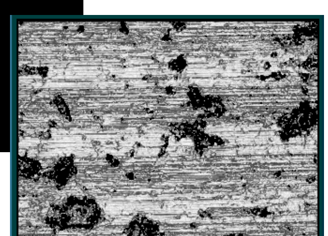
Preliminary Results

Comparison of residual stress measurements for Method A and C processed specimens

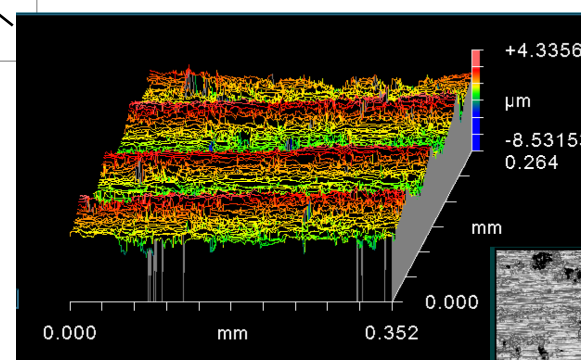


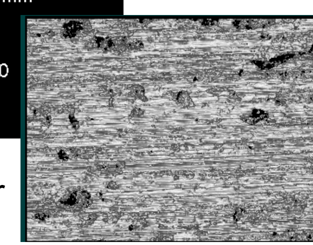
- All residual stress measurements and surface roughness measurements have been completed
- All results have been entered into the DOE to determine which method and process parameters would produce optimum finish and deep, compressive stresses
  - Finish and depth of compressive stress are key to enhancing fatigue life of specimen





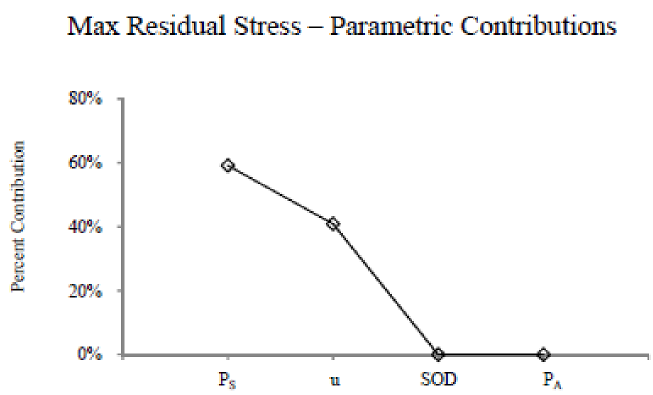
Representative surface image for spec. Method C where the ave. Ra measured was 43 µin.

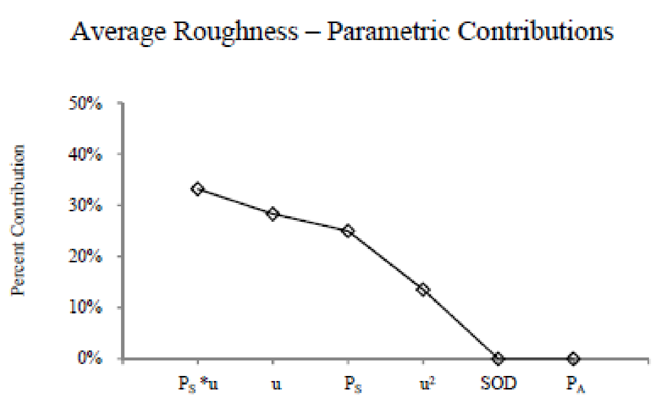


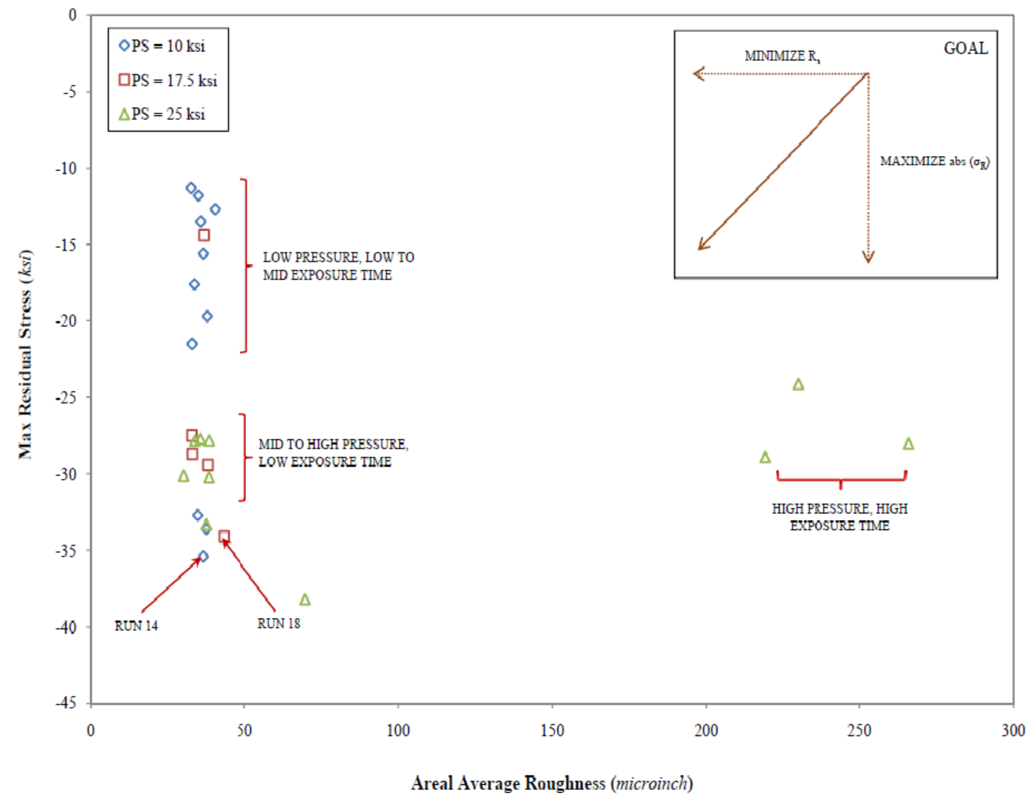


Representative surface image for spec. Method A where the ave. Ra measured was 35 µin.

DOE Results







- A Pareto was performed to understand the parametric contributions to residual stress and surface roughness
  - Supply pressure and traverse rate determined to be important contributors
- Two processing parameters (one from each method) yielded similar results in the DOE
- Fatigue test evaluations will be performed on both processing parameters

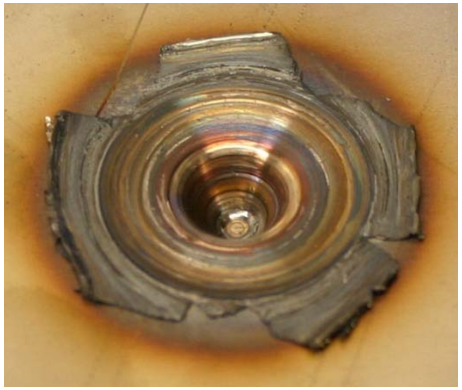
Technical Progress - FSP of Cast Iron

- Cummins' cast iron surface treatment project with South Dakota School of Mines and Technology under IUCRC grant (Leverages DOE and Cummins Inc. resources)
  - Developed new coil design to improve plasticization
  - Investigating cold spray Fe on cast iron surfaces and evaluating effect of surface modifications
  - Investigating flame coating cast iron plates with a mild steel to allow better induction preheating

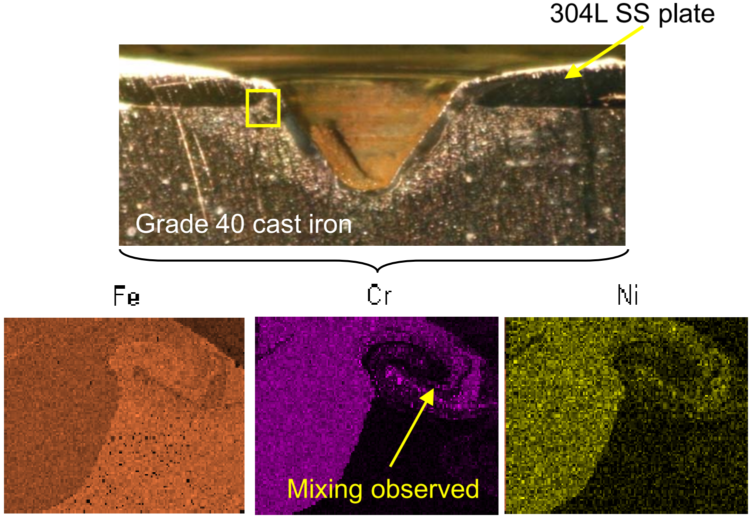
- PNNL hybrid cast iron surface treatment and joining development using PNNL FSW machine (high vertical force capability)
  - Microstructural analysis of friction joined cast iron parts performed
    - Developing fundamental understanding of structures formed and optimization of the microstructure
  - Development of friction stir processing of cast iron is ongoing
    - Focusing on achieving plasticization of the material

Progress Results Summary

Excessive chip formation observed when no cover plate is used with cast iron.

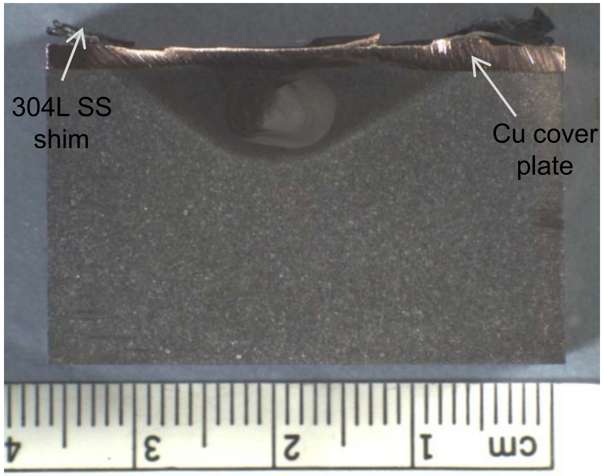


No chips observed when a cover plate is used with cast iron.



Plunge cross-section showing the area analyzed and the resultant EDS maps. Cr and Ni in the 304L allows for observation of any mixing between the materials.

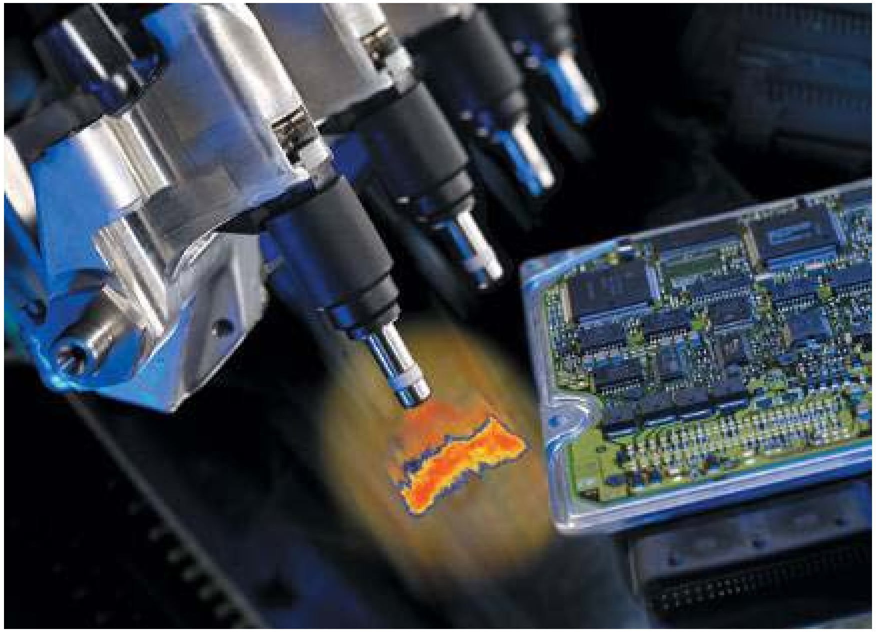
- Work has focused on evaluating challenges of friction stir processing/welding cast iron and investigating potential solutions to overcome these challenges
  - Use of cover plates (304L SS,1018 steel, & Cu) to aid in the development of friction stir processing/joining without pre-heating
- The use of a cover plate prevented the extrusion of cast iron material during friction stir welding
- Plasticization of cast iron was observed between a 304L SS cover plate and cast iron and between a Cu cover plate and cast iron without pre-heating the materials
- No segregation of the graphite was observed in the plunge cross-sections analyzed
- Work is continuing on the translation of the tool with the use of cover plates on cast iron



A 1-inch translation cross-section of the Cu cover plate on cast iron showing a consolidated joint.

Technical Progress

- Technology Deployment
  - Cummins Inc. has identified a series of components for full scale evaluation of LSP that obviously cannot be discussed here
    - Prototype development has been initiated
  - Cummins Inc. has initiated work outside of the CRADA



Future Work

- Test real components enhanced by LSP
  - To be done by Cummins Inc.
- Determine thermal stability of LSP induced compressive stresses in 52100 steel
- Complete RBF testing of waterjet peened cast aluminum alloy A354
- Continue development of surface treatment techniques of cast iron material via friction stir processing/joining
- Develop a cost model for process deployment

Summary

- Fatigue life of Laser Shock Peened and ground 52100 steel showed significant increase in RBF life over the other populations
  - Cummins statistical analysis of the fatigue results showed ~12% increase in high cycle fatigue
  - As expected, the effectiveness of shallow peening methods like shot peening were removed by post peening grinding
- Fatigue life of Laser Shock Peened and ground 52100 steel showed significant increase in RCF life over the control population
  - Cummins statistical analysis of the fatigue results showed ~50% increase in RCF life
- Promising results have prompted Cummins Inc. to move to Technology Deployment
- LSP fatigue life of cast aluminum alloy A354 was better than the baseline
  - Further testing is needed to determine whether any statistical significance observed in fatigue life between the LSP & as-LSP populations at higher cycles
  - Both LSP and as-LSP populations showed an improvement in fatigue life in comparison to the control

Summary, cont.

- Waterjet peening can produce surface compressive residual stresses while maintaining surface finish
  - The DOE identified two promising processing parameters (one from Method A and C) for further fatigue evaluations
- Friction Stir Processing/Joining of cast iron developments are ongoing
  - Plasticization of cast iron observed with the use of cover plates and no pre-heating
  - No segregation of graphite was observed in the plunges or translations