Characterization and Properties of Surface Modified Steels for Fuel System Components

PURDUE UNIVERSITY
School of Materials Engineering

Student names: Lute Lahrman, Mitchell Brezina, Renee DiNino, Praneet Kabra
Faculty Advisors: Dr. David Bahr, Dr. Mark Gruninger
Industrial Sponsors: Brian Wright, Ashwin Balasubramanya
Acknowledgements: Dr. Gary Cheng, Sen Xiang

The purpose of this project was to characterize the effects of laser surface texturing on four different types of steel coupons and determine which type of laser and surface pattern provides optimal properties. A continuous or pulsed laser was used to make a line or grid texture. The characterization methods performed were residual stress, contact angle, microhardness, surface profilometry, and surface analysis by AFM. Contact angle results showed that all laser textured surfaces were hydrophilic. The residual stress results determined that pulsed laser texturing maintained compressive stress better than continuous laser texturing. Pulsed laser texturing was also optimal for hardness because it did not cause softening while the continuous laser did.

This work is sponsored by Cummins Inc., Columbus, IN

Project Background

- ❑ **Technical problem:**
  - ❑ Significant wear and corrosion on steel components within Cummins' fuel system due to impurities.
  - ❑ Insufficient lubrication and wetting behavior decreases the overall efficiency and allows for impurities to come in contact with the steel surface of the fuel system.
- ❑ **Scope:**
  - ❑ Characterize and quantify properties of the alloys before and after laser texturing on surfaces.
  - ❑ Correlate and explain trends between varying textures/morphologies and their properties and performances.
- ❑ **Materials (Steels):**
  - ❑ 4140 - Vacuum hardened, <20% bainite, avg. 610 HV
  - ❑ 8620 - Atmosphere carburized, avg. 750 HV
  - ❑ H13 - Vacuum hardened and nitrided, avg. 1108 HV
  - ❑ M2 - Vacuum hardened, tempered, avg. 820 HV

Experimental Procedure

Residual stress:
- ❑ Pulstec μ-X360
- ❑ Testing completed parallel and perpendicular to line textures.
- ❑ Notable results were Debye ring and residual stress

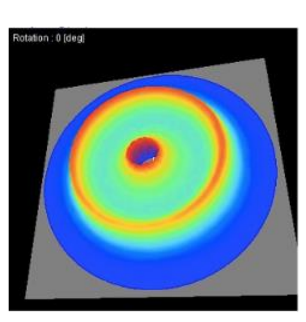

Figure 1: Debye ring result from residual stress measurements

Contact angle:
- ❑ Coupons cleaned in ultrasonic bath
- ❑ Static contact angle measured using the ramé-hart goniometer
- ❑ Liquids used: DI water, calibration fluid, and oil
- ❑ Five angles were measured for each type of liquid

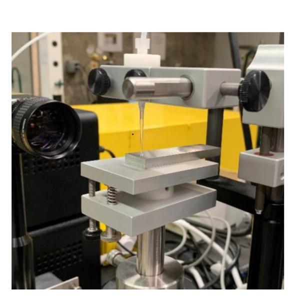

Figure 2: Goniometer set up

Hardness:
- ❑ Arrays of 10 indents
- ❑ 500 g load
- ❑ Tests performed on and around textured regions

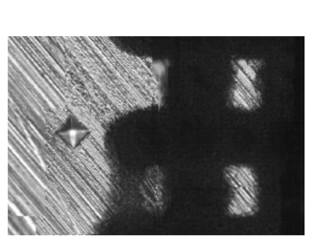

Figure 3: Example of indent just outside of grid texture

AFM:
- ❑ Bruker multimode AFM was used in contact mode.
- ❑ Ra, Rz values and other topographical features were analyzed.
- ❑ The scan areas were 150 um, 100 um and 50 um with scan height set at 1 um, 2 um and 5 um.
- ❑ The 50 um scans were performed at a lower speed to adjust for sharper surface features.

Optical Profilometry: Images/data produced were from the ZYGO 3D Optical Profilometer and analyzed using the website https://www.profilmonline.com/.

- ❑ **Coupon Geometry and Texture Parameters:**
  - ❑ Coupon Set 1 – ground steels, no texture
  - ❑ Coupon Set 2 – continuous laser, line texture
  - ❑ Coupon Set 3 – pulsed laser, line texture
  - ❑ Coupon Set 4 – pulsed laser, grid texture
  - ❑ Coupon Set 5 – pulsed laser, line ten pass texture

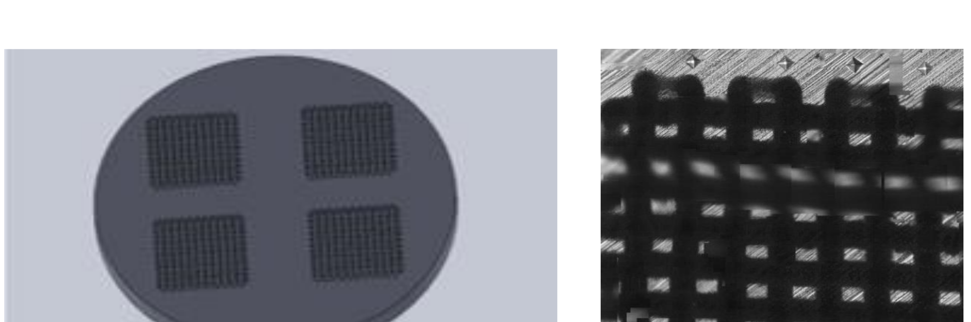

Figure 4: Rendering image of grid coupon (left) and grid textured coupon (right)

Results

Residual Stress

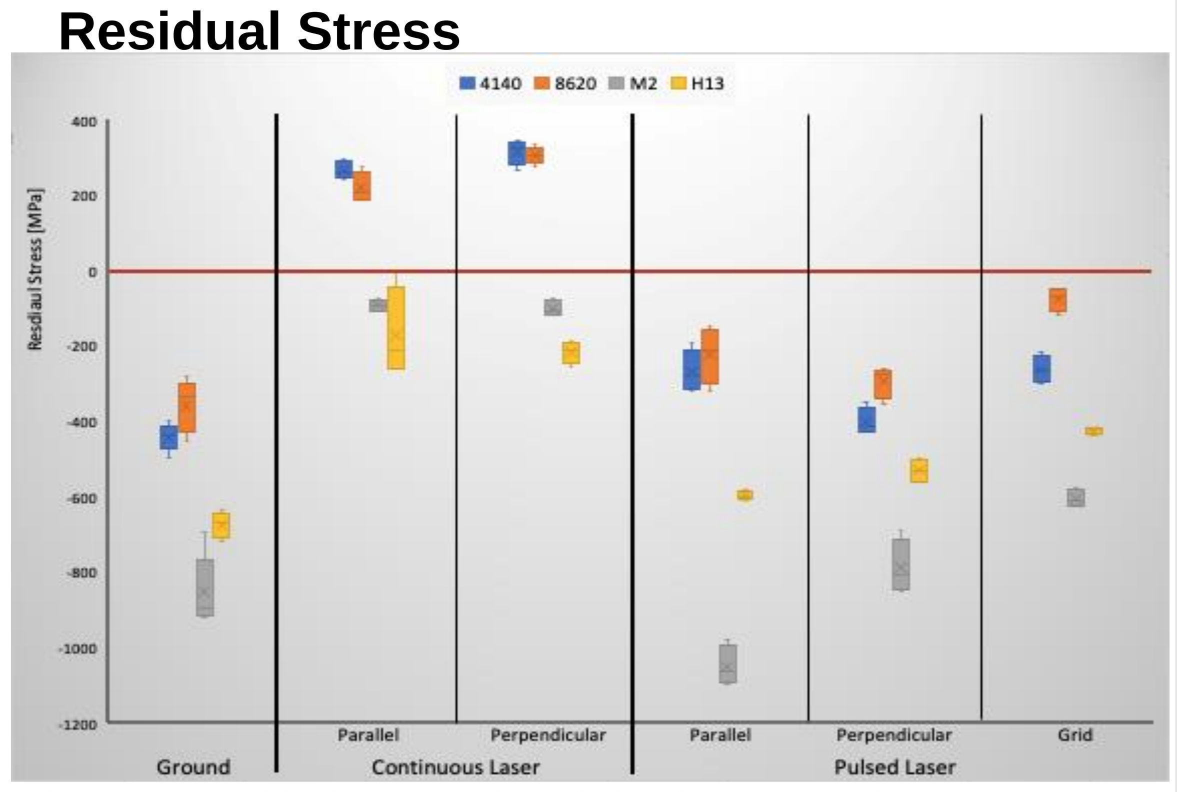

Figure 5: Residual stress plot of the four steels from untextured ground (left) to the pulsed grid texture (right) in order.

The pulsed laser retained the majority of or generated more compressive stress. Red line is threshold between compressive and tensile stresses.

Contact Angle

Table 1: The average static contact angle with standard deviation for four of sample sets with all the three liquids.

Coupon Condition	DI Water	Calibration Fluid	Oil
Set 1 – Ground Steel, no texture	65.8° ± 6.78°	6.80°± 0.935°	17.7° ± 2.20°
Set 2 – Line texture, continuous laser	62.3° ± 4.81°	7.07° ±1.53°	16.7° ± 1.62°
Set 3 – Line texture, pulsed laser	65.3° ± 3.92°	7.61° ± 1.67°	17.4° ± 2.00°

Statistical t-tests show **no statistically significant difference** between that the ground coupons and the textured coupons. All angles show **hydrophilic behavior** since the angles are less than 90°.

Surface Analysis AFM & Optical Profilometer

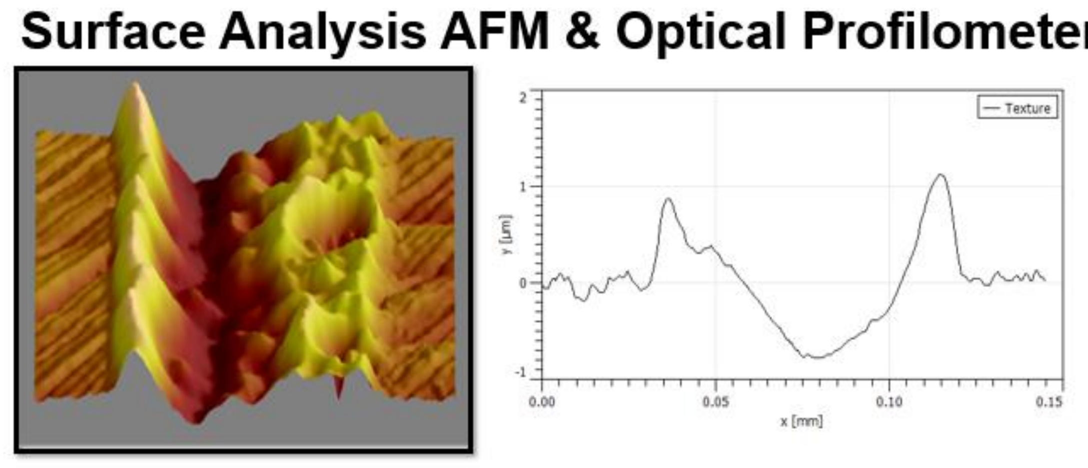

Figure 6: The image on the left is AFM scan of 4140 line continuous laser texture and its surface profile on right. Thermal expansion due to large thermal gradients let to plastic yielding led to accumulation of residue around the texture.

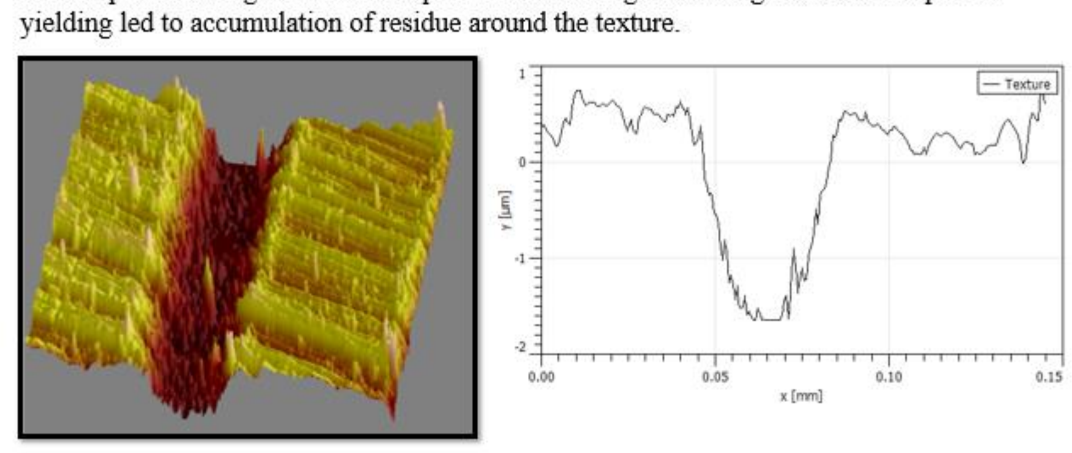

Figure 7: The image on the left is AFM scan of 4140 line pulsed laser texture and its surface profile on right. The pulsed laser resulted in sharper edges and low residue deposition.

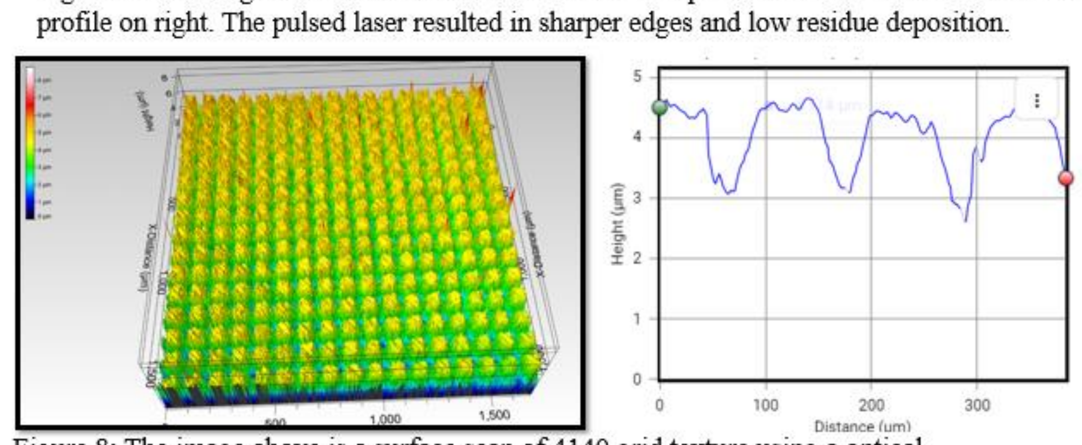

Figure 8: The image above is a surface scan of 4140 grid texture using a optical profilometer. The grid was made using pulsed laser and has a texture similar to line texture.

Table 2: Table 2 highlights Rz value from AFM scans and max depth of texture

Coupon Set	Rz (Avg Peak-Valley Distance) in nm	Depth of Texture (Trench) in μm
4140	457.8 nm (continuous) 645.6 nm (pulsed)	1.985 μm (continuous) 2.567 μm (pulsed)
8620	713.8 nm (continuous) 878.3 nm (pulsed)	2.878 μm (continuous) 2.981 μm (pulsed)
M2	231.2 nm (continuous) 363.8 nm (pulsed)	0.310 μm (continuous) 0.834 μm (pulsed)
H13	73.17 nm (continuous) 479.7 nm (pulsed)	1.106 μm (continuous) 1.578 μm (pulsed)

Hardness

Table 3: Average hardness values (HV) for 4140 steel coupon trials

Coupon Condition (4140 Steel)	Avg. Hardness (HV)
Set 1 – Ground Steel, no texture	611 ± 26
Set 2 – Line texture, continuous laser	536 ± 37
Set 3 – Line texture, pulsed laser	603 ± 22
Set 4 – Grid texture, pulsed laser	621 ± 21

- ❑ Steels other than 4140 showed no statistically significant difference between coupon sets
- ❑ 4140 Set 2 **(continuous laser) showed statistically significant softening** from ground (control) coupons
- ❑ **Pulsed laser coupons** (Set 3, Set 4) **showed no softening** from ground (control) coupons

Discussion

- ❑ **Contact angle did not change for current textures; larger groove geometry differences may cause surface behavior change**
  - ❑ Contact angle was determined to be unnecessary for coupon set 4 because of its similar groove geometry to the previous coupon sets
  - ❑ Future contact angle measurements are needed to determine hydrophilic or hydrophobic behavior if the ratio of groove width to spacing between the grooves changes dramatically
  - ❑ Depth of grooves is also important and can influence which wetting model the surface follows
- ❑ **Pulsed laser retained significant or increased compressive stress than continuous laser**
  - ❑ M2 reached an apex performance over all steels in parallel orientation for Coupon Set 3
  - ❑ Residual stress between textures on same coupon are significantly different from t-test (not repeatable accurately)
  - ❑ Residual stress was not uniform across the coupon prior to texturing so may be potentially responsible for stress variation after texturing
- ❑ **Texturing can be done without softening steel**
  - ❑ Pulsed laser shows no softening in any steel coupons
  - ❑ Continuous laser significantly softened 4140 steel coupons
  - ❑ Softening is likely due to increased exposure time with continuous laser, potentially resulting in a microstructural change
- ❑ **Laser Texturing is driven by thermal diffusion length, Heat Affected Zone & Surface Roughness**
  - ❑ Higher Thermal diffusion length allows HAZ to dissipate heat outwards into the material lattice at faster rate in M2 and H13, which hinders ablation.
  - ❑ In 4140 and 8620, lower thermal diffusion length provides HAZ with enough energy to undergo ablation but sometimes excess energy causes plastic yielding.
  - ❑ The average surface roughness could dictate how laser will interact with the material surface.

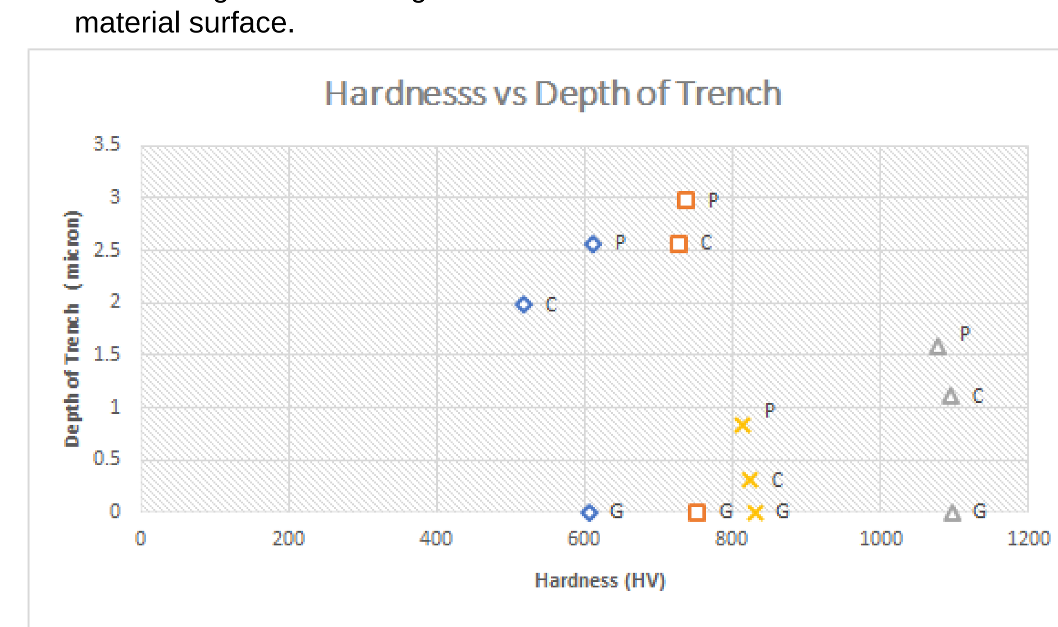

Figure 9: Graph showing average depth of trench vs hardness (HV) along with continuous laser (C) vs. pulsed laser (P)

Recommendations

- ❑ Specific heat and coefficient of thermal expansion are significant factors in laser texturing of steels
- ❑ Different width to spacing ratios in the grooves could affect surface behavior
- ❑ Microstructure of coupons after laser texturing affects strength of steel
- ❑ Coupon Set 5 (multiple line pass) investigates changes in depth of grooves