PURDUE UNIVERSITY
School of Materials Engineering

Effect of Plastic Deformation on Residual Stress Profiles in Induction Hardened 4140-Steel Shafts

Student Names: Brandon Camp, Junjie Li, Zach Logar, David Mathew
Faculty Advisors: Dr. Eric Kvam, Dr. Mark Gruninger
Industrial Sponsors: Chase Everett, Justin Jennings, Chris Fantauzzi, Carl Wesolowski

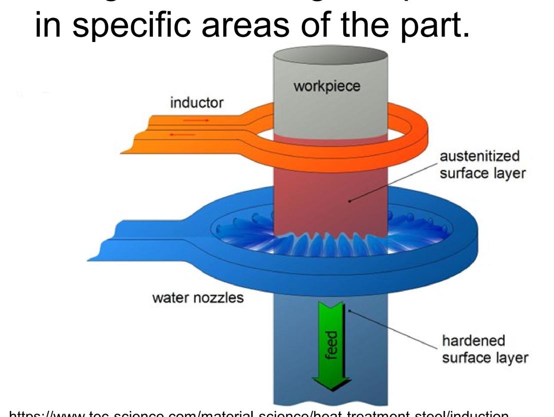
Utilization of compressive residual stress, from induction hardening, is important for the fatigue life of automotive gears and shafts. This project sought to investigate the changes in residual stress following a post-processing operation to reduce shaft runout. Mechanical straightening of induction hardened steel bars caused localized reduction in the residual stress profile at the bend location. Single and multi-hit corrections had no significant difference on the change in residual stress.

This work is sponsored by:
John Deere (Waterloo, IA)
Inductoheat (Madison Heights, MI)

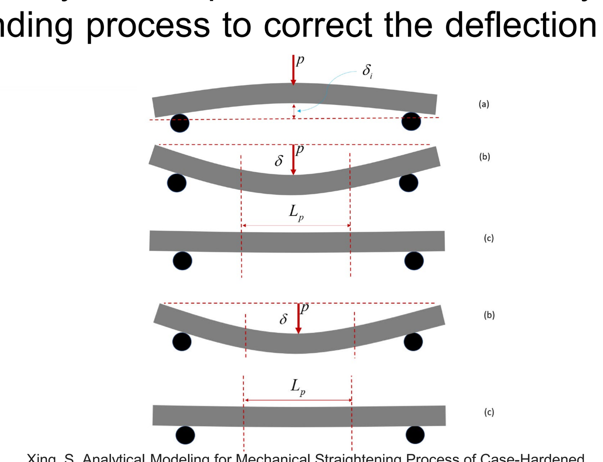
JOHN DEERE
INDUCTOHEAT An Inductotherm Group Company

Background

Induction hardening involves using an **electromagnetic current** to heat up an object, followed by a **rapid quench procedure** to complete phase transformation (*austenite to martensite/bainite/pearlite*) on the exterior of steel parts. The role of induction hardening is to **increase strength and improve fatigue properties** with compressive residual stresses. Following the quenching procedure, steel parts can be out of tolerance for design and need to be straightened. Due to the complexity of the parts, these are usually straightened using a 3-point bending process to correct the deflection in specific areas of the part.



https://www.tec-science.com/material-science/heat-treatment-steel/induction-hardening-surface-hardening/



Xing, S. Analytical Modeling for Mechanical Straightening Process of Case-Hardened Circular Shaft. *Appl. Mech.* **2023**, *4*, 715-728. https://doi.org/10.3390/applmech4020036

Project Goal

The goal of our project is to understand how **plastic deformation** (caused by mechanical straightening) **affects the residual stress profile** of induction hardened medium carbon steel sample bars.

Our subgoals are:

1. Residual stress characterization of mechanically straightened induction hardened samples (both **surface and depth**).
2. Runout measurement to ensure straightening operation was successful (**reduction in runout**).
3. Metallography to profile induction hardening case treatment.

Experimental Design & Methods

Induction Hardening

Inductoheat completed induction hardening on **2ft long x 2-inch diameter 4140 steel bars**.

3x Low Case (LCT) – 3 mm

3x Med. Case (MCT) – 7 mm

5x High Case (HCT) – 12 mm

The extra HCT bars (HCT 5 & 6) are for investigating the effect of **multiple straightening operations.**

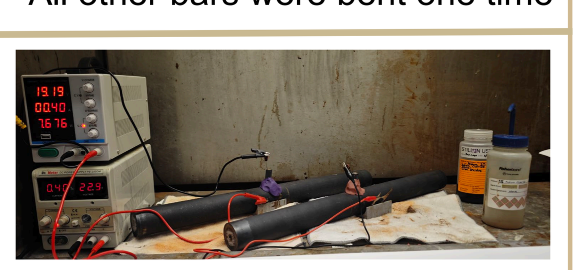
Mechanical Straightening

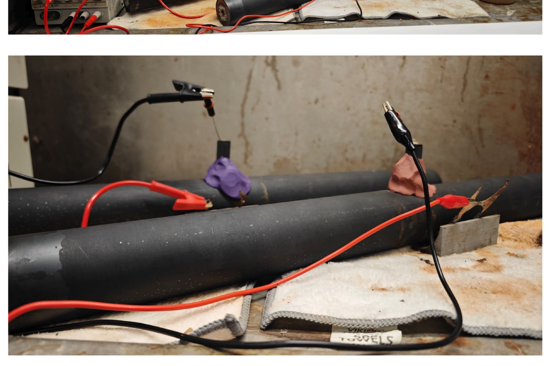
John Deere completed mechanical straightening operations on the bars. These straightening operations consisted of a series of 3-point bend "hits" that bend the bar to reduce runout.

- LCT 1 & 2 were **overbent** (increase in runout)
- MCT 2 was **hit more than 10x**
- HCT 5 & 6 were hit five and six times, respectively, in the same location
- All other bars were bent one time

Electropolishing

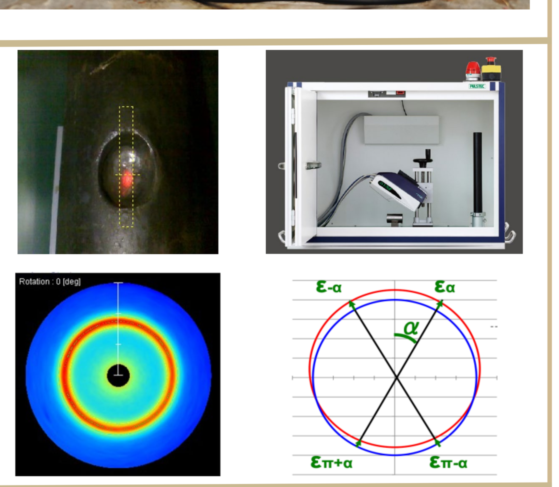
To investigate **residual stress** at various depths, electropolishing was used to minimize machining-induced stress. A platinum electrode was suspended in a PVC tube containing a 3% NaCl solution, secured with mounting putty. A pipette was used to replace solution every 5-8 minutes. The process operated at a **constant current of 0.45±0.05A .**





Residual Stress Measurements

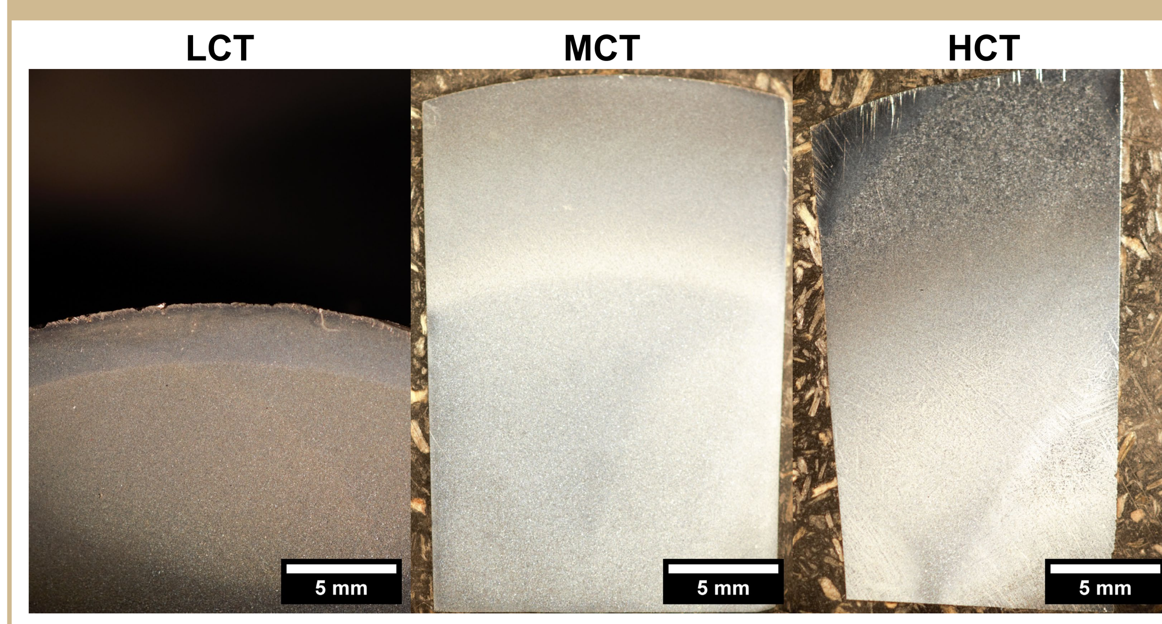
Residual stress was measured using a **PulsTec μ-X360S Residual Stress Analyzer**. The device measures the reflected X-rays from the samples and compares the data against typical steel XRD data (α-ferrite) to measure strain difference, displayed through a **Debye-Scherr Ring**.

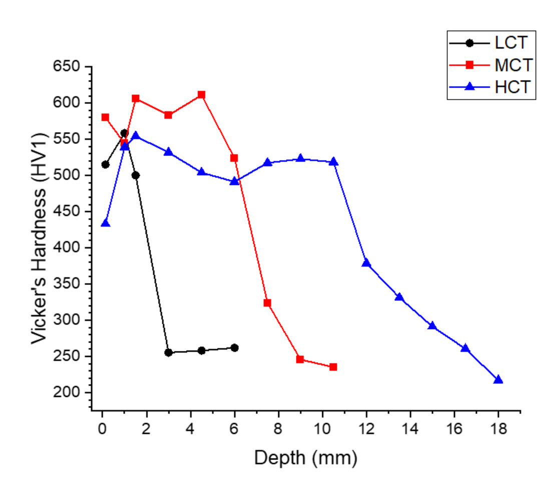


Metallography

Macro and Optical Images will be taken to characterize the induction hardened case. Samples were etched with a 10 seconds 2% Nital swab and imaged using an Olympus GX-41 Reflection Microscope and Canon EOS 5D Mark III Camera. To further characterize martensite, Vickers Hardness measurements were taken with a Wilson Hardness Indenter.

Results





Characterization of the case treatments **confirmed phase transformation to martensite** through visual and hardness testing.

Larger samples like HCT proved difficult to polish due to the hard (~55 HRC) outer core

Runout Measurements

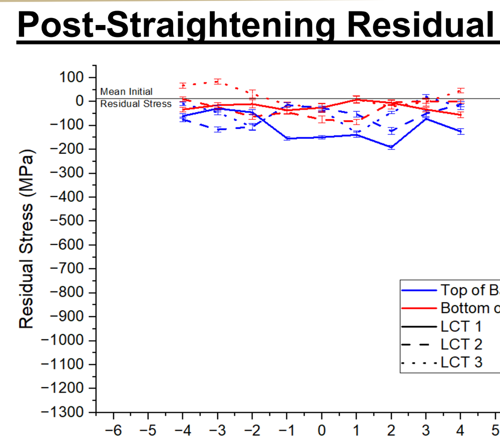
Initial runout data from the Purdue team has been excluded as it was collected with a different method.

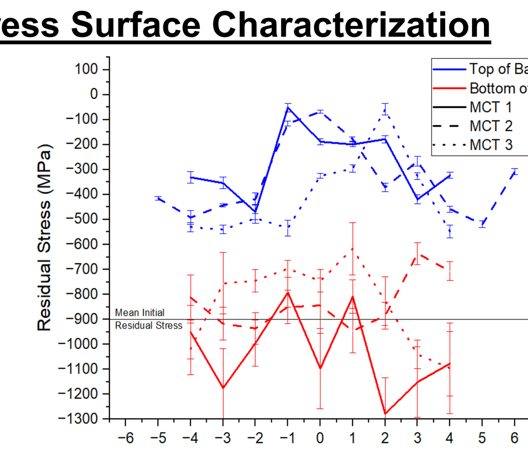
Runout measurements confirm:

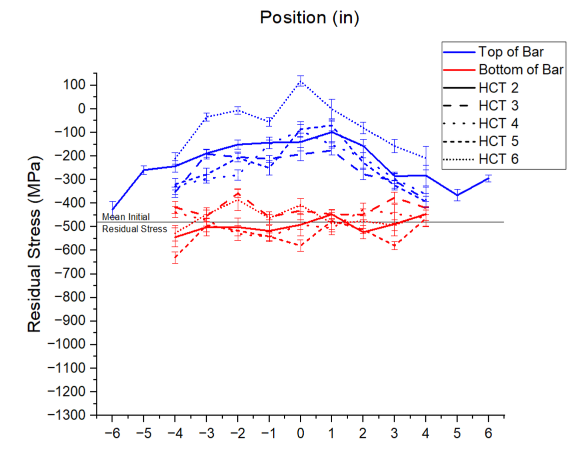
1. Bending **reached plastic deformation**
2. Most samples were **successfully straightened**.
3. LCT 1 and LCT 3 were overbent.

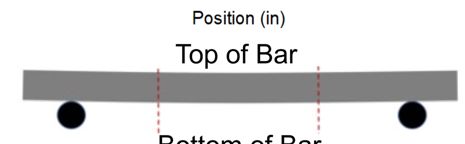
	Initial Runout	Final Runout	
Sample	John Deere (in)	Purdue (in)	John Deere (in)
LCT 1	0.029	0.043	0.0443
LCT 2	0.0027	0.011	0.0017
LCT 3	0.0113	x	0.0537
MCT 1	0.0287	0.01	0.0039
MCT 2	0.0223	0.015	0.0144
MCT 3	0.0234	0.008	0.0035
HCT 2	0.0705	0.056	0.0634
HCT 3	0.0588	0.035	0.0523
HCT 4	0.0359	0.025	0.0307
HCT 5	0.0144	0.005	0.0073
HCT 6	0.1075	0.075	0.0941

Post-Straightening Residual Stress Surface Characterization





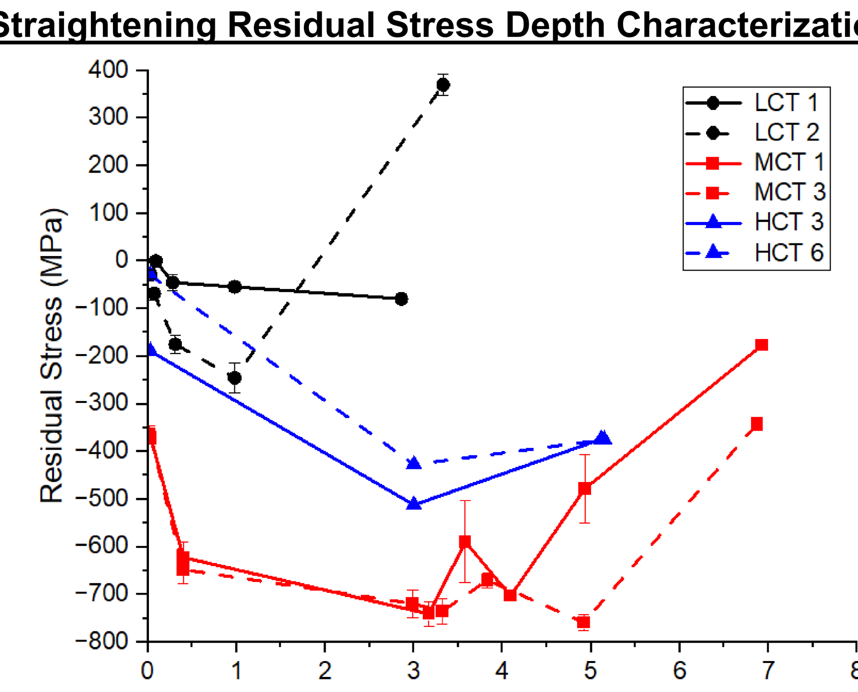




Top: Large reduction in residual stress at impact site, returns to normal away from bend location. The bend location is not necessarily located at the center (0 in) of the bar.

Bottom: Minimal change to residual stress profile from baseline

Post-Straightening Residual Stress Depth Characterization



- Residual stress depth profiles **follow a typical pattern**.
  - As depth increases: increasing compressive stress, which then decreases through the case-core interface.
- Change in residual stress is a result of bending operation on an initial compressive stress from the thermal gradients in induction hardening.

Discussion

John Deere's straightening process is to correct out of tolerance transmission shafts and axles post heat treatment.

- The LCT, MCT, and HCT cases on steel bars served as **model samples** to production parts.
  - **MCT and HCT were prioritized** as they were more similar to production part treatments.

Metallography and hardness confirmed phase transformation, and image analysis profiled key transformation depths to compare against residual stress depth profiling.

Effect of Single Straightening Operation on Residual Stress

Surface:
Our results **confirmed expectations** based on literature – the mean **compressive stress was partially nullified** by the straightening operation at impact.

- Magnitude of change **decreased moving away from impact site**
- The bottom of the sample relative to the 3-point bend location saw no significant changes to residual stress.

Depth:
The straightening operation **removed compressive stress at the surface.**

- Tensile residual stress was measured or expected near the case-core interface.
  - Deep measurements were restricted by the aperture of the hole and the incidence angle of the X-ray.
- The case treatment determined how deep the residual stress was altered and how quickly it transitioned back to tensile stress.
- Depth measurements were only taken at the middle of the bar (exact bend spot varied slightly); further research could investigate a large depth profile around impact and other sides of the bar.

Effect of Multiple Straightening Operation "Hits"

In John Deere's straightening process, many bars are bent more than one time to reduce runout within specification. MCT 2, HCT 5, and HCT 6 were all bent more than once to investigate the effects of this process.

Surface: Samples with multiple bends do not show a significant difference in residual stress surface profiles. Interestingly, the one bend and multiple bend conditions both reduce the compressive residual stress at the impact site by the same amount.

Depth: Samples with multiple bends, specifically HCT 5 and 6, do not show a significant difference in residual stress depth profiles compared to single hit, high case bars.

Potential Future Research
Multiple Hits, Same Location = No Significant Change After First Hit
Multiple Hits, Different Locations = Likely a complex, varied profile in residual stress

Conclusion & Recommendations

Based on our results, John Deere **should investigate more research** into understanding how the bending situation affects residual stress profiles. Between overbent and multi-straightened bars, there were large degradations to residual stress profiles on our bars. Deeper understanding of the residual stress change will help design engineers better prepare for these post-processing corrections in final design performance criteria. Some areas of investigation can be **corrections in multiple locations and magnitudes** along the length of the bar. Before bending depth profiles would provide better understanding of residual stress changes through the outer case.

Acknowledgements

The Senior Design Team would like to thank our advisors, sponsors, and the following people for making contributions to the project and helping the team find success!
Dr. Kevin Trumble - Knowledge on straightening and case hardening
Dr. David Johnson - Knowledge and support on electropolishing
Jia-Huei Tien – Knowledge on PulsTec equipment
Matthew Kaboolian – Support with Macrophotography