Remediation of Lost Compressive Residual Stresses in Carburized Steel Gears

PURDUE MATERIALS ENGINEERING

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The formation of non-transformation products and grinder burn on heat-treated steel gears is a serious problem for John Deere. These defects reduce hardness, residual compressive stresses and fatigue life, increasing scrap costs. John Deere has suggested shot peening as a possible way to restore mechanical properties. Shot peening induces compressive residual stress into the gears, potentially undoing the damage caused by grinder burn. Residual stress, metallography and microhardness measurements were conducted on gear samples provided by John Deere in order to recommend whether or not John Deere should pursue the shot peening approach.

This work is sponsored by John Deere, Waterloo, IA

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Project Background

This work provides an analysis and evaluation of the non-transformation products, intermediate products, and grinder burn issues that John Deere is experiencing as a result of current heat treatment and finish machining.

A carburizing heat treatment is applied to the 8620 steel gears in order to create a hard outer martensitic surface while retaining a tough pearlitic core (Fig. 1). Quenching after carburization produces a compressive residual stress profile that improves fatigue life and minimizes crack propagation.

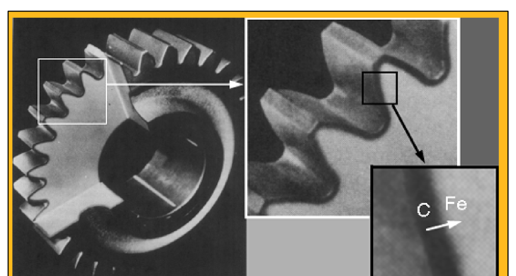

Figure 1: A cutaway of a carburized gear is shown. Notice the difference in color between the black martensitic case and grey pearlitic core.

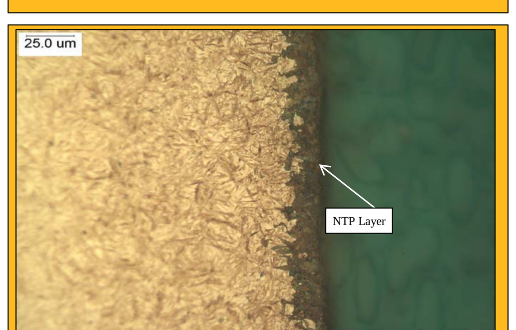

Figure 2: The NTP layer can form during the carburization process and is thought to be composed of de-alloyed elements.

During the carburization heat treatment process, softer non-transformation products (NTP) are sometimes formed on the gear surface. This NTP layer is thought to result from de-alloying during carburization. If any NTP affected zone measures deeper than 25 µm, the part is scrapped.

Figure 3: Burned areas on gear teeth can either be tempered or untempered martensite depending on burn severity.

Grinder burn occurs during finish grinding and can over-temper or re-harden the surface, depending on severity. This results in an inhomogeneous surface with hard and soft spots, making the tooth vulnerable to failure in bending.

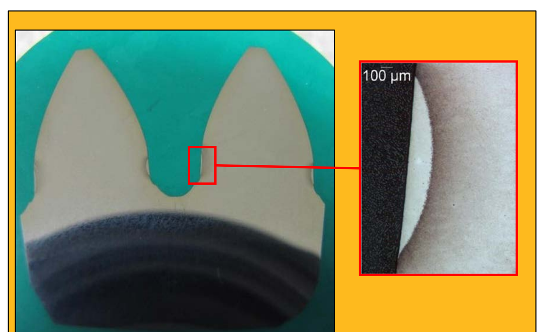

Figure 4: This cross section shows a burned location near the root of a gear tooth. Notice how the burn penetrates past the tooth surface.

Burned areas are detected using an acid bathing process and present themselves as black streaks. The darker that a streak comes through, the more intense is the burn. John Deere uses a gradient scale to pass or reject burned gears.

Shot peening is being implemented in an attempt to rectify lost residual stress and surface hardness. Shot peening imparts compressive residual stress into the parts by plastically deforming the surface via the shot media impacts.

Figure 5: The shot peening process imparts additional compressive stresses into the gear surface. The shot media is usually in the form of small steel balls with a hardness greater than that of the material. A desirable post shot peening stress profile is shown to the left.

Experimental Procedure

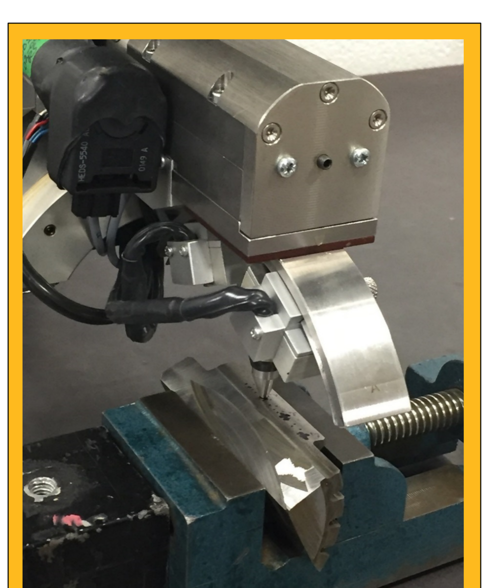

Figure 6: XRD residual stress machine at American Stress Technologies taking surface stress measurements on a burned gear tooth.

Gears affected by NTP development and grinder burn were sectioned and prepared for X-ray diffraction testing, optical microscopy, and Vickers hardness measurements.

An audit part with previous residual stress measurement history was used to verify XRD machine capability. A surface profile along the length of the grinder burn (red line in Fig. 12) was created on both the base grinder burn part and the subsequently shot peened part. A depth profile was also taken from 0-200 µm depth at the middle of the burn.

A depth profile was taken from 0-200 µm depth at the 30° offset location (Fig. 7) of the NTP and subsequently shot peened part.

Vickers hardness and optical microscopy were used to verify levels of NTP and grinder burn. Cross-sections were cut to measure the depth and hardness of each area. Surface hardness was also measured along the surface of the burnt part.

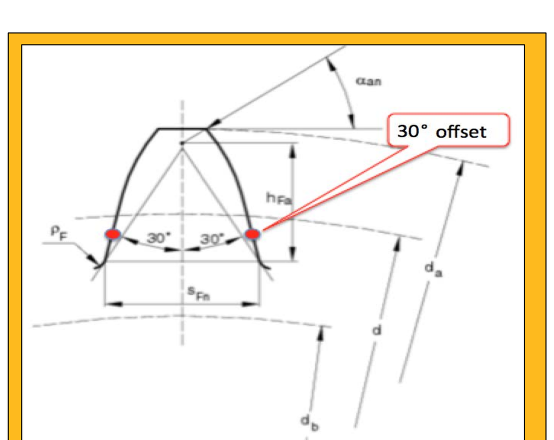

Figure 7: The 30° offset location on gear tooth profile according to AGMA standards.

Results & Discussion

Non-Transformation Products

Optical microscopy and residual stress and hardness measurements were performed on a set of shot peened and non-shot peened poor microstructure gears. As shown in Fig. 8, the greatest amount of NTP was found near the 30° offset location (Fig. 7).

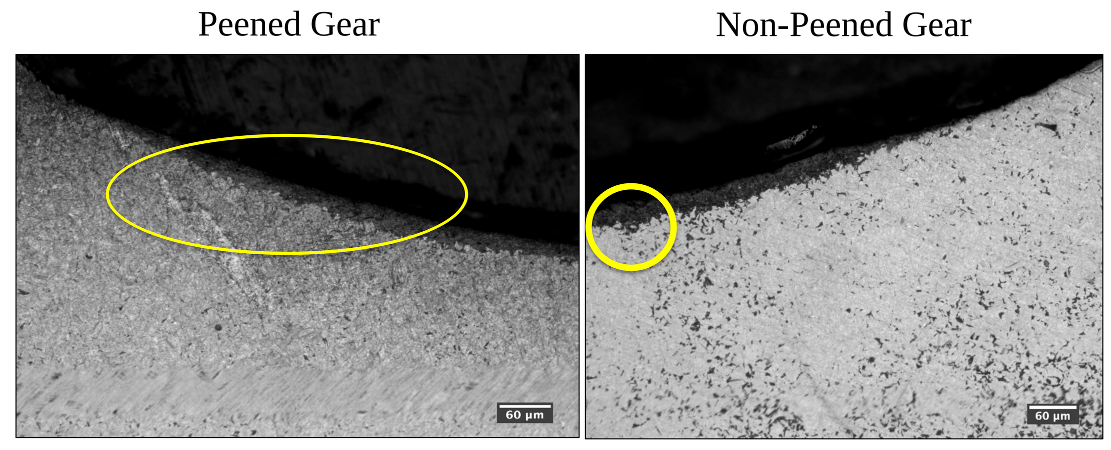

Figure 8: Optical microscope images of a poor microstructure peened and non-peened gear teeth near the 30° offset location. The yellow circles indicate where the maximum NTP layer was found. The thicknesses were measured to be 34 µm and 42 µm respectively.

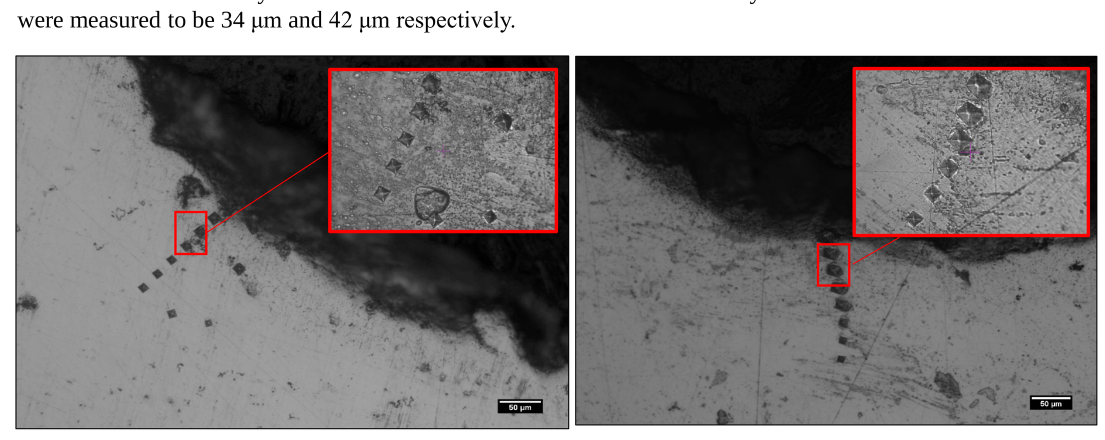

Figure 9: Optical microscope images of Vickers hardness indentations on a poor microstructure shot peened and non-shot peened gear teeth near the 30° offset location. The close up view highlights the poor microstructure area.

Application of shot peening was able to improve the internal stress state and recover some of its hardness lost due to NTP layer formation at the surface. The application of shot peening introduced up to 1400 MPa of compressive residual stress into the surface of the gear. The effect of shot peening on residual stress and hardness decreases as depth increases, and is negligible beyond a depth of 220 µm.

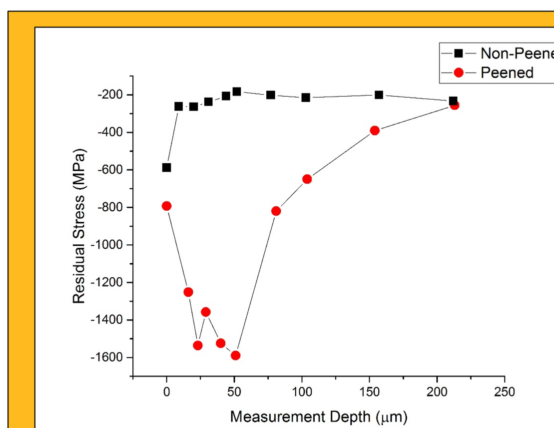

Figure 10: Residual stress vs. depth to surface profile for peened and non-peened poor microstructure gears near 30° offset location.

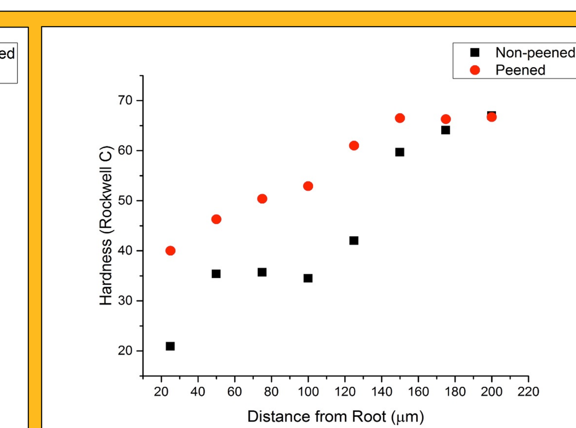

Figure 11: Hardness vs. distance to root profile for peened and non-peened poor microstructure gears near 30° offset location.

In Figure 11, the hardness profile had unexpected data points. For non-peened data, the hardness jumped from 21 HRC to 35 HRC at depths of 25 µm and 50 µm. This is much lower than expected. In Figure 9b we can see that there is a poor microstructure layer between the NTP layer and martensitic layer. The location of this soft layer is around 50-150 µm below surface. The application of shot peening did not improve the microstructure in this region but it improved the hardness by 10-20 HRC.

Grinder Burn

A severe grinder burn region was selected by visual inspection and measurements were taken along the burned area. The average surface hardness of a shot peened tooth was shown to be higher than a non-shot peened. Figure 13 shows a clear surface hardness difference between shot peened and non-shot peened teeth. The greatest post-peen hardness difference presented itself in the burned zone. This shows that shot peening cannot fully recover lost surface hardness in the grinder burn region.

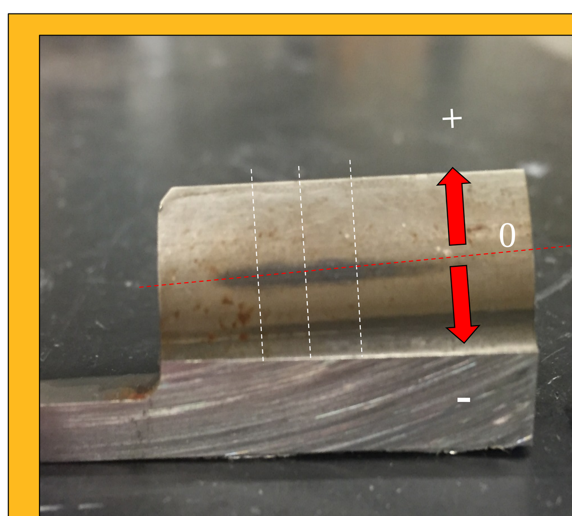

Figure 12: Sectioned grinder burn gear with white dashed lines indicating Vickers hardness test locations. White lines are spaced in increments of 3mm.

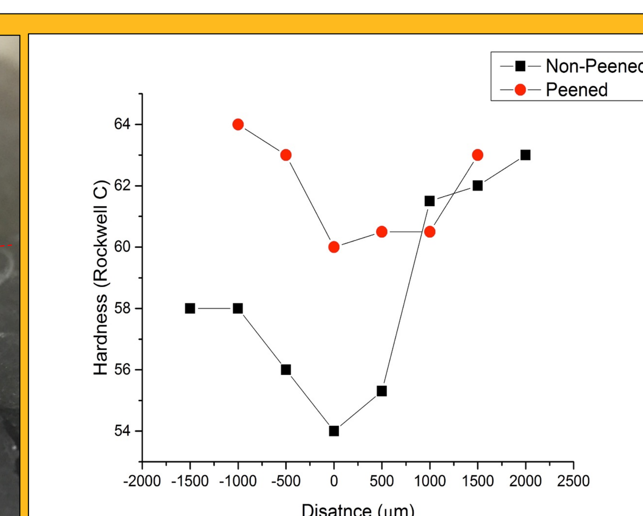

Figure 13: Vickers hardness of Grinder burn region is measured along the white dashed line. Non-Shot peened had 8 points of each white dashed lines and shot peened had 6 points. Three were taken along the red dashed line and were averaged and changed to Rockwell hardness C scale.

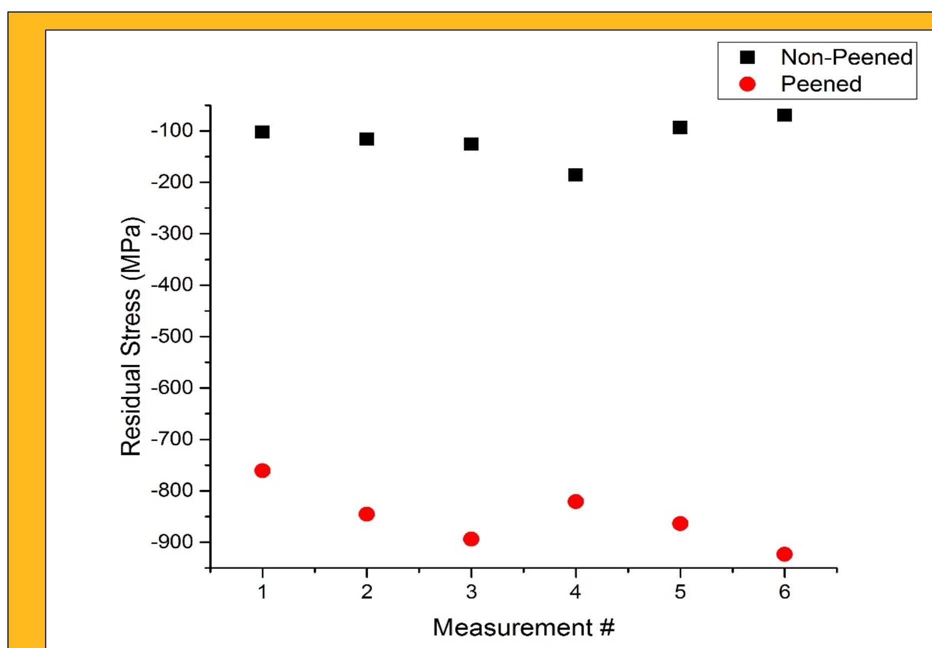

Figure 14: XRD residual stress measurement on 30 degree offset horizontally on the surface of grinder burned shot peened and non-shot peened.

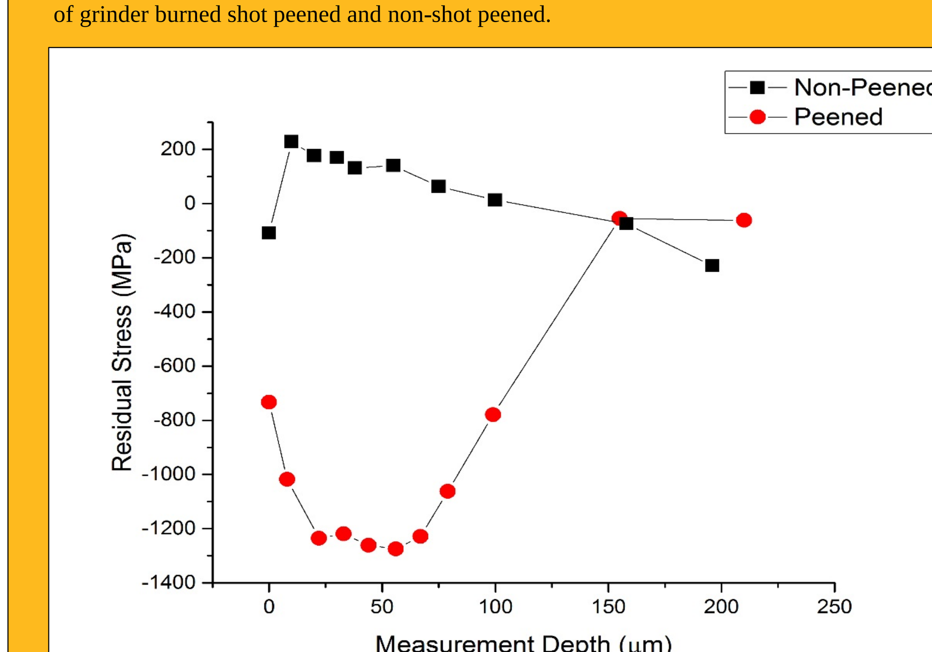

Figure 15: XRD residual depth profile on the 30 degree offset on the surface of grinder burned shot peened and non-shot peened.

After grinder burn, it was expect to see high tensile stress in non-shot peened and compressive stress in shot peened. In Fig. 14, the non-shot peened part still has lower compressive stress. Surface residual stress of the shot peened part shows significantly higher residual stress compared to non-shot peened. It shows application of shot peening was able to recover a large amount of lost compressive residual stress on the grinder burn surface.

Non-peened grinder burn shows that it lost significant residual stress after being burned but it still keeps lower compressive stress and does not go up to tensile stress. Residual stress profiles (Fig. 15)show development of tensile stress near surface after grinder burn. It shows the application of shot peening is able to recover the residual stress lost from burning.

Recommendations

Our team recommends that John Deere further pursue shot peening as a countermeasure to offset the negative effects of excessive surface NTP and grinder burn. Additionally, we suggest more testing to be done to establish a correlation between residual stress recovery and a non-destructive testing method such as Barkhausen Noise.

Future Work

Further work should be performed to verify the efficacy of shot peening in residual stress recovery. An increased and varied sample volume in XRD residual stress testing and subsequent fatigue testing should be performed to verify applicability of results to all products subject to remediation. Analysis can be used to provide in-line quality assurance.