Non-destructive Testing for Surface Hardness and Case Depth

Report No. 2013-01

Research Team:  Richard D. Sisson Jr.  (508) 831-5335  sisson@wpi.edu
Mei Yang  (508) 353-8889  mei@wpi.edu
Lei Zhang  (508) 241-1260  zhanglei@wpi.edu

1. Project Statements

1.1. Objective:
The objective of this project is to identify and develop a nondestructive hardness and case depth measurement technique that can be applied accurately, rapidly, and directly to carburized steel parts. The inspection technique should be capable of accurately measuring hardness within a range of 35 to 65 HRC to a maximum case depth of 2.54 mm. It is also desired that the technique have minimal manual preparation or data interpretation, allowing for the part to continue as a production asset after inspection.

1.2. Scope:
Identify candidate nondestructive hardness and case depth measurement techniques and experimentally evaluate their effectiveness. Validation of a successful non-destructive or minimally invasive measurement technique will require correlation with traditional destructively tested traveler test specimens and part cutups. Candidate techniques will be evaluated for three steel alloys, 1018, 8620 and 4140, for three part geometries representing a range of gear tooth radii and spacing. Gage reliability and repeatability assessments shall be conducted to determine the capability of the candidate measurement systems.

1.3. Strategy:
To address the goals of this project, the following strategies are adopted:
• Perform literature review on nondestructive techniques for hardness and case depth
• Identify the most promising nondestructive technologies to be tested
• Identify the alloys and heat treat conditions to be tested
  o Alloys – 1018, 8620, 4140
  o Range of hardness
  o Range of case depths
  o Surface conditions
  o Geometries
• Fabricate heat treated alloy standards to be destructively and nondestructively tested
• Use the carburization model (i.e. CarbTool®) to determine the process parameters
• Use the integrated heat transfer, mechanics, and phase transformation software (i.e. DANTE) to predict the hardness and residual stress

The project work is divided into the following tasks:

• Task 1 – Literature review
  o Nondestructive testing techniques
    ▪ Physics of measurement
    ▪ Sensitivity to microstructural features
    ▪ Sensitivity to residual stresses
    ▪ Depth of penetration for measurement
  o Microstructure \(\rightarrow\) hardness relations
  o Microstructure \(\rightarrow\) NDE measurement relations
  o Residual stress \(\rightarrow\) NDE measurement relations

• Task 2 – Select nondestructive techniques for testing
  o Select nondestructive testing techniques
- Obtain access equipment
- Test on standard parts and components

- Task 3 – Select Alloys and Heat treating conditions for testing
  - Surface hardness
  - Case depths
  - Temper conditions

- Task 4 – Select test part geometries and surface finishes

- Task 5 – Fabricate and verify metallurgy of standard test parts
  - Surface Hardness (Rockwell C)
  - Microhardness profiles
  - Carbon concentration profiles (OES)
  - Microstructure –characterization and analysis for Martensite and carbide distribution (Optical, SEM and XRD)

- Task 6 – Conduct nondestructive tests and determine the correlations between the destructive test results and the known results in the standards

- Task 7 – Determine the correlations among nondestructive test measurements, hardness and microstructure for standard test parts

- Task 8 – Verify effectiveness of nondestructive test technique at CHTE member companies
2. Executive Summary

The heat treating industry is in need of an accurate, rapid, and nondestructive technique for the measurement of surface hardness and case depth on carburized steels for process verification and control. Current methods require destructive test of “traveler” specimens that are not always representative of production part configurations and the associated subtleties of thermal history, carbon atmosphere, and geometry. Traveler specimens are often accompanied by a requirement for periodic production part cut-ups to validate carburization hardness and case depth profiles of parts, particularly for critical shaft and gear teeth configurations. Preparation of traveler specimens and part cut-ups is labor intensive, expensive, and sensitive to operator error. In addition, the process of using traveler coupons and periodic destructive production part cutup can be time consuming and costly. This project will focus on the identification, development and verification of nondestructive techniques for surface hardness and case depth measurement for selected carburized steel. The initial nondestructive techniques to be evaluated include Eddy Current, Meandering Winding Magnetometer (MWM), Barkhausen Noise and Alternating Current Potential Drop (ACPD). The goal is the identification of techniques that are sensitive to hardness microstructure and residual stress. A challenge of this project will be the ability to distinguish among microstructure, hardness and residual stress.

3. Achievements in this semester

3.1. Standard samples

3.1.1. Samples design

The 1018, 8620 and 4140 steels were selected to fabricate into the standard samples. The standard chemical compositions are presented in Table 1. The samples were heat treated to obtain appropriate case depth. The techniques that will be used to measure the case depth are sensitive to the case depth that will be determined by the hardness
distribution as well as the stress distribution \[^1\]. A series of metallurgy characterization techniques are performed to analyze the properties of the steels.

*Table 1. The chemistry composition of 1018, 4140 and 8620 steel measured by OES*

<table>
<thead>
<tr>
<th></th>
<th>C</th>
<th>Cr</th>
<th>Fe</th>
<th>Mn</th>
<th>Mo</th>
<th>Ni</th>
<th>P</th>
<th>S</th>
<th>Si</th>
</tr>
</thead>
<tbody>
<tr>
<td>1018</td>
<td>0.184</td>
<td>0.120</td>
<td>Bal.</td>
<td>0.745</td>
<td>0.0225</td>
<td>0.0810</td>
<td>0.0044</td>
<td>0.014</td>
<td>0.2150</td>
</tr>
<tr>
<td>4140</td>
<td>0.377</td>
<td>1.025</td>
<td>Bal.</td>
<td>0.695</td>
<td>0.1505</td>
<td>0.1565</td>
<td>0.0071</td>
<td>0.011</td>
<td>0.2265</td>
</tr>
<tr>
<td>8620</td>
<td>0.214</td>
<td>0.560</td>
<td>Bal.</td>
<td>0.805</td>
<td>0.1535</td>
<td>0.4525</td>
<td>0.0065</td>
<td>0.014</td>
<td>0.2355</td>
</tr>
</tbody>
</table>

The geometry of the test samples is presented in Figure 1. Both cylinder and plate geometries are applied with diameters of 1.0 inch, 1.5 inch, 2.0 inch. They are designed after simulation by DANTE to determine the residual stress after carburizing processes.

![Figure 1. Geometrical design of standard samples](image-url)
3.1.2. The samples fabrication procedure

Samples were heat treated after machining and surface finishing. The heat treatment processes include gas carburizing, quenching and tempering. CarbTool© was used to calculate the carbon concentration profile. The fabrication procedure is presented in Figure 2. This process produced samples with several carbon case depths and residual stress conditions.

![Sample fabrication procedure diagram]

*Figure 2. Sample fabrication procedure*
3.1.3. **Recipe of the carburizing process**

CarbTool© was used to develop the carburizing process to achieve a case depth of 0.8 mm. The samples were heated to 1700 °F and held 180 minutes in endothermic gas with a carbon potential of 1.0%, then keep it at 1700 °F for 105 minutes in an atmosphere with a carbon potential of 0.7% as a transition process. In the ‘diffuse process’ samples were held at 1550 °F for 30 minutes in an atmosphere with a carbon potential of 0.7%, then quenched in oil between room temperature and 160 °F.

![Figure 3. Carburizing recipe by CarbTool©](image)

3.1.4. **Carbon concentration and microhardness profiles of test samples**

Carbon concentration profile and microhardness are studied experimentally with destructive methods. The results are presented in Figure 4, Figure 5 and Figure 6. The carbon profile is measured with Optical Emission Spectroscopy (OES). Microhardness profile is measured with a Vickers microhardness tester. There is good agreement for the 1018 and 8620 steel data. 4140 Steel is typically not subjected to
the carburizing process because of the high carbon concentration. There is not much change in the microhardness for 4140.

**Figure 4. Carbon concentration and microhardness profile of 1018**

**Figure 5. Carbon concentration and microhardness profile of 8620**
3.1.5. Retained austenite (RA)

Retained austenite exists in the surface region of the samples after carburizing with martensite as the primary phase\[^{[3]}\]. The retained austenite was measured by X-ray Diffraction (XRD) simulated in DANTE.

No retained austenite was observed in the carburized 1018 sample in agreement with the DANTE prediction.

![Figure 7. Xray measurement of retained austenite of 1018 steel](image-url)
The carburized 4140 steel exhibits 17.2% retained austenite, while DANTE predicted 20%. This difference is being investigated.

**Figure 8. XRD measurement of retained austenite of 4140 Steel**

The carburized 8620 steel exhibits 19.8% retained austenite by XRD. DANTE simulation predicted 6.4%.

**Figure 9. XRD measurement of retained austenite of 8620 Steel**
3.1.6. **Surface residual stress study**

The samples with different diameters are designed to exhibit different stress distributions. The DANTE simulation results were used to differentiate the hoop and axial residual stress distribution for each test sample. Residual stress can also be measured using XRD.

\[
\begin{align*}
\sigma_z &: \text{Axial stress} \\
\sigma_r &: \text{Radial stress} \\
\sigma_t &: \text{Hoop stress}
\end{align*}
\]

*Figure 10. Stress distribution on cylinder surface*

For each stress measurement, axial stress and hoop stress will be measured as shown in Figure 10. The hoop stress is plotted in Figure 11 which presents the comparison between XRD measurement and the simulation results. The cylinder with the 1.5 inch diameter has a smaller compressive stress than the 2.0 inch sample. XRD measurement results are lower than the DANTE simulation results.

*Figure 11. Hoop stress of the 1018 sample of XRD and simulation results*
3.2. Meandering Winding Magnetometer (MWM)

3.2.1. Introduction of MWM technology

Meandering Winding Magnetometer (MWM) eddy current sensors provide a very practical and robust capability to measure electrical and magnetic properties of alloys on surfaces with complex geometries \[^7\].

The MWM sensor is sensitive to flaw, stress, microstructure. It can be used for a number of applications, including fatigue monitoring and inspection of structural components for detection of flaws, degradation and microstructural variations well as for characterization of coatings \[^6\].

Carburizing process will change the surface concentration and stress distribution of the sample \[^2\]. With MWM sensor, correlation between electromagnetic field and case depth will be studied in this project.

![The MWM mechanism](image)

**Figure 12. The MWM mechanism** \[^1\]

The sensor consists of a meandering primary winding which will be the input of the current. The meandering secondary windings are used for sensing the response with voltage attached on. \[^1\] The primary winding is typically fabricated in a square wave pattern with the dimension of the spatial periodicity termed the spatial wavelength as
Figure 12 presents. The magnetic vector potential produced by the current in the primary can be accurately modeled as a Fourier series summation of spatial sinusoids. There is software named GridStation to convert the sensor impedance magnitude and phase response into material properties, such as the conductivity and permeability.

3.2.2. Equipment for MWM

The MWM system is produced by JENTEK to address the need for quality assessment and control of high-value added processes, such as coating, welding, heat treatment and shot peening. Figure 13 presents the JENTEK GridStation® system.

![Image of GridStation System](image)

**Figure 13. MWM GridStation System**

Measurement procedure is presented in Figure 14. The system needs to be set up carefully. All the configurations are finished by the software GridStation developed by JENTEK. For different material, the frequency should be set properly to avoid saturation. For our measurement, the probe is calibrated in air.
Figure 14 Procedure of measurement with MWM probe
3.2.3. MWM measurement results

The MWM system is used to measure the electrical conductivity and magnetic permeability of the carburized samples. To study well the relationship between the conductivity and material properties, a series of measurements are applied. For cylinder samples, the measurement is applied to three directions as Figure 15 presents.

![Figure 15 The MWM measurement directions](image)

a) Conductivity of carburized 1018 steel

Figure presents the conductivity of carburized 1018 steel test sample range from 2MHz to 50MHz. Higher frequency leads to higher conductivity. MWM employ high frequency which leads to a lower skin depth. The relationship between conductivity and skin depth is plotted in Figure 17.

![Figure 16 The conductivity of carburized 1018 steel](image)
Figure 17 The conductivity of carburized 1018 steel verse case depth

Figure 18 presents the effects of the sensor direction on the conductivity. At lower frequency, there is not big difference. At a higher frequency, difference start to exhibit between two perpendicular directions.

Figure 18 The conductivity of carburized 1018 steel in three directions
b) **Comparison between original and carburized test samples**

Figure 19, Figure 20 and Figure 21 present the conductivity of all three original and carburized samples. 1018 and 8620 present the carburized test samples with lower conductivity than original one over the frequency range. Carburized 4140 sample presents lower conductivity at lower frequency. Further investigation should focus the performance at lower frequency.
Figure 21 The comparison of conductivity of carburized and original 8620 steel

Figure 22 presents the conductivity of original and carburized steels at 2M Hz frequency.

Figure 22 Conductivity comparison of carburized and original test samples at 2M Hz
Figure 23 presents the permeability of original and carburized steels at 2M Hz frequency. It is similar with the conductivity figure. Carburized samples have a smaller permeability value than original one.

![Figure 23 Permeability comparison of carburized and original test samples](image)

c) Bent strip stress measurement

The bent saw blade measurement is to determine the effects of the stress on the conductivity and permeability. Total length of the saw is 18 inch. Two ends are fixed and the d value is measured to control the stress strength including 1, 2, 3, 4 and 5 inch as Figure 24 presents. The probe is applied inside of the arc where compressive stress exists.

![Figure 24 The setup of bent saw experiment](image)
Figure 25 reveals that larger stress lead to lower conductivity. The measurement of 6 inch reverse is applied on the surface outside of the arc where tensile stress exists. The tensile stress leads to a higher conductivity than the compressive stress.

Figure 25 The conductivity of the bent saw measured by MWM

Figure 26 reveals that the stress has significant effect on the permeability. Higher stress leads to a much lower permeability. Further tests are planned to determine the relationship between the stress and the MWM results.

Figure 26 The permeability of the bent saw measured by MWM
3.3. Barkhausen Noise Testing

3.3.1. Introduction of Barkhausen noise technology

The Barkhausen noise phenomenon found in ferromagnetic materials is shown in Figure 27. The physical principle behind the method is that microstructural defects (dislocations, small carbides, grain boundaries, etc.), which are responsible for mechanical properties, are also responsible for magnetic behavior: shape of the hysteresis loop, coercive force, and permeability\textsuperscript{[9]}. When a ferromagnetic material is subjected to magnetic excitation, the magnetization is not obtained continuously but in discrete jumps owing to domain walls interacting and overcoming barriers in their path. These jumps, due to sudden changes in magnetization, yield electromagnetic and acoustic signals that can be detected by a coil or an acoustic transducer\textsuperscript{[12]}. For carburized and nitrided steels, the carbon or nitrogen content increases the number of defects or pinning sites and hence improves hardness. These pinning sites also change the behavior of block walls in magnetic domains and thus the Barkhausen noise level\textsuperscript{[9]}.

![Barkhausen noise phenomenon](image)

_Barkhausen noise phenomenon_

Barkhausen noise is now one of the most popular magnetic NDE methods for investigating intrinsic properties of magnetic materials such as grain size, heat treatment, strain and other mechanical properties such as hardness\textsuperscript{[10]}.

To produce Barkhausen noise, it is necessary for the specimen to be subjected to varying levels of magnetization to the point of magnetic saturation at a certain rate.
This can be achieved by employing a yoke, particularly in surface analysis. To maintain constant induction, the yoke is fed by a bipolar variable source of triangular waveform. The Barkhausen noise sensor consists of an air coil of copper wire with or without a ferrite core. Usually, signals are amplified, filtered, rectified, and integrated to produce a spectrum. The height, half height width, and position with excitation are parameters that provide useful information \[11\]. Measurements were carried out at different frequencies using electronic filters to distinguish between the signal from the bulk and that from the surface.

Figure 28. The Barkhausen noise equipment\[9\]

Figure 28 presents the equipment used for MBN testing. Figure 29 shows the origin MBN signal under different applied stress; the left image shows MBN signal without applied stress, right shows MBN signal under a tensile stress of 60.44 Mpa.

Figure 29 The process of Barkhausen noise measurement
To collect all the information contained in the signal, the frequency spectrum of the Barkhausen noise was recorded. To do this, the samples were magnetized, as shown schematically in Figure 30, with a yoke at an excitation frequency of 3 Hz. The signals were detected by a coil of copper wire with a ferrite core. These signals were amplified and filtered by a low pass filter at a cut off frequency of 200 kHz. Based on these data, a fast Fourier transform (FFT) was determined and used on the raw Barkhausen data. The spectrum obtained was integrated on ten frequency bands, each 20 kHz wide, from 0 to 200 kHz. These ten values, for each sample, were plotted as a function of the measured case depth of specimens. Based on this, it was possible to determine which range of frequencies was the most appropriate for case depth evaluation\textsuperscript{[11]}.

![Figure 30. The process of Barkhausen noise measurement\textsuperscript{[11]}](image)

To conduct the Barkhausen Noise testing, the STRESSCAN 500C unit, developed by American Stress Technologies, Inc., was selected. It employs dedicated, patented sensor designs to activate and detect the magneto-elastic signal. It incorporates sophisticated microprocessor technology to energize the sensors and process the signals.

The STRESSCAN 500C calculates the magneto-elastic parameter by averaging the peak values of Barkhausen Noise signals over ten magnetizing cycles. The output in the non-calibrated mode is provided in a magneto-elastic parameter called MP.
3.3.2. Barkhausen Noise Measurement Depth

The device provides a magnetic field (relative value) from 0 to 150. And it also provides three different penetration depth, 0.02mm, 0.07mm and 0.2mm corresponding to the frequency range of 3-15Hz, 20-70Hz and 70-200Hz. \[13\].

In an electromagnetic field, the skin depth is thus defined as the depth below the surface of the conductor at which the current density has fallen to 1/e (about 0.37). In normal cases it is well approximated as:

$$\delta = \sqrt{\frac{2\rho}{\omega \mu}}$$  \hspace{1cm} (1)

Where,

$\rho$ = resistivity of the conductor

$\omega$ = angular frequency of current $= 2\pi \times$ frequency

$\mu$ = absolute magnetic permeability of the conductor

The chart in Figure 31 can be used to approximate the depth of measurement. Since after carburizing the case depth would be around 0.8mm, the smallest frequency is picked.

![Figure 31 Depth of nominal depth of measurement chart\[13\]](image-url)
3.3.3. Barkhausen noise measurement results

(1) Barkhausen noise changes with magnetic field

To test how Barkhausen noise changes with magnetic field, a 1018 plate sample with 1.5 inch diameter was used. Figure 32 presents how Barkhausen noise changes with magnetizing current (MAGN) where nominal skin depth is 0.2mm. Within a small range 0 to 50 (relative value), Barkhausen noise increases as the magnetic field increases. When the magnetic field reaches 50, the Barkhausen noise maintains a constant value. During the measurement, the device will have a test run first to tell the saturated point for the specific sample you measure. Following testing, the magnetic field will be set less than, but close to, the limit as the instruction indicates \[^{13}\].

![Figure 32 Barkhausen Noise changes with magnetic field for carburized 1018 steel](image)

*Nominal case depth=0.2mm*
(2) Barkhausen Noise changes with frequency

Nominal case depths provided by the STRESSSCAN are 0.02mm, 0.07mm, 0.2mm corresponding to the frequency range of 3-15Hz, 20-70Hz and 70-200Hz, respectively

Using the same Magnetizing current (MAGN) of 30 (relative value), the 1018 sample is measured under different nominal case depth as Figure 33 presents. Smaller case depth will result in a larger Barkhausen Noise because the frequency is larger. After the carburizing process, the surface carbon increases, and at the same time the resistivity of the material will increase. The case depth will be deeper than the material without carburizing. This also provides us the potential application for the case depth measurement on the carburized samples.

\[ \text{Figure 33 Barkhausen Noise changes with nominal skin depth for 1018 sample} \]

\[ \text{MAGN}=30 \]
(3) Barkhausen noise changes with hardness

The samples without carburizing will reach saturated limit at a magnetic field of 50 or lower. The magnetic field of 30 is picked to compare the change of MP after carburizing. Figure 34 shows original and carburized samples of 1018, 4140, 8620. In the figure, 1018C, 4140C, 8620C represents carburized samples with a much smaller MP value than the non-carburized samples. After the carburizing process, the domains will be pinned by the dislocation and impurities which also increase the hardness of the samples.

![Figure 34 Barkhausen Noise within original and carburized samples](image)

Tempering was applied for the samples at 177°C for 4h. The hardness decreases from 64 HRC to 59 HRC as Figure 35 presented. Barkhausen noise decreases for 1018 sample, but for other samples, there is little variation.

![Figure 35 Barkhausen Noise within carburized and tempered samples](image)
(4) Barkhausen noise changes with stress

Barkhausen noise is also sensitive to the stress. The bend saw testing is performed to study the effects. As presented in Figure 36, the original saw has a length of 18 inch. Then the height of the arc d is adjusted to obtain different stress. In the figure, d is set to be 0, 1, 2, 3, 4 and 5 then converted to a respective stress value. The top of the stripe has a tensile stress, while the bottom has a compressive stress.

![Figure 36 Bend saw testing](image)

As presented in Figure 37, the MP increases with compressive stress. But in Figure 38, with the increasing of the tensile stress, the MP decreases. When the tensile stress reaches a certain value, the MP remains unchanged.

![Figure 37 Barkhausen noise changes with compressive stress](image)

Nominal case depth=0.2mm MAGN=30
(5) Barkhausen noise changes with stress for cylinders

The residual stress effects on Barkhausen noise is also studied. The cylinder is measured by STRESSCAN 500C at different position presented in Figure 39.
The surface residual stress for 8620 has been modeled by DANTE, as presented in Figure 40 and Figure 41. The main residual stress is hoop stress which has a compressive residual stress around 300Mpa. The cylinder with a large diameter should have a larger residual stress. The cylinder with a 2.0 inch diameter has about 10% higher hoop stress than the 1.0 inch diameter cylinder.

\[ \text{Surface hoop stress of 8620 (Mpa)} \]

\[ \begin{align*}
\text{Axial and Hoop stress of 8620 (Mpa)} \\
\text{Axial stress} & \quad \text{Hoop stress}
\end{align*} \]

*Figure 40 The surface axial and hoop stress of 8620 cylinders*

\[ \text{Surface hoop stress of 8620 cylinders with different diameters} \]

\[ \begin{align*}
\text{Surface hoop stress of 8620 (Mpa)} \\
\text{d=1.5} & \quad \text{d=2} & \quad \text{d=1}
\end{align*} \]

*Figure 41 Surface stress of 8620 cylinders with different diameters*
As presented in Figure 42, Barkhausen noise signal varies with position into the steel. The case depth will not change much; it tells more about the residual stress distribution. As discussed in the bending study, larger compressive stress will lead to larger Barkhausen noise; position E has larger residual stress than position A. Also, the cylinder with a 2.0 inch diameter has larger stress at C,D,E than the other two cylinders.

![Barkhausen noise distribution on the surface of cylinder](image)

**Figure 42** Barkhausen noise distribute on the surface of cylinder

Nominal case depth=0.2mm MAGN=30

### 3.4. Future work plan

- Determine the correlations between the nondestructive tests results from the MWM, Barkhausen testing and the hardness and case depth results of the standard samples.
- Conduct the other nondestructive tests including Alternating Current Potential Drop (ACPD) at ISU.
References

[1]. Neil Goldfine, David Clark, MWM Introduction to the Meandering Winding Magnetometer (MWM) and the Grid Measurement, SPIE Vol. 2944/ 187


[13]. STRESSSCAN 500C Operating Instructions V 1.0b