A novel testing method to evaluate edge formability non-destructively with eddy current

J Gu¹, N Pathak¹, S Freed¹, E Todorov¹ and H Kim¹
¹ EWI - Forming Center (EWI-FC), Columbus, Ohio, United States

Abstract. Eddy current (EC) testing is one of the most extensively used NDE techniques in the automotive industry for automatic in-line inspection of ferrous materials such as advanced high strength steels (AHSS). In addition, shearing is a very common forming operation in the automotive industry. With the increase of shearing clearance, the sheared-edge experiences significant work-hardening that normally decreases the formability of the sheared edge. This paper introduces a novel and real-time monitoring NDE method based on the EC sensor to characterize variations in shear edge quality for two different grade advanced high strength steels, DP780 and 980GEN3. The developed NDE method was applied to scan the edges sheared at various clearances between 5 and 25% of the material thickness. The NDE signal received was correlated with pre-straining introduced during the shearing process at various clearances. Microhardness measurements were taken to compare the trends obtained from the NDE tool with the hardness values. To evaluate the edge formability, half-specimen dome testing (HSDT) was conducted for the edges sheared at various clearances. A digital image correlation (DIC) system was used to measure failure strain during the HSDT. The failure strain of sheared edges was correlated with the NDE measurements for each clearance to assess the application of an NDE measurement in determining edge quality. The NDE method can potentially be used to inspect the sheared edge quality for sheet metal stamping process.

1. Introduction
The eddy current (EC) technology has been widely used for detecting surface and internal flaws of metal structures nondestructively. Eddy current is the induced current with a closed-loop contour pattern generated by the alternating magnetic field, according to Faraday’s law [1]. The EC signal contour is affected by the electric property of the material, stand-off distance and sample geometries. Discontinuity in the microstructure such as micro-cracks can significantly distort the contour of the EC signal, shown in figure 1 [2]. Therefore, the work hardening induced by the shearing can be evaluated by EC based nondestructive evaluation (NDE).

Figure 1. Schematics of the eddy current contour distorted by the surface crack.
Edge cracking has been widely observed during the stamping process of advance high strength steel (AHSS). Local edge formability after shearing is observed to have a significantly lower forming limit than the base metal. The sheared edges experience out of plane local pre-straining due to the shearing process, which is subsequently stretched in stamping. Therefore, the process is challenging to simulate accurately. Various research has been performed to evaluate and predict edge formability. The critical parameters that affect local edge formability were investigated by Pathak, et.al [3]. The study concludes that the edge formability was mainly affected by the work-hardening introduced by the shearing process. Various lab-scale testing methods were introduced to evaluate work hardening and edge formability, such as hardness test, grain rotation and half specimen dome test [4, 5, 6]. However, most testing methods are difficult to use for inspecting the sheared edge quality in the industrial production environment.

The test was conducted based on the previous work published by EWI [7]. The study contributed further developments in correlation of EC based NDE on the sheared edge. However, this setup requires tight tolerance of the sensor alignments, and is limited by the sheared edge geometry. In this study, NDE setup was upgraded to scan the sheared edge directly across the fracture surface. In the upgraded setup, multiple stacked samples can be measured together using a high-resolution sensor and computer numerical control (CNC) fixture as shown in figure 2.

![Figure 2. Eddy current probe setup and the eddy current probe.](image)

2. Shearing test
In this study, a DP780 material with 1.2-mm thickness was selected. The following edge conditions were considered to create the different sheared edge conditions in table 1.

| Sample Label | Edge condition |
|--------------|----------------|
| 5%           | Die shearing with 5% shearing clearance |
| 10%          | Die shearing with 10% shearing clearance |
| 15%          | Die shearing with 15% shearing clearance |
| 20%          | Die shearing with 20% shearing clearance |
| 25%          | Die shearing with 25% shearing clearance |
| Machined     | Milled edge |
| Sheared      | Sheared using a conventional lab shear machine with unknown shear clearance |
The shear clearance was calculated with percentage respect to the material thickness (1.2 mm). US Steel supplied EWI most die-sheared samples. EWI prepared the machined and conventionally sheared samples. Most samples were prepared to have the sheared edges perpendicular to the rolling direction.

3. Eddy current based NDE

3.1. Test setup

An extra-small sized EC probe was used to collect the NDE signal at the edge, as shown in figure 2. The test samples were stacked with interested sheared edge aligned. Each sample was separated with non-conductive spacer layer by layer to eliminate the interference of signal across the neighboring samples. The CNC fixture allows the probe to move in x and y direction horizontally, as shown in figure 3. The probe was set to travel 25-mm horizontally, limited by the CNC fixture. Each horizontal measurement path in x-direction collected approximately 16,000 data points. 1000 data points were collected every second. The horizontal scan paths had 0.2-mm index distance with each other in x-direction. A total of 200 scan paths were measured for five stacked samples.

The test setup uses the highest frequency setting of the EC coil, which is 500 kHz, to obtain the high-resolution NDE data. The EC signal that was sensitive to the edge hardening was calibrated as the representative EC parameter indicating edge hardening level. This EC signal component was referred to as the vertical component.

![Figure 3. EC measurement setup and schematic of sample line-up.](image)

3.2. Test result

Figure 4(a) shows a colormap of the NDE data collected with five samples stacked with five different edge conditions. Red color indicates higher EC parameter, while blue color indicates lower EC measurement parameter. The data were sliced and plotted in figure 4(b). The five peaks correspond to the five samples stacked and measured together as shown in figure 3. The peak NDE value occurs around the middle point of the material thickness. The EC peak values for each edge condition are summarized in figure 5.
Figure 4. (a) Colormap of EC scanning and schematic of selection of data slices from EC scanning of machined edge, 20%, 25%, 5% and 10% sheared clearance (L-R). (b) Example of peak data across the thickness in the same order.

| Vertical component of eddy current (Volt) | 5%  | 10% | 15% | 20% | 25% | Sheared | Machined |
|-----------------------------------------|-----|-----|-----|-----|-----|---------|----------|
| EC peak data                            | 0.008 | 0.021 | 0.014 | 0.013 | 0.023 | 0.02   | 0.005 |

Figure 5. The EC peak values of different edge conditions

4. HSDT and hardness test

4.1. HSDT
HSDT was used to evaluate the edge formability by stretching the straight sheared edge with a 100-mm diameter dome punch as shown in figure 6. The local strain distribution was captured using DIC cameras as shown in figure 6. The maximum equivalent strain before cracking initiation was used as the important indicator to compare the local formability. HSDT was conducted with three repetitions for each edge condition.
4.2. Hardness test

Vickers microhardness test was also conducted on the sample cross section for each edge condition to evaluate the work hardening level. Ten indentations were made in every 0.15-mm interval for each sample from the sheared or milled edge to the base metal, as shown in Figure 7. Each measurement pattern started at the transition of burnished zone to fracture zone.

![Figure 7. Locations for microhardness indentation testing.](image)

4.3. Results of HSDT and microhardness test

The failure strain and hardness measurement from the HSDT are summarized in Figure 8. The normalized hardness was calculated using Equation (1) to compare the increased hardness on the sheared edge.

\[
\text{Normalized Hardness} = \frac{HV_{\text{max}}}{HV_{\text{base}}} \tag{1}
\]

The failure strain from the HSDT and hardness test result have a negative correlation with each other. Lower HSDT equivalent failure strain and higher normalized hardness indicates poor edge quality, which has lower edge local formability and higher work hardening level.
4.4. Correlation of NDE result with HSDT and hardness test

The NDE data were compared with the failure strain from HSDT at the onset of cracking and normalized edge hardness from the microhardness test. Figure 9 compares the parameters relating to the work hardening level from NDE and the two destructive tests. EC peak parameter shows the consistent negative correlation with the HSDT failure strains and positive correlation with hardness results. The samples showing the higher equivalent failure strain indicate better edge formability and gave the lower NDE peak values.

The relationship among EC measurement parameter, the HSDT failure strain, and hardness value was further analyzed using a power regression model as shown in figure 10. The r-squared value of the regression model of NDE results is 80.2% with HSDT failure strains and 94.7% with normalized
hardness values. This method can be used for predicting edge local formability and evaluating work hardening level nondestructively. However, to validate this method, more experiments should be considered as future work.

![Relationship between NDE measurement and HSDT](image1)

![Relationship between NDE measurement and normalized hardness](image2)

Figure 10. Correlation of NDE measurement with HSDT failure strains and hardness values.

5. Conclusions
The following conclusions can be drawn from the study:

- The NDE measurement parameter has strong correlation with the edge formability from HSDT and the microhardness test.
- The NDE value increases as the HSDT strain decreases and edge hardness increases, which indicates higher edge work hardening level.
- Eddy current based NDE can be used to evaluate the edge work hardening level on the sheared edges.
- The NDE measurement parameter might predict the edge failure by correlating with the edge local formability result. However, it needs more experimentation and validation.

6. References
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