Sample edge effects on tensile properties and sheet formability

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Sample edge effects on tensile properties and sheet formability

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Abstract. It is well known that the condition of the edge, whether sheared or milled, can affect the results in edge formability tests (i.e. a hole expansion test). In the current investigation, two experimental studies were performed to evaluate the effects of edge condition on the results of tensile tests and a laboratory formability test for sheet steels. The first study evaluated the tensile properties of a QP980 steel with samples prepared by four different machining methods: wire electro-discharge machine (EDM); mechanical milling; laser cutting; and waterjet cutting. It was found that the EDM and milled samples produced statistically similar values for yield strength, ultimate tensile strength, uniform elongation and total elongation. The yield strength and tensile strength from samples prepared by laser cutting were statistically different. Water jet cutting produced statistically different values for almost all four properties when compared to the EDM and milled samples. In the second study a DP600 steel was subjected to an angular stretch bend formability test with samples prepared by either shearing or milling. It was found that the sheared samples required higher forces but smaller displacements to reach the formability limit. Fracture for the sheared samples initiated on the edge of the sample whereas for the milled sample necking and fracture initiated in the center of the sample, close to the plane-strain condition. Results from both of these studies clearly show the importance of the edge condition on reported mechanical properties and on the formability of the sheet.

1. Introduction
To assess the formability of sheet steels, tensile properties must be determined. Studies have shown that the method used to prepare tensile samples can affect measured mechanical properties [1,2]. Laboratory tests have also been used to determine the formability of sheet steels. For example, the hole expansion test has been used to determine the hole expansion ratio, a measure of resistance to edge cracking. The method of introducing the reference hole and the quality of the cut edge have been shown to affect the hole expansion ratio [3,4]. The edge condition can also affect the edge formability during production especially for the newer advanced high strength steels (AHSS).

The objective of the present study is to examine the effects of specimen preparation technique on the tensile properties for an advanced high strength steel (QP980) and also to evaluate the effects of edge preparation on samples of DP600 used for a simple laboratory formability test – the angular stretch bend test (ASB).

2. Experimental Procedures
The experimental procedures for the two studies are given in the following two subsections.
2.1. **Tensile testing**
The tensile properties of a 1.4 mm thick QP980 sheet steel were evaluated with full sheet thickness sub-size tensile specimens with a reduced section length and width of 31.75 mm and 6.35 mm respectively, prepared according to ASTM E8. The gage length was 25 mm. Specimens were prepared by conventional milling, wire electro-discharge machining (EDM), laser cutting and waterjet cutting at local machine shops. Measurements of the width of the reduced cross section for the milled and EDM specimens were within ±0.025 mm of the nominal dimension. Measured widths of the laser and waterjet specimens were within ±0.075 mm and ±0.050 mm, respectively. The steel was supplied as a half span of coil width sections. The section was cut into four quadrants and one quadrant was sent for each type of cutting. The tensile parameters evaluated were: yield strength (YS), ultimate tensile strength (UTS), uniform elongation (UE), and total elongation (TE).

Additional samples of the QP980 steel used to assess microstructural damage on the machined surfaces were sectioned and polished for optical microscopy and microhardness testing.

2.2. **Angular stretch bend testing**
The formability of a DP600 steel was evaluated using an angular stretch bend test with two different edge conditions. These edge conditions were sheared and milled. The sample sizes were 1.45 mm thick by 25 mm wide by 180 mm long. The samples were extracted from near proximity within the coil location. The edges for both conditions were characterized with microhardness profiles. ASB tests were performed with 1.0, 2.5, and 5.0 mm radii punches at a speed of 5 mm/s using PTFE (Teflon) film coated with LPS2 lubricant. Three samples were tested per radius. Load versus displacement curves from the ASB test were used to determine height at failure and maximum load values.

3. **Results and Discussion**
The results and discussion of the two studies are given in the following two subsections.

3.1. **Tensile properties - specimens with different machining processes**
Figure 1 summarizes the tensile properties for the QP980 steel. For each machining process, the data shown represent the average of five tensile tests. A statistical comparison of means was accomplished using a Student’s t test at a 95 pct confidence level. Figure 2 shows which edge conditions can be considered statistically equivalent with regard to each tensile parameter. The symbol = in Figure 2 denotes that two processes can be considered statistically equivalent for a given tensile parameter. Likewise, ≠ indicates that the two processes cannot be considered equivalent.

The statistical analysis summarized in Figure 2 shows that wire EDM and conventional milling can be considered equivalent for all mechanical properties, and that they are the only two edge conditions for which YS and UTS can be considered equivalent. EDM, mill and laser are all statistically equivalent with respect to UE and TE. Waterjet can be considered equivalent only to milling, and only with regard to TE.

The waterjet results are somewhat anomalous. The mean YS for the waterjet samples is almost exactly between the means for laser and EDM/mill samples, considering the latter two as equivalent. On the other hand, the mean UTS for waterjet is lower than all the other processes. Mean UE and TE are both higher than all the other processes. A possible reason for the lower UTS is that the edge is relatively free of hardening as compared to the other three processes. The wedge profile that is found with waterjet was on the discard side of the cut and not part of the sample.

Figure 3 shows SEM micrographs of the cross sections of the surfaces for each of the four machining processes. The image in Figure 3a shows a relatively smooth damage free edge cut via conventional milling. The damage visible on the machined edge is pitting that formed preferentially near the edge during polishing, and is not related to the machining process. The edge cut with waterjet exhibits severe damage as shown in Figure 3b. The milled and water jet samples exhibit a consistent microstructure throughout. The edge cut via wire EDM, shown in Figure 3c, exhibits damage
comparable to waterjet, with the addition of a narrow band approximately 25 μm thick of altered microstructure along the edge, likely induced by the thermal energy imparted by the EDM process. The image shown in Figure 3d of the laser cut edge reveals the smooth undulating edge of a recast layer and an altered microstructure approximately 75 μm thick indicating the presence of a heat affected zone (HAZ) induced by laser machining. Consistent with previous literature [1, 2], elevated YS and UTS combined with the lower UE and TE values exhibited by the laser cut samples also indicate the presence of HAZ.

![Figure 1](image1.png)

**Figure 1** Comparison of tensile test results on a 1.4 mm thick QP980 steel with ASTM E8 sub-size specimens manufactured via wire EDM, conventional milling, laser, and waterjet cutting. Each bar represents the average of five tensile tests. Error bars denote ±1 standard deviation from the mean. (a) Yield strength, (b) ultimate tensile strength, (c) uniform elongation, and (d) total elongation.
Figure 2 Results of statistical comparison of means of data shown in Figure 1 using a Student’s t-test with a 95 pct confidence level for the QP980 steel tensile data. The symbol = denotes that the two processes can be considered statistically equivalent for a given tensile parameter. Accordingly, ≠ denotes that the processes cannot be considered equivalent. (a) Yield strength, (b) ultimate tensile strength, (c) uniform elongation, and (d) total elongation.

To further confirm and quantify the HAZ behind the laser cut edge, Vickers micro hardness measurements were taken along a line oblique to the cut face on a sectioned sample. A total of 23 indents were made with a 100 gf load, spaced 65 μm apart, with the first indent 60 μm away from the cut face. Indent spacing relative to the cut face was approximately 35 μm. The same testing procedure was applied to a wire EDM sample for comparison. Results, shown in Figure 4, indicate that the elevated hardness of the HAZ on the laser sample extends approximately well away from the cut face. The most severely affected region extends about 150 μm from the edge, which is approximately twice the distance suggested by the altered microstructure visible in Figure 3d. Micro hardness values for the EDM sample are fairly constant, indicating that the depth of the HAZ suggested by Figure 3c is very shallow.

Damage on the wire EDM sample was more severe than expected, especially in light of tensile results statistically equivalent to and exhibiting less scatter than tensile data for the conventionally milled samples. It is possible that the more severe edge damage on the wire EDM edge was stabilized by the shallow HAZ visible in Figure 3c, thereby negating the deleterious influence edge damage would normally have on tensile results.

3.2. Angular stretch bending - specimens with different machining processes

Figure 5 shows micro hardness profiles for the two different edge conditions used to prepare DP600 samples. Figure 5a shows the milled edge condition where essentially no shear affected zone (SAZ) exists. There is a slight work-hardened effect near the edge, but the magnitude of change in micro hardness between the edge and base material is limited, ~20 HV. Figure 5b shows the sheared edge condition where a SAZ, evident by the high surface hardness is present. The magnitude of change in micro hardness between the edge and base material is approximately 100 HV.
The peak loads and the maximum displacements at fracture depend on the surface preparation method. Figure 6 shows representative load versus displacement curves for milled and sheared edge conditions tested with the 1.0 mm radius punch and Table 1 summarizes failure heights and maximum load values for the three punch radii for the each of the two surface conditions. The data are the average of three tests at each condition and the uncertainty is one standard deviation. For each punch radius, the maximum loads were higher and the maximum displacements were lower for samples prepared with sheared edges.

![Milled and Sheared Edge Conditions](image)

(a) Milled edge, (b) Sheared edge with 1.0 mm radius punch.

Figure 3 Backscatter scanning electron microscope (SEM) images of QP980 sample edges machined with (a) milling, (b) water jet, (c) wire EDM, and (d) laser cutting. Backscatter z-contrast reveals that the microstructure was altered by a HAZ on both the laser and EDM samples.
Figure 4  Micro hardness versus distance from the cut edge on laser and EDM cut samples of QP980 steel. Measurements, taken in a line oblique to the machined edge on a section, confirm the presence of a HAZ visible in Figure 3d.

Figure 5  Average micro hardness profiles for DP600 (a) milled edge and (b) sheared edge conditions.

There is also a difference in the location of failure initiation between milled and sheared edge conditions. Figure 7a shows the top view of a representative milled edge specimen tested with a punch radius of 5.0 mm. Figure 7b shows the side view of the edge of the same specimen. Figure 8a shows a top view of a representative sheared edge specimen tested with a punch radius of 1.0 mm. Figure 8b shows the side view of the edge of the same specimen. It can be observed that in the milled edge specimen the crack initiated at the center and propagated out to the edges, while in the sheared edge specimen the crack initiated at the edge and propagated towards the center. Similar results were seen for all punch radii, but these two conditions represent the only tests that were successfully stopped at fracture initiation due to machine inertia and rapid fracture after initiation. The difference in the
location of fracture initiation can be attributed to the SAZ and the shear face where the fracture region and burr have a significant amount of damage caused by the shearing process and potentially create micro cracks.

Figure 6  Representative load versus displacement curves of a single test specimen for milled and sheared edge conditions. Specimens were tested with the 1.0 mm radius.

| Punch Radius (mm) | Edge Condition | Height at Failure (mm) | Maximum Load (kN) |
|------------------|----------------|------------------------|-------------------|
| 1.0              | Milled         | 13.7 ± 0.05            | 12.80 ± 0.01      |
| 2.5              | Milled         | 16.4 ± 0.05            | 15.90 ± 0.01      |
| 5.0              | Milled         | 19.2 ± 0.16            | 19.14 ± 0.05      |
| 1.0              | Sheared        | 13.6 ± 0.04            | 13.33 ± 0.00      |
| 2.5              | Sheared        | 16.2 ± 0.07            | 16.79 ± 0.21      |
| 5.0              | Sheared        | 19.0 ± 0.15            | 20.22 ± 0.27      |

4. Conclusions
Tensile test results indicate that wire EDM and conventional milling produce samples which exhibit equivalent properties. The laser cut samples exhibited higher yield and ultimate tensile strengths, in addition to lower uniform and total elongations, as compared to wire EDM and conventional milling. Waterjet results are inconclusive due in part to the absence of a hardened edge.

For the angular stretch bend (ASB) formability test, the sheared samples required slightly higher loads for failure and failure occurred at lower punch heights. The failure initiated on the edge for the sheared samples and in the middle for the milled samples.

In performing laboratory tests either for tensile properties or for the assessment of formability of sheets, the specimen preparation process can affect the values of tensile properties that are obtained or the determination of the fracture conditions.
Figure 7  Representative milled edge specimen tested with a 5.0 mm punch. (a) Top view and (b) side view.

Figure 8  Representative sheared edge specimen tested with a 1.0 mm punch. (a) Top view and (b) side view.

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