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A Practical Methodology to Evaluate and Predict Edge Cracking for Advanced High-Strength Steel

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Abstract. With the increased application of advanced high strength steel (AHSS), the development of a reliable methodology for evaluating and predicting edge cracking is in high demand. In this study, different shear edge conditions of three different AHSS materials, TRIP 780, DP 980, and DP 1180, were evaluated. The edge cracking is evaluated in four steps: shear test, sheared edge characterization, HSDT, and prediction of edge cracking using FEA. The shear edges were prepared with five different shear clearances between 5 and 25% of the material thickness to obtain variable shear quality. In the HSDT, the strain and thinning distribution is captured using a digital image correlation system as the edge cracking limit and failure criteria in FEA. The preferred shear clearance is characterized by the largest stroke in HSDT and highest thinning value of the onset of edge cracking. FEA showed good correlations with the experiment comparing strain and load-displacement curves. The optimized shear clearance for TRIP 780 is 15% material thickness which for DP 980 and DP 1180 is 20%. By comparing test results from shear test, HSDT and FEA simulation, the peak shear load and burr height from simple experiment observation were found to be important indicators of edge condition, which can be monitored in production.

1. Introduction

The lightweighting strategy of automotive involves replacement of conventional steel with advanced high-strength steel (AHSS), which is more susceptible to edge cracking. The sheared edge of AHSS is more severely hardened, which causes cracks when the edge is stretched. The edge cracking effect is difficult to predict using conventional simulation technique. Unpredicted edge cracking issues occur in the sheet metal stamping process, as well as during the crash test of a vehicle; therefore, a practical and reliable methodology to evaluate edge cracking needs to be developed.

2. Background

Currently, the edge cracking is commonly evaluated by ISO standard (ISO/TS 16630:2003E) using hole expansion test by hole expansion ratio (HER) [1]. However, this testing method has its limitations [2]. HER results are highly dependent on lab testing conditions, which have different conditions for edge failure observed in production. In addition, the shear affected zone in the hole expansion test is different from the production trimming setup. The relationship between tensile properties and HER were addressed [3, 4, 5]. Strain hardening rate at uniform elongation in a tensile test was correlated to HER

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[3]. Non-linear correlation between ultimate tensile strength and HER were addressed [6, 7]. The HER for the machined hole and sheared hole were empirically modelled for various high-strength steels as a function of the normal anisotropy, total elongation, work hardening exponent, and thickness [8, 9, 10]. A procedure was presented to develop hole-edge failure criteria using several formability tests and applied to predict hole edge failure in the component bend test with the AHSS structure [11].

Unfortunately, the ISO standard testing method with a 10-mm initial diameter of the hole often gives highly inconsistent test results, with the same material depending on the hole preparation methods and interpretation procedure. From these impractical limitations, the material supplier and automotive original equipment manufacturers (OEM) need better testing methods [12]. A large hole expansion testing (LHER) method was recently introduced and used to reliably evaluate the edge cracking [13]. Both LHER and HSDT were correlated [14] and the maximum thinning based failure criteria for edge cracking was correlated to edge cracking of industry scale stampings [15].

3. Approach

To evaluate and predict edge cracking, a new methodology is introduced as depicted shown in Figure 1. In this study, the shear test with different clearances was applied to obtain a consistent edge quality. The half dome specimen test (HSDT) was implemented to evaluate edge cracking experimentally. Finite element analysis (FEA) was conducted using the failure criteria obtained from HSDT.

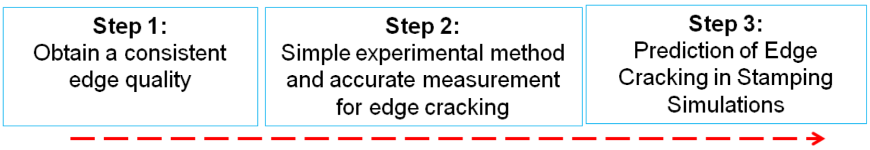

Figure 1. New methodology in prediction and evaluation of edge cracking.

The following three sheet materials were selected for evaluating edge cracking:

- Electro galvanized (EG) TRIP 780 (1.4-mm thickness)
- Cold-rolled DP 980 (1-mm thickness)
- Cold-rolled DP 1180 (1-mm thickness)

The tensile properties of the three materials are shown below in Figure 2.

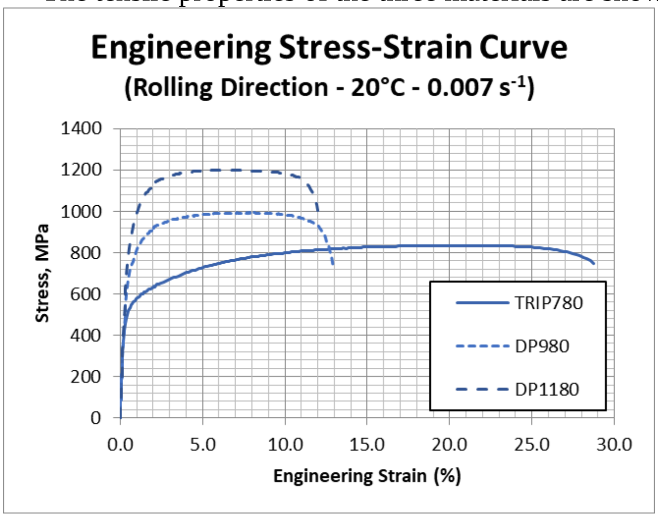

Figure 2. Rolling direction stress strain curves of TRIP 780, DP 980 and DP 1180 material used in the study.

The shear test was prepared by United States Steel Corp. (USS) using optimized shear conditions in different clearances. In HSDT, the 100-mm diameter dome punch and die were used. The HSDT failure condition was recorded by a Digital Image Correlation (DIC) system and load cell. The best shear test condition was identified by comparing the maximum punch displacement and the highest thinning value at onset of edge cracking.

3.1. Shearing test

All three materials are provided by the United State Steel Corporation (U.S. Steel). The shearing test is conducted using 2-degree rake angle. The test tool schematic is shown in Figure 3. The actual test setup is shown in Figure 4. The testing equipment was also equipped with a load cell to provide load-displacement data during the shearing process. US Steel conducted all the shearing tests. The shearing clearance is adjusted to create different shearing conditions. In the test, the shearing clearance was adjusted from 5% to 25% of the metal thickness in 5% increments.

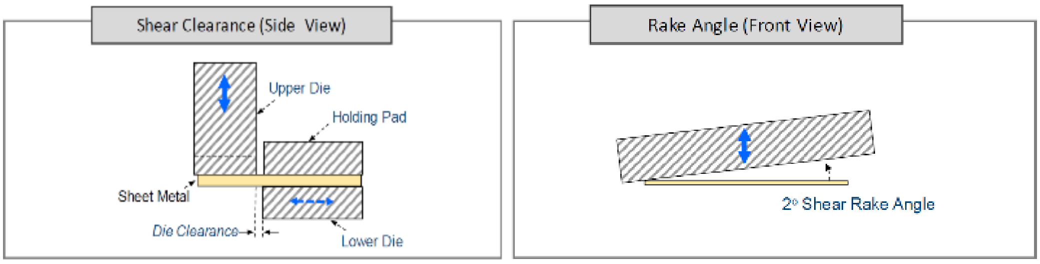

Figure 3. Schematic of shearing testing tools. [16]

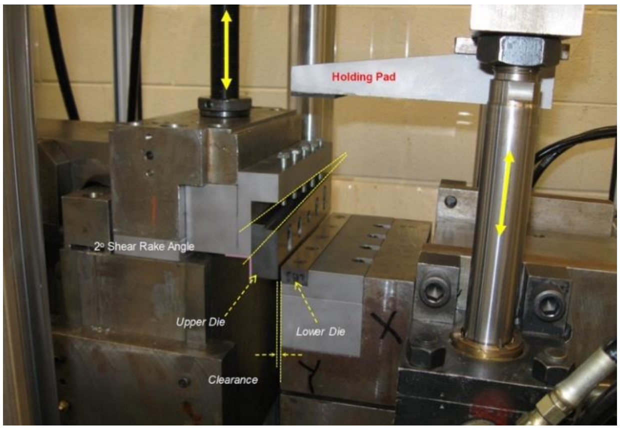

Figure 4. Tooling setup of shearing test at USS.

Micro-hardness test with 300 grams load was conducted by Honda R&D. The rollover, burnished, fracture and burr height were also measured at the sheared edge. Table 1 gives the shearing test conditions. One sample for each discrete condition was measured for hardness and shear zone height measurement.

Table 1. Matrix of the shearing test.

Materials	Specimen orientation	Repetitions	Shear rake angle	Shear clearance
TRIP 780 EG (1.4 mm) DP 980 CR (1.0 mm) DP 1180 CR (1.0 mm)	Transverse to rolling direction	3	2 degrees	5 10 15 20 25

3.2. Half specimen dome test

HSDT is used to evaluate edge cracking failure criteria to be implemented in FEA simulations. The HSDT uses a 100-mm diameter dome punch. The schematic of HSDT is shown in Figure 4. In the test, the rectangular blank size is 170 mm on the long edge and 100 mm on the short edge. The long edge is the sheared edge from previous shear test and is placed 10 mm offset from the center of the die cavity, with the burr side facing away from the punch. The transverse direction (TD) of the blank is edge tested since the TD is more prone to edge cracking compared to the rolling direction (RD) edge. There was no lubrication applied to the blank to tooling. Figure 5 shows five representative tested samples for five different edge conditions that were obtained from 5%~25% shear clearances. Most samples consistently showed edge cracking between the apex of the dome and lock bead areas.

EWI used a DIC system to measure the strain path and thinning at the onset of edge cracking. The higher thinning and draw depth indicates higher resistance in edge cracking. Figure 6 shows an example strain path of TRIP 780 HSDT sample that was measured using DIC.

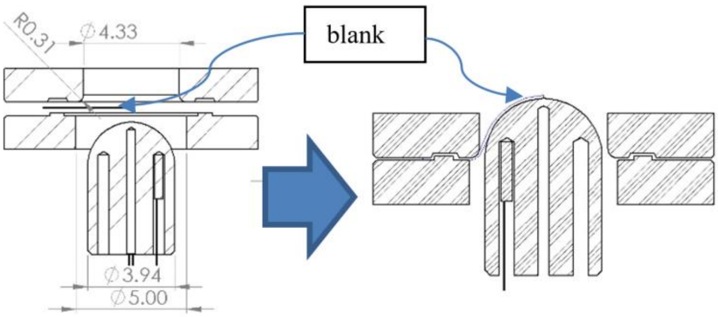

Figure 5. Schematic of HSDT from the starting position (left) to the final state (right).

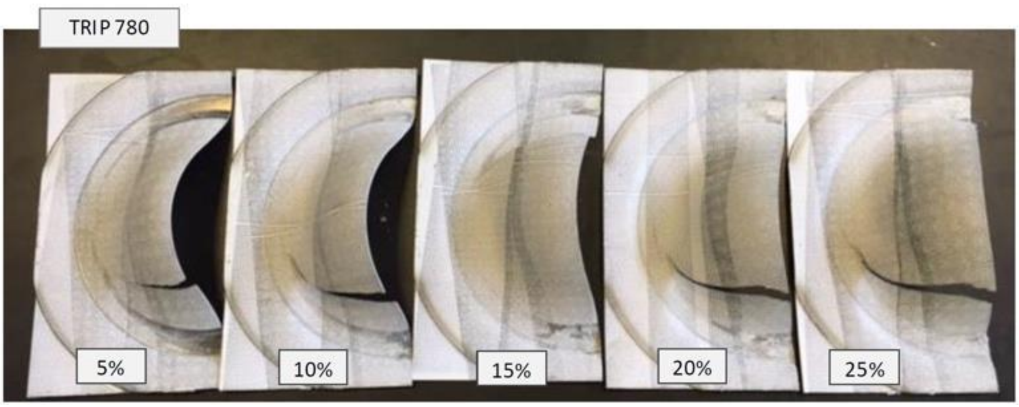

Figure 6. HSDT of TRIP 780 DIC sample cracks initiated at the edge between apex and bead.

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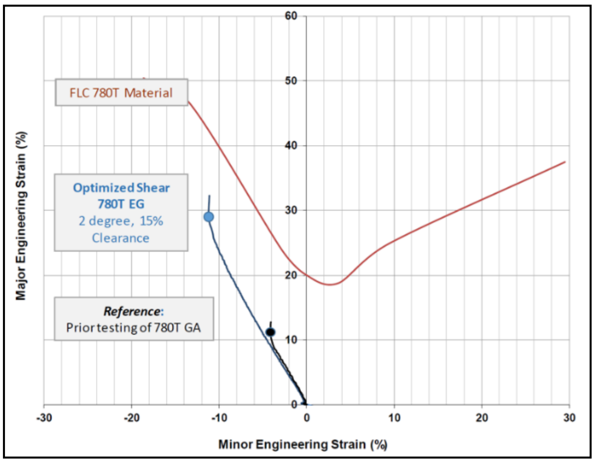
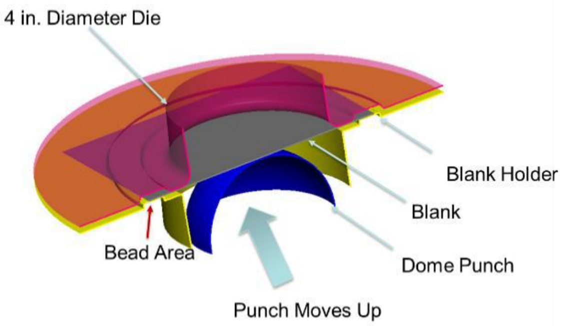


Figure 7. The DIC measured strain path with the Forming Limit Diagram (FLD) of the TRIP 780.

3.3. Finite element analysis

A simulation model was prepared using a commercial FEM code, PAM-STAMP. The cross section of the model and simulation matrix are given in Figure 8. The FEA-predicted thinning is the failure criteria from the DIC measured thinning at failure. When elements reach to the DIC measured critical thinning value, the FE blank mesh model starts element erosion to emulate edge cracking.



Materials	Shear gap (%thickness)	Exp. Thin. Avg	FEA Predicted Thinning
TRIP 780 - 1.4mm	5%	11.1%	11.0%
	10%	10.6%	
	15%	11.3%	
	20%	10.7%	
	25%	10.0%	10.0%
DP980 - 1mm	5%	12.4%	12.4%
	10%	12.5%	
	15%	11.5%	11.5%
	20%	13.8%	13.2%
	25%	13.2%	
DP1180 - 1mm	5%	8.5%	8.5%
	10%	9.4%	9.2%
	15%	9.3%	
	20%	10.4%	10.2%
	25%	10.0%	

Figure 8. Cross section view of PAM-STAMP simulation model and table of simulation input matrix.

4. Result and discussion

4.1 Correlations between shear test result and HSDC

A larger burr height usually indicates poor shear edge quality in stamping production. The shear edge micro images and the measurements of each shear region is shown in Figure 9. From the micro-images and measurement, as shear clearance increases, the rollover zone gets larger and burr height first decreases and then increases after 10% clearance shear condition. However, DP980 and DP1180 did not show any burr height increase as the shear clearance increased from 5% to 25% since the materials have relatively higher hardness compared to TRIP780.

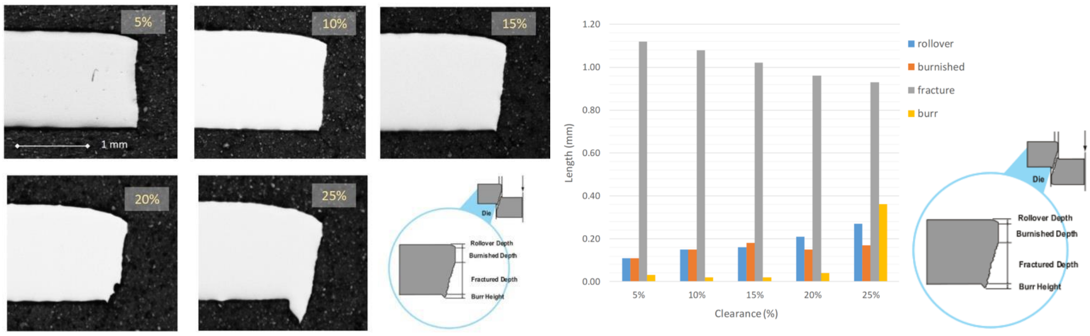


Figure 9. Edge condition micrograph of TRIP 780 and measurement.

Corresponding to the burr height in different shear conditions, the HSDT result of the total stroke at edge cracking and thinning shows the same trend. The maximum thinning value at edge cracking of the three materials is shown in Figure 10. A higher thinning value at edge cracking indicates better edge quality. For TRIP 780, 15% sheet thickness shear gap shows the best edge quality. For DP 980 and DP 1180, 20% and 25% shear gaps have the best shear edge quality.

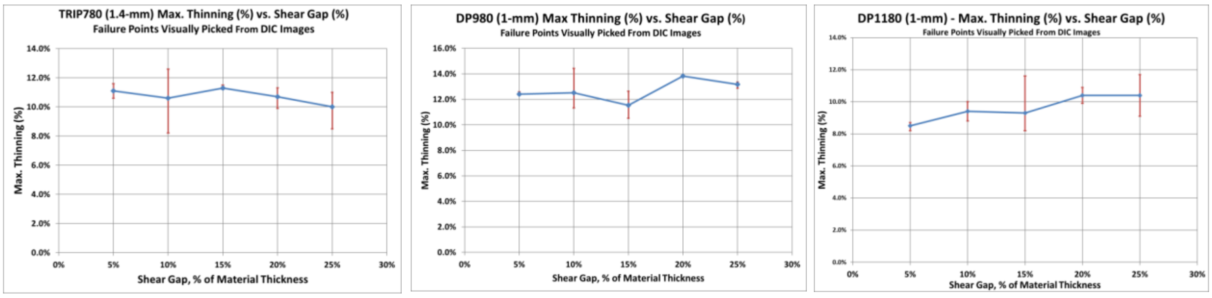


Figure 10. Maximum thinning value at edge cracking in HSDT of TRIP 780 (left), DP 980 (middle) and DP 1180 (right).

Figure 11 compares the shear load-displacement curves and the peak shear load of TRIP780 material for different shear clearnaces. As shown in Figure 11, the lowest peak load was measured at 15% shear clearance. This lowest shear peak load can imply the lowest damage on the shear edge which can result in the better edge quality compared to other shear clearances.

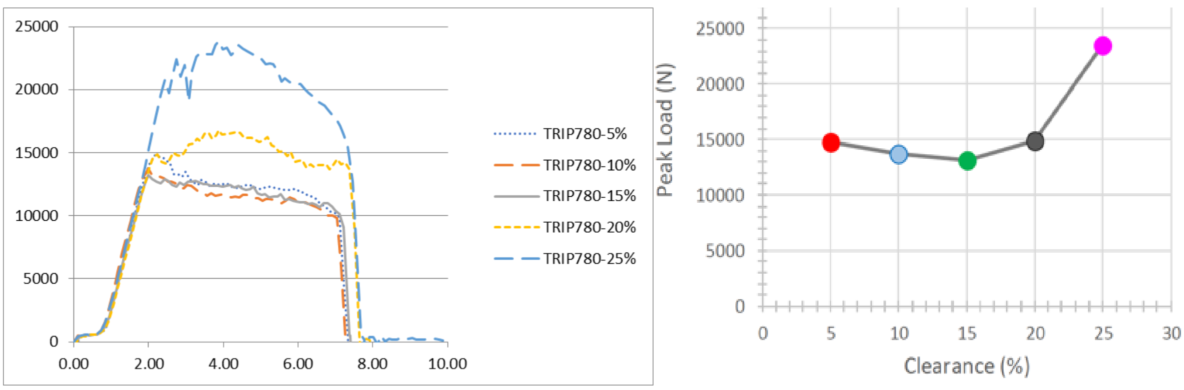


Figure 11. Comparisons of the shear load-displacement curves and the peak shear load at different shear clearances.

4.2 HSDT correlation with simulation

Three simulation results are compared with experimental HSDT results:

- Thinning and edge cracking locations
- Maximum strain at edge cracking
- Load-displacement curves

In HSDT, edge cracking consistently occurred between bead and dome apex as shown in Figure 7. Figure 12 shows the FEA predicted thinning distribution of the HSDT. The simulation uses the max thinning value from the HSDT as failure criteria and initiate element erosion, which initiates the crack. As the crack propagates, the load drops as observed in HSDT. The load displacement curve from experiment shows good correlation with simulation in Figure 13.

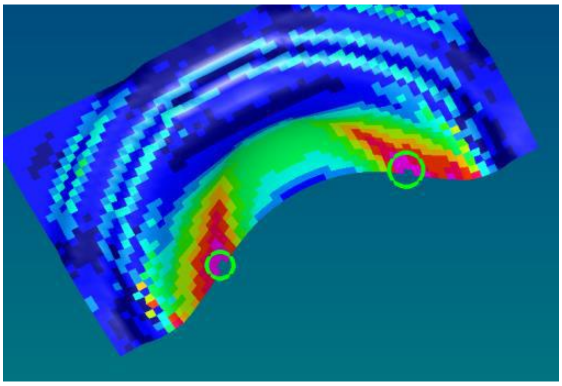


Figure 12. Edge cracking location of DP 980 with failure criteria of 25% sheet thickness shear clearance (the circles indicate the crack location).

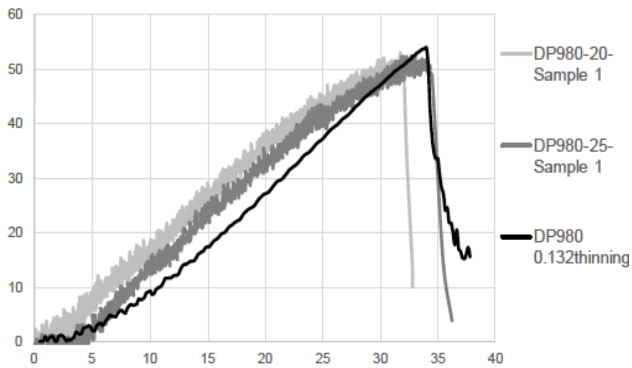


Figure 13. Load displacement curves from simulation and experiment.

The simulation result shows good correlation using thinning as the failure criteria on HSDT. The deviation of the simulation result from the experimental maximum strain at edge cracking is small. The deviation is mostly within ±5%. Also, the simulation shows high localized thinning in the bead area close to the edge. This thinning can result failure in the bead during the HSDT, which is also observed occasionally.

5. Conclusions

A ranking table was established to relate the key factors with edge cracking test results for three selected AHSS as shown in table 2. The ranking indicates the value from 1-the highest to white-the lowest. The colour indicates the edge cracking risk, from dark for the highest edge cracking risk to white for the lowest edge cracking risk. For example, highest punch force us ranked as 1-highest value and red as highest risk as well.

Table 2. Colour map of edge cracking risk evaluation for TRIP 780, DP 980 and DP 1180.

% C.L.	MAX. Punch Force Ranking	Avg. Punch Force Ranking	Hardness at Edge Top (HV)-value	Roll-over zone Ranking	Fracture Zone Ranking	Burr Height Ranking	Max. Thinning (%) value	Final stroke (mm) value
				TRIP 780				
5	3	3	321	5	1	5	11	36
10	3	3	328	4	2	5	11	36
15	3	3	331	3	3	5	11	36
20	2	2	347	2	4	5	11	36
25	1	1	348	1	5	1	10	33
				DP980				
5	1	2	341	5	1	-	12	33

10	3	4	337	4	2	-	13	**33**
15	3	3	371	3	4	-	12	**32**
20	5	4	347	2	2	-	14	**34**
25	2	1	-	1	-	-	13	**34**
	DP1180							
5	1	1	392	2	1	1	9	**28**
10	2	3	401	4	4	2	9	**29**
15	2	3	404	4	2	2	9	**29**
20	4	**5**	411	2	3	2	10	**31**
25	4	2	409	1	5	2	10	**31**

The following conclusions can be drawn from this study:

- The HSDT is a simple and practical testing method to evaluate the edge cracking and thinning is a reliable indicator for edge cracking limit.
- The optimized shear clearance for 2-degree rake angle shearing was found to be 15% for TRIP 780 and 20-25% for DP 980 and DP 1180, which is summarized in Table 3.
- FEA showed good correlations with the HSDT using the maximum thinning based failure criterion.
- The higher shear load can increase local strain hardening and burr height on the shear edge, which easily leads to edge cracking.
- The maximum shear load and burr height can be monitored in process to have real-time evaluation on shear edge quality.

Table 3. Summary of edge strechability and recommendations for tested material.

Materials	Major Eng. Strain at Edge Cracking	Max. % Thinning at Edge Cracking Readings from the data trends (The reference data)	Preferred Shear Gap % for Better Edge Quality
TRIP780 (1.4-mm)	0.23 - 0.25	10 – 11 % (7% with the conventional sheared edge and 13% for the water-jet sheared edge)	15%
DP980 (1-mm)	0.27 - 0.32	12 – 13% (6% with the conventional sheared edge and 9% for the water-jet sheared edge)	20 – 25%
DP1180 (1-mm)	0.18 - 0.23	8 – 10% (No reference data available)	20 – 25%

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