Topological Characterization of Machined Edges Prepared by Different Cutting Methods, and Edge Evolution in Tensile Deformation

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Abstract. To understand better on edge cracking in sheet metal forming, the edge preparation methods, edge topological characteristics, and its evolution in uniaxial tension are investigated. Tensile specimens were prepared by waterjet cutting, milling, and EDM methods. The as-machined and fractured edges were measured with a Laser Scanning Confocal Microscope (LSCM (Keyence VK-9710), which provides statistical roughness parameters and raw data of surface 3D surface geometry at up to 1nm z-direction resolution, allowing topological analysis. The edge evolution during tensile straining was reported achieved by interrupted tensile tests at different strains, and replication of the edge surfaces without unloading using a metallurgical replica technique, for post-measurement after the tests. The quality of the three edge preparation methods and the effect on edge cracking in tension are investigated.

1. Introduction
In the last two decades, advanced high strength steels (AHSS) have been developed rapidly and applied in automotive body structures.[1]. With the increase in strength of AHSS the ductility often decreases, and edge cracking becomes one of the formability concerns. Thus, the sensitivity of sheet metal edge quality to the edge cracking is of current interest [2]. There are many published works on investigating the cutting quality effect on AHSS formability, for example by [3-6]. But there is a lack of topological studies on the edge surface characteristics and its correlation to the edge cracking. Pathak et al [7] studied the roughness contribution on the hole expansion ratio and found the effect was minor due the profile direction in the loading orientation, and the machined surface had a good roughness value. The surface roughening and orange peel phenomena of aluminium sheet during deformation can affect the formability of the sheet metal [8]. The effect of rolling induced surface roughness on the formability were reported by [9-11], for various materials (aluminium, copper, steel, etc.). In addition, surface defect types were studied by [12].

Dykeman et al [13] investigated the edge fracture of various AHSS specimens that were prepared by laser cutting, punching and water jet cutting. The resulting fracture strains vary among: some materials have higher fracture strain for water jet cut specimens, while other materials have a better formability for punched and laser cut specimens. Pathak et al [14] performed uniaxial tension using the DP780 specimens with a central hole of 10-mm diameter with the edge prepared by two methods: reaming and shearing, and the maximum equivalent strains were measured by DIC. In comparison, the maximum equivalent strains for reamed and sheared specimens were 0.55 and 0.27, respectively.

Formability modelling relies on correct material properties and fracture limit to predict forming limit of a given forming process. The sheet metal properties are commonly obtained from uniaxial tension based on ASTM-E8 specimens, which specifies the standard geometry, but did not specify the
method to machine the specimen. For advanced high strength steels, during sheet metal stamping it is sensitive to edge cracking, and during uniaxial tension the edge cracking may also occur. To assure the tensile properties are not affected by edge cracking, the edge quality of the tensile specimen and its effect on the tensile properties are of current interest. This paper is to characterize the topological feature of the tensile specimen’s edges preparation by three different methods, and to investigate evolution of the edges in tensile deformation and its effect on tensile behaviour of materials.

2. Experimental Procedure

DP780 sheets of 1.0-mm nominal thickness were machined to tensile specimens following ASTM-E8 standard, with three sheet metal cutting methods: milling (Mil), electrical-discharge machining (EDM), and water jet, (WJ). The tension direction is along the rolling direction (RD), or transverse directions (TD).

Uniaxial tensile tests were performed in a standard servo-hydraulic load frame (Instron model 8801, 100kN capacity), equipped with a servo-hydraulic actuator, a digital closed-loop controller, and a pair of hydraulic grips. Strain distribution was measured using a Digital Image Correlation (DIC) system (Dantec) at 25 frames per second and with 0.1mm facet size.

The machined edge surfaces were measured using a 3D laser scanning confocal microscope (Keyence model VK_9700) at 1 nm resolution in z (height) direction and 1.381μm/pixel in x-y field of view. The specimen gauge section edges were measured before and after the tensile tests, at selected edge locations with corresponding strains obtained from nearby DIC strains on the normal surface.

3. Results

3.1. The as-machined edge surfaces.

The as-machined edges from above mentioned three machining methods are shown in figure 1, from which it is notable that the milling generated a well-defined smooth edge surface with the scratch lines in the tensile direction, while EDM cutting used charged wire that moves in through-thickness direction, and WJ spraying direction was also in through-thickness direction, with the edge surface showing certain microstructural features from their individual machining principles, but no clear machining markers were observed.

![Figure 1](image1.png)

**Figure 1.** As-machined edges viewed on the side thickness of gauge sections. The edge surfaces were produced by (a) Milling, (b) EDM, and (c) Water Jet. The width of the images is close to entire sheet thickness at 1mm, and the tensile loading axis is along the vertical direction.

3.2. Tensile Test.

The engineering stress-strain curves of specimens from different cutting methods are shown in figure 2, which shows that the WJ specimens have the lowest total elongation, for both the RD and TD loading.
Figure 2. Engineering stress-strain curves for three specimen edge cutting methods, for tension in (a) rolling direction; and (b) transverse direction.

Figure 3 shows the von Mises effective strain contours of these tests at the last DIC frame before fracture. For the milling and EDM prepared specimens large fracture true strains (>50%) were obtained, and the highest fracture strains appeared at the specimen centre away from the machined edge, with significant necking development, indicating the edge quality is not the formability controlling factor. In this case the strain path within the localized necking zone tends to change from uniaxial tension to plane strain, which is up to 15% higher than the plane stress loading condition at the edge, resulting in fracture initiating away from the edge. In contrast, for the WJ specimens, before significant local necking could be developed, a high edge strain developed, for both RD and TD. This led to premature fracture at much lower strain (0.3 and below), with limited necking development, especially for the WJ-RD specimen. In this case the tensile fracture is controlled by the edge preparation quality, and edge cracking occurred before material’s intrinsic fracture strain was reached.

Figure 3. The effective true strain distribution at the last frame before fracture, for RD and TD from three edge cutting methods, with the maximum strain indicated. For WJ specimens the circled area indicates the high strain appeared at the edge, so the specimen fracture was affected by the WJ machining method.

3.3. Edge Surface Roughening.
The results of the edge roughness vs. local tensile true strain are shown in figure 4, where the different strain values were obtained from the same fractured specimen at different longitudinal distances from the fractured section, within the necking zone. The local tensile true strains were obtained from DIC strains at the position close to the measured edge surface location, and the roughness parameters Ra and Sa were used to describe the statistical surface properties: Ra is the arithmetic mean of a 1D line profile $Z=f(x)$, obtained in 3 lines 1.2 mm long in tensile direction, and Sa is the arithmetic mean of 2D profile
Z(x,y) over the measured edge area of 1 mm x 1.2 mm in size. The expressions of Ra and Sa are given by Equations (1) and (2) [15, 16].

\[ R_a = \frac{1}{l} \int_0^l |f(x)| \, dx \]
\[ S_a = \frac{1}{\lambda} \iint_A |Z(x,y)| \, dx \, dy \]  

For different local strain values, the Ra were measured in three lines along the tensile direction at top, mid and bottom thickness positions within a field of view of confocal microscope measurements. Ra values show wide range of scattering, and the effect of strain on the Ra is difficult to see, especially for WJ specimens. For the EDM and Mil specimens, however, the scattering is much reduced. For Sa vs. strain plot, on the other hand, the measurement used entire data points within the field of view, where the area A covered 1.4 mm in tensile direction and the sample thickness, which varies depending on the local strain, so that only single Sa value was obtained that summarizes the surface roughness based on Equation (2). The roughness is the highest from WJ, and the lowest from Mil. In comparison of RD and TD, for WJ and Mil specimens the RD is rougher than TD, but for EDM the results are opposite. It is not clear how the material orientation affected the surface roughness in each of the three machining methods. One possible reason is that the RD fracture strain is larger than the fracture strain in TD, and the uniform strain is also higher in the RD than in the TD, allowing more chance to develop surface roughening effect. Note the difference of total elongation between RD and TD are large for Mil and WJ, but not much different for EDM.

In terms of the strain effect on the edge roughness, apparently the roughness may not always increase with strain at the lower strain range. One possible explanation is that with initial roughness as a reference, within a low and more uniform strain range, the range of edge surface asperity peaks and valleys may be reduce by small strain, or say the surface notches were flattened, similar to a wave to be stretched in the longitudinal direction and with reduced wave amplitude. But close to the fractured section, at a larger and less uniform strain range, the edge notch flattening effect gives the way to the edge roughening due to notch-induced stress concentration. A similar phenomenon was also previously reported [11].

**Figure 4.** Edge surface roughness Rₐ and Sₐ for different locations with different tensile true strain (the major principal strain E₁).

Another way to represent the strain effect on the surface roughness is to use the range of the peaks and valleys of the scanned line profile for each measured area, which represent the edge net height from bottom to top of the surface asperity. The mean height as a function of local strain is shown in figure 5, with the error bar representing the standard deviation within the scanned line of each measured area. This plot clearly shows the trend as that in figure 4(b), suggesting there may exist two competing processes of edge smoothing and edge roughening.
3.4. Edge Crack Growth for Milled Edges under Tension.

The milling prepared specimen edge has clear longitudinal scratches over the smooth and shining reflective machined edges. Under tension, cracks develop in the direction perpendicular to the tensile axis, which provides an opportunity to measure the crack numbers and their lengths for different measurement areas with different local strains. The crack length statistical parameters subtracted here are the maximum, average and standard deviation of the crack lengths, which are plotted as a function of local strain as shown in figure 6. The results show a general trend that the crack length parameter increases with strain, with some fluctuation. The number of the cracks is higher on the lower strains and ranging between 7-13 on the measured areas, not plotted here. For the EDM and WJ specimens the edge surfaces were too rough to see the crack and its growth (see figure 1 edge morphology).

4. Conclusions

- Comparison of the three-edge machining methods: The initial roughness of the milled surface is the lowest, the waterjet cut specimen is the highest, and EDM is in between.
- Roughness evolution: The surface roughness generally increases with strain based on Ra and Sa measurement and mean height (range) measurement, but there also exists combined edge smoothing and roughening effects at relatively lower strain range. Further investigation with larger sample size and modelling of the edge evolution over straining are needed for further exploring this phenomenon.
- Fracture behaviour: Within the current experimental condition the WJ prepared edges show that edge cracking is a limiting factor of total elongation to failure, while EDM and Milling prepared specimens did not fracture from the edge.
• Comparison of rolling and transverse directions: The RD tends to roughen more than TD, and this is related to the general situation that the RD fracture strain is often larger than the fracture strain in TD, allowing more chance in development of surface roughening. In addition, the uniform strain is generally higher in the RD than in the TD, resulting in greater surface roughening before necking. But this does not apply to EDM results.

• Milling prepared edge and crack length development: The milling scratches/grooves were in a favourable orientation along the tensile direction, making it more stable and less affected by the strain-induced roughening, as compared with the EDM and waterjet machined edges that machine the edge in the through-thickness direction; however, for EDM with relatively low initial roughness (than WJ) the strain effect on roughening is not significant. The smooth machined edge provides the chance to observe edge crack development during tension. The results on roughening and smoothing are also consistent with the roughness evolution during straining.

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References
[1] N. Fonstein, Advanced high strength sheet steels: physical metallurgy, design, processing, and properties: Springer, 2015.
[2] K.-i. Mori, Y. Abe, and Y. Suzui, "Improvement of stretch flangeability of ultra high strength steel sheet by smoothing of sheared edge," Journal of Materials Processing Technology, vol. 210, pp. 653-659, 2010.
[3] A. Dalloz, J. Besson, A. F. Gourgues-Lorenzon, T. Sturel, and A. Pineau, "Effect of shear cutting on ductility of a dual phase steel," Engineering Fracture Mechanics, vol. 76, pp. 1411-1424, Jul 2009.
[4] D. J. Thomas, M. T. Whittaker, G. W. Bright, and Y. Gao, "The influence of mechanical and CO2 laser cut-edge characteristics on the fatigue life performance of high strength automotive steels," Journal of Materials Processing Technology, vol. 211, pp. 263-274, 2011.
[5] M. Feistle, R. Golle, and W. Volk, "Determining the influence of shear cutting parameters on the edge cracking susceptibility of high-strength-steels using the edge-fracture-tensile-test," Procedia CIRP, vol. 41, pp. 1078-1083, 2016.
[6] D. J. Thomas, "Effect of mechanical cut-edges on the fatigue and formability performance of advanced high-strength steels," Journal of Failure Analysis and Prevention, vol. 12, pp. 518-531, 2012.
[7] N. Pathak, C. Butcher, and M. Worswick, "Assessment of the Critical Parameters Influencing the Edge Stretchability of Advanced High-Strength Steel Sheet," Journal of Materials Engineering and Performance, vol. 25, pp. 4919-4932, November 01 2016.
[8] K. Yamaguchi, N. Takakura, and S. Imatani, "Increase in forming limit of sheet metals by removal of surface roughening with plastic strain (Balanced biaxial stretching of aluminium sheets and foils)," Journal of Materials processing technology. vol. 48, pp. 27-34, 1995.
[9] W. Xu, L. Zhang, and C. Liu, "Surface roughness controlling of AA6061 sheet under uniaxial tension," Procedia Engineering, vol. 207, pp. 1344-1348, 2017.
[10] R. Mahmudi and M. Mehdizadeh, "Surface roughening during uniaxial and equi-biaxial stretching of 70-30 brass sheets," Journal of Materials Processing Technology, vol. 80, pp. 707-712, 1998.
[11] I. Shimizu, T. Okuda, T. Abe, and H. Tani, "Surface roughening and deformation of grains during uniaxial tension of polycrystalline iron," Jsme International Journal Series a-Solid Mechanics and Material Engineering, vol. 44, pp. 499-506, Oct 2001.
[12] D. Raabe, M. Sachtleber, H. Weiland, G. Scheele, and Z. S. Zhao, "Grain-scale micromechanics of polycrystal surfaces during plastic straining," Acta Materialia, vol. 51, pp. 1539-1560, Apr 2 2003.

[13] J. Dykeman, S. Malcolm, B. Yan, J. Chintamani, G. Huang, N. Ramisetti, et al., "Characterization of edge fracture in various types of advanced high strength steel," SAE Technical Paper 0148-7191, 2011.

[14] N. Pathak, C. Butcher, M. J. Worswick, E. Bellhouse, and J. Gao, "Damage evolution in complex-phase and dual-phase steels during edge stretching," Materials, vol. 10, p. 346, 2017.

[15] E. S. Gadelmawla, M. M. Koura, T. M. A. Maksoud, I. M. Elewa, and H. H. Soliman, "Roughness parameters," Journal of Materials Processing Technology, vol. 123, pp. 133-145, Apr 10 2002.

[16] B. Bhushan, Modern tribology handbook, two volume set: CRC press, 2000.