Trim Die Damage and "Self-Reconditioning" Effect on Trimmed Edge of Sheet Metal Blanks

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Abstract. Tooling durability for advance high-strength steels has been investigated by Auto/Steel Partnership at an industrial site using AISI D2 die for trimming DP980 up to 100,000 hits. The topological characterization of the trimmed workpiece edges were measured by a laser confocal microscope that provided 3D surface geometries, and further analysed. It was found that, despite of initial portion of edge roughening and edge quality deterioration from the new trim die, in the majority portion of the trimming operation up to 100,000 hits the edge quality of the trimmed sheet metal edges show combined roughening and smoothing cycles, or called a "self-reconditioning" effect, with the edge quality to be within a stable roughness window. The non-even wear between two pieces of trim die pair and along the die cutting edge is observed and analysed. This finding leads to the need of better redefinition of trim die failure or trim die reconditioning criterion.

1. Introduction

Sheet metal shearing (including blanking, trimming, piercing) is one of the basic stamping operations for blank preparation and feature forming involving sheet metal shearing and material removal. For automotive industry, the energy conservation, environmental protection and vehicle safety have been driving the application of wide variety of lightweight structural materials. One class of new materials is the ultra-high strength steels (UHSS) for autobody structures that has reached above 1.5 GPa strength. This brings up a great challenge for cutting tool materials to have sustained service life, as the tool cutting edge experiences a much severe loading condition involving highly concentrated stress at a high magnitude and gradient, high intensity impact loading and high-amplitude fatigue loading. On the other hand, many advanced high strength steels are sensitive to edge cracking in the proceeding stretch deformation, requiring improved edge quality. Thus, despite that trimming is a traditional manufacturing problem being well studied, the damage process and edge evolution of both trim tools and the sheared sheet metals edges are continually of great interest in academia and industry.

A large body of literature on sheet metal mechanical shearing are available, and the topic is reviewed earlier by Johnson et al. [1] and by Levy and Van Tyne [2], in which the major problems and concerns in cutting various materials, and the main variables were addressed, and it was pointed out that there is a need to better quantify the effect of shearing process on edge stretchability. Recently a general guideline of AHSS was provided by Keeler, Kimchi et al [3] that indicates that a larger die clearance can be used in trimming AHSS without significant increase in burr height, but with the benefit to reduce

trim die damage. Most experimental observations indicate that the sheared edge generally consists of four zones: roll-over zone, burnish zone, fractured zone and burr zone. Goijaerts and his co-workers [4-7] studied blanking used digital image correlation method and FEA analysis with ductile fracture model. Fine blanking was studied by Thipprakmas et al [8]. Golovashchenko and his co-workers published a series of trimming studies involving advanced high strength steels [9], aluminum alloys [10-13], the effect of material anisotropy and trim method on elongation [14], the burr formation in trimming and the effect on edge stretchability [11, 12, 15, 16], and tool wear in trimming DP980 [17]. The morphology of sheared edge and metal flow of AHSS was studied by one of current authors [18] who developed a method to determine strain distribution within the sheared zone by tracing metal flow lines. The methods for tool condition monitoring were reviewed by Rehorn et al. [19]. The research activities in Europe are reviewed by Buzzichelli and Anelli [20].

This paper focuses on the correlation of trim die damage and sheared edge quality at a high number of trimming cycles based on the topological analysis of measured burnish zone surfaces, and report the first finding of a "self-reconditioning" phenomenon in a 100,000-cycle study with topological analysis trimmed edges and related trim tool damage.

2. Experimental Conditions

Trim die wear and the trimmed workpiece edge topology have been studied under a progressive stamping production press containing piercing, forming, trimming and flanging. The last trimming process involves the shearing of a pre-formed waved part at its front section, see the trim die inserts and the sheared surface of the parts in Figure 1. The upper die insert has a flat horizontal bottom face and vertical cutting front face, moving downwards. The stationary lower die insert has a waved bumper shape in match with the formed part shape. The intended trim die clearance is 10% sheet thickness. The shearing started at the highest point of the bumper center, gradually extended to two sides, and at the last stage the two flat part portions were cut in straight cutting line on flat tool surfaces.
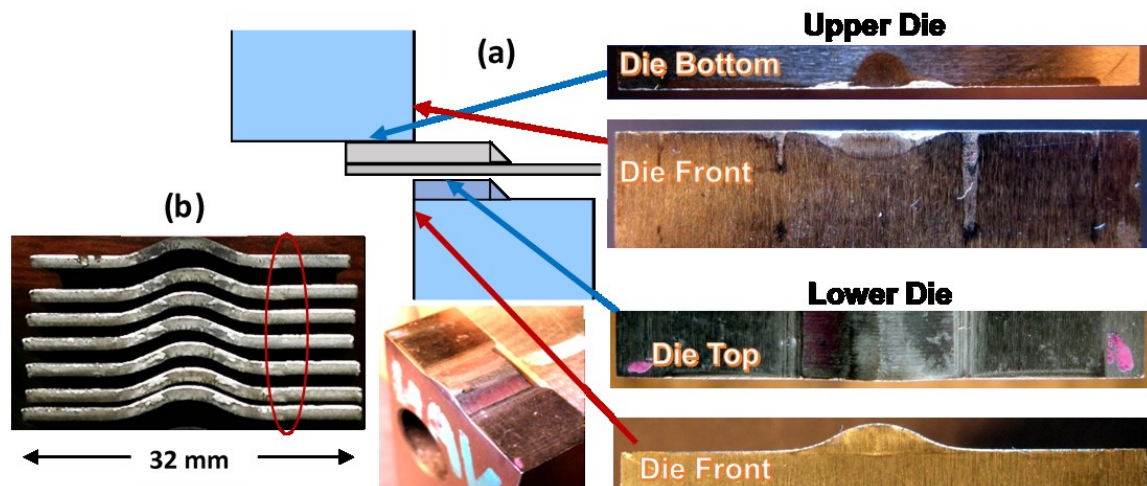
Figure 1. (a) Schematic view of trim die configuration along with the images of upper and lower die inserts after 100k hits; (b) the sheared surface of the trimmed parts.

The trim die inserts were made of AISI D2 die material without coating. They were fabricated from hot-rolled plate, cut into blocks, machined and heat treated to reach hardness HRc = 60±2, and surface grinded to use. The die inserts have the rolling direction in parallel to the vertical trimming direction. The sheared parts at selected hits (cutting strokes) were collected for edge measurement, and after completion at 100k hits the die cutting edges were imaged from different angles, and the volume of lost metal due to die wear was measured with triangulation method.

DP 980 steel at nominal thickness of 1.2 mm was used for shearing. The chemical composition and mechanical properties are given in Table 1. The selected parts were collected, more frequently in early stage, and then one sample in every 1000 hits.

Table 1. Chemical composition (w%) and mechanical properties of DP980.

C	Si	Mn	P	S	Cr	Mo	V	Ni
0.15	0.6	0.6	0.03	0.03	12	0.105	1.0	0.03

Yield Strength (MPa)	UTS (MPa)	Elongation (%)	n-value
624.0	1079.7	17.0	0.104

The sheared surfaces were measured with a commercial Color 3D Laser Scanning Microscope (Model VK_9700 from Keyence [21], which outputs the surface raw data of z=f(x, y) in 3D coordinates, at 1 nm resolution in z-direction and 0.1μm of pixel spacing in x-y plane. It also produces focused 2D images over rough surfaces. The raw surface data were analysed using custom-developed MATLAB codes. For die damage measurement, limited by the production and large size that do not allow confocal microscope measurement, at the end of 100k hits, a set of images were taken from different angles, at the image resolution at 4.5 μm/pixel, and used for estimating the volume of lost metal at the damaged cutting edges with triangulation method.

3. Results

3.1. Morphology of sheared edges

The flat portion of sheared edge was used for surface measurement and analysis in order to avoid complicity in oblique cutting, see Figure 1(b) circled region. The relative heights of four sheared edge zones (rollover zone, burnish zone, fractured zone and burr zone) were measured, where the burr formation was affected by the side metal flow from the bumper region to the flat sides, to be analyzed later. With the reference of burr edge markers at the end of the bumper region the burnish zones of selected samples were measured, and the images from the measured raw data of z=f(x,y) are shown in Figure 2. These burnish surfaces contain detailed die feature of scratch lines or grooves/valleys. Note that those scratch lines are not perfectly in the vertical direction, but with tilting in width direction during shearing, as seen more clearly for samples at 60k-80k. The formed hills and valleys of these scratch lines on the parts are inversely related to the die surface valleys and hills. For better correlating the sheared edge to the die wear, only burnish zone evolution was presented in this paper.
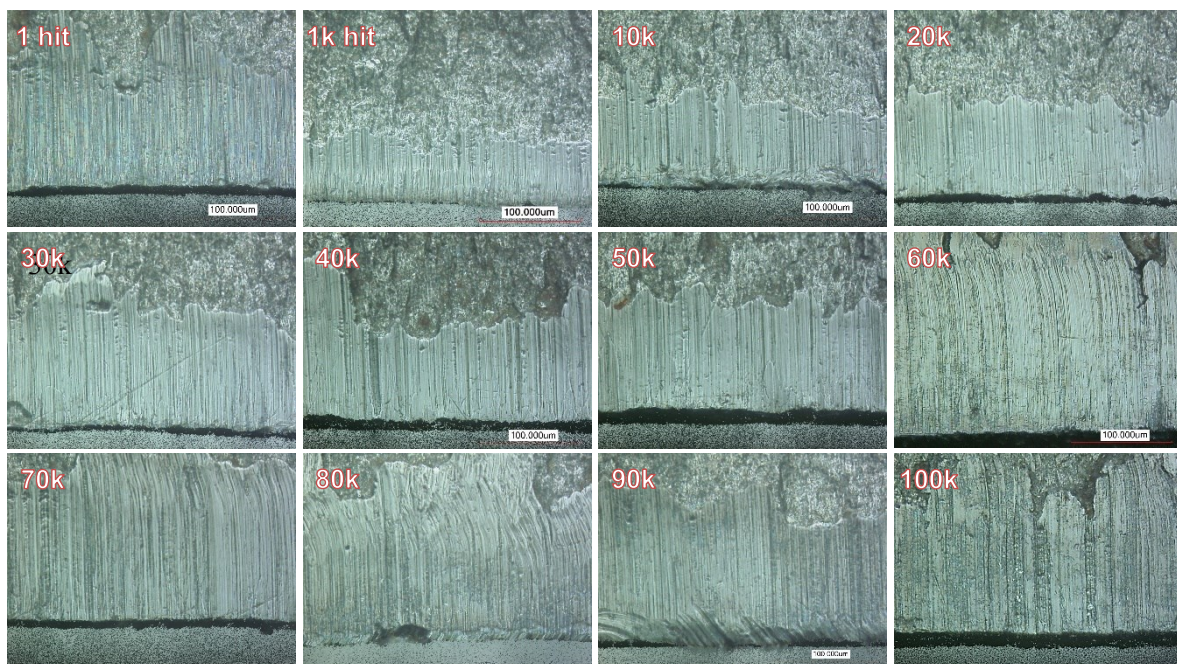

Figure 2. Burnish zones of selected samples from different numbers of hits at 1, 1k, 10k, 20k, 30k, 40k, …, 100k, form of laser confocal microscope.
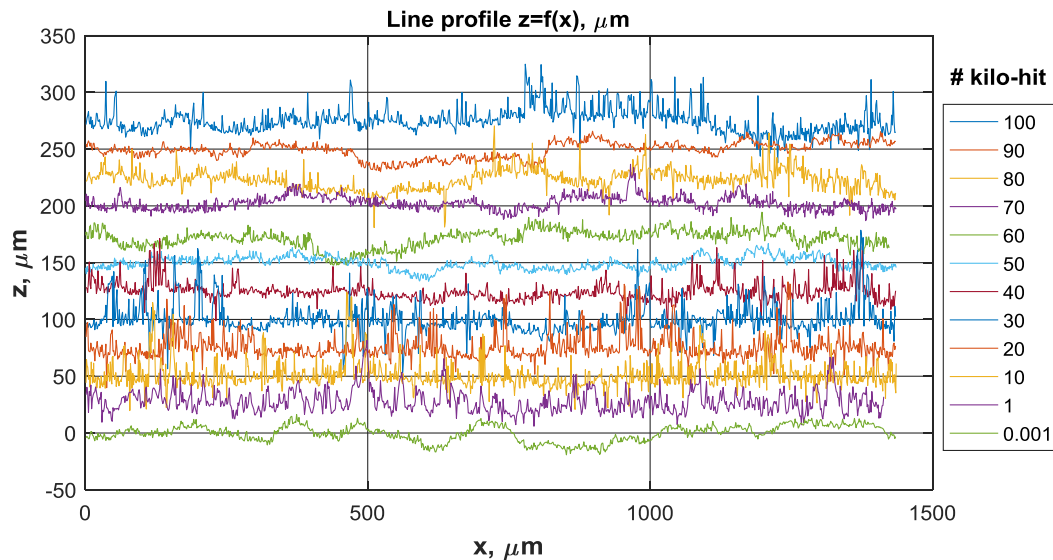
Figure 3. Line profile z=f(x) at section y=20μm of the burnish surface data for different number of hits (in kilo hits), with the mean of z value offset by 25 μm for each consecutive line in order to see more clearly the profile evolution. The data were measured under identical settings of from laser scanning confocal microscope.

The roughness of the samples measured from three y sections are shown in Figure 4, with the mean of z-values off-set to zero for each measured profile, where Ra is the arithmetic mean and Rq is the squred root mean (and with zero off-set it is the same as stangard deviation). The edge initial roughness
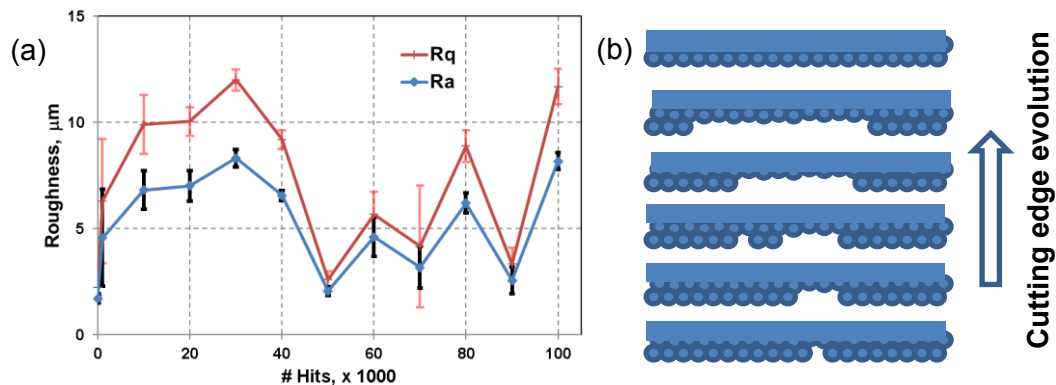
**Figure 4.** (a) Ra and Rq vs. number of hits, with the error bar representing the 1σ deviation from three y-section lines of 1.4 mm length on the burnish zone; (b) The schematic demonstration of "self-reconditioning" process with cutting edge in top-view.

is low, then it quickly increases, but after 40k hits it turned out to be smoother over quite high number of hits, and gradually increases till the end of this experiment at 100k hits. More roughness parameters can be generated but all follow the same trend. From Figure 4, there exists a roughening/smoothing cyclic process without artificial die reconditioning. This "self-reconditioning" process is explained as follows, see Figure 4(b). The D2 material has the microstructure of martensite particles surround by continuous primary carbide network. When cutting ultra-high-strength steels (here DP980) the tool damage often takes the form of chipping along the carbide boundaries, resulting in sharp boundaries of missing metals (holes or grooves), which inversely generates peaks on burnish zone profile in Figure 3. These die sharp edges would bear higher contact pressure to support concaved missing metals, so with increased local wearing, that blunt or smooth-out the chipped edge. Statistically there exist two

completing processes of roughening and smoothing at both die and workpiece cutting edges, with roughening dominate in initial stage of die use, and then under cyclic alternation of smoothing and roughening in competition. This finding suggests that the trim die failure or reconditioning criterion needs to be better defined.

3.2. Trim die damage

Without direct measurement of die wear by laser confocal microscope, one set of high-resolution photo images were taken, and the top view and front view of the die inserts have been shown in Figure 1(a). Image processing was performed to trace the boundaries of the damaged areas consisting a more severely damaged zone and two lightly damaged outside zones. For the upper die viewed from two planes, the bottom (horizontal) plane) was wear-out at the central portion (that has heavy contact with the bumper portion) and the more severe wear-out area in the two down-hill area (in red), and its front (vertical) cutting plane has been severely worn in two bumper end portions of severely damaged zones (uneven wear out occurred with the right side worn much more severe than left side). For the lower die, the top surface worn more severely on top-right side of the waved bumper, and the cutting edge worn zone is narrow but deep.
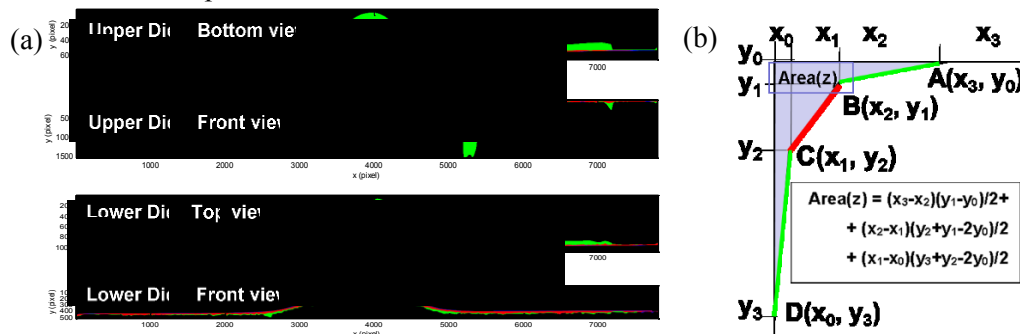

Figure 5. (a) The measured edge zone areas of missing metal for the upper die and lower die cutting edges, with red area to be severely damaged and green area lightly damaged based on the light reflection; (b) the simplified method to calculate cross-sectional area of missing metal at the cutting edge, based on the images of two orthogonal cutting surfaces.

A simplified method is used to estimate the missing metal volume at the trim die cutting edge: see Figure 5(a), on the projected images from top view and front view the edge damage zone was traced and divided into three zones: the central severe-damaged zone and two less-damaged zones on the cross-section of the cutting edge. The curved (generally convective) damage area boundary is simplified by three straight segments, see Figure 5(b). From the image processing the coordinate of the die edge and the coordinates of point A, B, C, D are obtained. The total volume of the missing metals along the cutting line is the integration of the sectioned area over edge line. As the result for the upper and lower dies after 100k hits, the missing metal volumes are 5.399 mm^3 and 0.385 mm^3, respectively. Surprisingly the upper die damaged so much more than the lower die, probably due to the fact that only the upper die but not lower die was scratched by the stationary sheet metal sheared section that stayed on the top of the lower die. Interestingly, under such a severe wear out of the upper die edge it was still able to produce acceptable sheared edge quality of workpieces, based on the burnish zone roughness evolution results.

3.3. Non-uniform wear in oblique shearing

To explore the root cause of the non-uniform distribution of the wearing shown in Figure 5(a), Figure 9 shows a representative sample at the heavily worn area at the end portion of the waved bumper, which has a severely sheared band zone, and at the end of the band a step of burr height with discontinuous edge. Two factors contribute to the severe wearing at the end of the bumper region: In the two sides of the waved bumper the cutting penetration depth or effective cutting thickness increases from the flat cutting thickness t to the side cutting thickness of t/cosϕ, where ϕ is the angle of sheet normal relative

to the vertical direction, with the maximum thickness at 45 to be 44% thicker. The second contributor is that during this down-hill cutting the sheet metal flows from the bumper area to the flat area, compressive width stress will develop due to two reasons: the side metal flow sees the resistance from the constraint of the front/back ends of the sheet metal outside the cutting plane, similar to a plane strain deformation condition. In addition, the friction of the tool also generates resistance of the down-hilll metal flow that contributes to the compressive stress. As a result, the superimposed compressive width stress will increase the cutting resistance. This explains the uneven die wear. This oblique shearing process is more general in sheet metal trimming production, and further analysis will be given elsewhere.
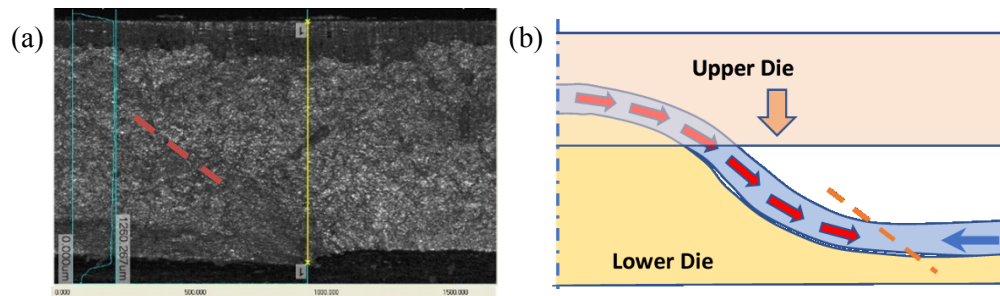
Figure 6. (a) The shear band at the end of the waved bumper zone, and a discountinuous burr step appeared at the end of the shear bands, (sample is from 40k hit sample and the cutting is in top-down position); (b) The schematic of compressive in-plane stress development from side metal flow, the inward friction during cutting, and the constraints of width deformation from metals outside the cutting planes (not shown).

4. Conclusions

The AISI D2 trim die edge damage and its effect on the DP980 sheared edges have been studied at industrial progressive line at high cutting cycles up to 100 kilo hits, and the topological characteristics of sheared sheet metal burnish zones have been measured and analysed by laser confocal microscope. The results indicate that

- A "self-reconditioning" phenomenon was found that the sheared edge was quickly roughened from new die to 1 kilo-hit, and then continually deteriorated to reach the maximum roughness at 40 kilo-hit. After that the sheared edge was getting smoothed, and gradually roughened again. This roughening/smoothing cyclic process is explained from the competition of roughening from sharp chipping edges development along the carbide/martensite interface, and the blunting/smoothing of these sharp edges by concentrated edge wear.
- The moving upper die in shearing and penetrating the sheet metal had much more severe damage than the lower die that was stationary and with limited sliding with sheet metals, indicating that the die in contact with and slide over the burnish zone will wear more severely than the die with workpiece holding the sheet metal in place without large relative movement.
- Despite severe trim die damage, the produced sheet metal edge can be much smoother than the worn die edge, indicating the produced edges are not only determined by the cutting edge, but by the envelop of the outmost surface or the entire cutting surface of the cutting tool.
- Non-uniform die wear along the cutting line direction is observed in oblique shearing, which increases the effective cutting thickness, and also generates transverse metal flow and the development of compressive stress along the cutting line. Since trimming curved cutting edge with variable cutting line curvatures is a more general stamping geometrical feature, it deserves further quantitative analysis.

5. References

[1]   W. Johnson, S. K. Ghosh, and S. R. Reid, "Piercing and Hole-Flanging of Sheet Metals - A Survey," *Memoires Scientifiques De La Revue De Metallurgie,* vol. 77, pp. 585-606, 1980.

[2]   B. S. Levy and C. J. Van Tyne, *Journal of Material Engineering and Performance,* vol. 21, p. 1205, 2012.

[3]   S. Keeler, M. Kimchi, and P. J. Mooney, "Advanced High-Strength Steels Application Guidelines Version 6.0," *WorldAutoSteel,* 2017.

[4]   Y. W. Stegeman, A. M. Goijaerts, D. Brokken, W. A. M. Brekelmans, L. E. Govaert, and F. P. T. Baaijens, "An experimental and numerical study of a planar blanking process," *Journal of Materials Processing Technology,* vol. 87, pp. 266-276, Mar 15 1999.

[5]   A. M. Goijaerts, Y. W. Stegeman, L. E. Govaert, D. Brokken, W. A. M. Brekelmans, and F. P. T. Baaijens, "Can a new experimental and numerical study improve metal blanking?," *Journal of Materials Processing Technology,* vol. 103, pp. 44-50, Jun 1 2000.

[6]   A. M. Goijaerts, L. E. Govaert, and F. P. T. Baaijens, "Evaluation of ductile fracture models for different metals in blanking," *Journal of Materials Processing Technology,* vol. 110, pp. 312-323, Apr 2 2001.

[7]   A. M. Goijaerts, L. E. Govaert, and F. P. T. Baaijens, "Experimental and numerical investigation on the influence of process speed on the blanking process," *Journal of Manufacturing Science and Engineering-Transactions of the Asme,* vol. 124, pp. 416-419, May 2002.

[8]   S. Thipprakmas, M. Jin, and M. Murakawa, "Study on flanged shapes in fineblanked-hole flanging process (FB-hole flanging process) using finite element method (FEM)," *Journal of Materials Processing Technology,* vol. 192-193, pp. 128-133, 2007.

[9]   S. F. Golovashchenko and A. M. Ilinich, "Trimming of Advanced High Strength Steels," pp. 279-286, 2005.

[10]   S. F. Golovashchenko, "A study on trimming of aluminum autobody sheet and development of a new robust process eliminating burrs and slivers," *International Journal of Mechanical Sciences,* vol. 48, pp. 1384-1400, 2006/12/01/ 2006.

[11]   X. H. Hu, X. Sun, and S. F. Golovashchenko, "Predicting tensile stretchability of trimmed AA6111-T4 sheets," *Computational Materials Science,* vol. 85, pp. 409-419, 2014/04/01/ 2014.

[12]   Q. B. Le, J. A. deVries, S. F. Golovashchenko, and J. J. F. Bonnen, "Analysis of sheared edge formability of aluminum," *Journal of Materials Processing Technology,* vol. 214, pp. 876-891, 2014/04/01/ 2014.

[13]   N. Wang and S. F. Golovashchenko, "Mechanism of fracture of aluminum blanks subjected to stretching along the sheared edge," *Journal of Materials Processing Technology,* vol. 233, pp. 142-160, 2016/07/01/ 2016.

[14]   A. M. Ilinich, S. F. Golovashchenko, and L. M. Smith, "Material anisotropy and trimming method effects on total elongation in DP500 sheet steel," *Journal of Materials Processing Technology,* vol. 211, pp. 441-449, 2011/03/01/ 2011.

[15]   X. H. Hu, X. Sun, and S. F. Golovashchenko, "An integrated finite element-based simulation framework: From hole piercing to hole expansion," *Finite Elements in Analysis and Design,* vol. 109, pp. 1-13, 2016/02/01/ 2016.

[16]   S. Golovashchenko, W. Zhou, S. Nasheralahkami, and N. Wang, "Trimming and Sheared Edge Stretchability of Light Weight Sheet Metal Blanks," *Procedia Engineering,* vol. 207, pp. 1552-1557, 2017/01/01/ 2017.

[17]   S. Nasheralahkami, S. Golovashchenko, S. Dawson, and R. Sohmshetty, "Analysis of Tool Wear for Trimming of DP980 Sheet Metal Blanks 2017-01-0302," *SAE Int. J. Engines,* vol. 10, pp. 233-238, 2017.

[18]   X. Wu, H. Bahmanpour, and K. Schmid, "Characterization of mechanically sheared edges of dual phase steels," *Journal of Materials Processing Technology,* vol. 212, pp. 1209-1224, 2012/06/01/ 2012.

[19]   A. G. Rehorn, J. Jiang, P. E. Orban, and E. V. Bordatchev, "Erratum to: State-of-the-art methods and results in tool condition monitoring: a review," *The International Journal of Advanced Manufacturing Technology,* vol. 26, pp. 942–942, 2005.

[20]   G. Buzzichelli and E. Anelli, "Present status and perspectives of European research in the field of advanced structural steels," *Isij International,* vol. 42, pp. 1354-1363, 2002.

[21]   Keyence.com, "User manual, Color 3D Laser Scanning Microscope, VK-8700/VK9700 Generation II.," *http://www.keyence.com/products/microscope/laser-microscope/vk-8700_9700_generationii/index.jsp*.