Study of deformation and fracture of high strength steel sheet during conventional and robust trimming by conducting partial trimming tests

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Abstract
An instrumented trimming press equipped with D2 grade steel die inserts with sharp edges was used to conduct trimming tests on DP980 sheets with clearances of 10%, 20%, and 30% of the sheet thickness. Trimming tests were conducted either with or without a support pad placed under the scrap piece and the trimming force was measured as a function of penetration distance of the upper die. The progression of plastic deformation and fracture processes that occurred in the shear affected zone (SAZ) of DP980 were observed on the polished cross-sections of the sheet by performing partial trimming tests. During conventional trimming with 10% clearance, cracks propagated simultaneously from the upper and lower surfaces of the sheet toward each other. However, when the clearance was increased to 30%, the main crack was initiated from the upper surface and propagated toward the lower surface resulting in the formation of a tensile-type burr. At 30% clearance, the trimming test conducted with a support pad prevented bending of the scrap piece, resulting in a uniform damage distribution within the SAZ. Thus, an improved sheared edge quality is achieved at larger clearances.

Keywords DP980 sheet · Partial trimming tests · Shear affected zone · Fracture mechanisms

1 Introduction
Advanced high strength steel (AHSS) sheets used in automotive body-in-white parts contribute to weight reduction of the vehicle and improve its crashworthiness [1]. The microstructure of dual phase (DP) steels, the most common grade of AHSS, consists of martensite islands embedded in a ferritic matrix. This microstructure provides high specific strength while maintaining sufficient ductility [2, 3]. Trimming operations are an integral part of the manufacturing of automotive enclosures and structural parts. In conventional trimming, there is little or no constraint on the scrap-side of the workpiece, and therefore the trim dies may apply a significant bending moment to the edge of the part at the beginning of the trimming operation; hence, conventional trimming can be considered as an asymmetrical shearing operation [4, 5]. During the penetration of the trim die into the sheet, a rollover zone is formed as a result of plastic deformation at the sheared edge. A burnish zone, with a smoother surface, and a width that depends on the depth of penetration of the upper insert [5] is formed below the rollover zone. Immediately below the burnish zone, a fracture zone is generated. Finally, a burr is usually formed at the exit side of the sheared sheet metal part; the height of the burr depends on trimming parameters such as the clearance, trimming angle, and tool radius [5–8] and on the mechanical properties of the sheet material.

Hamblen et al. [9] measured the blanking force and tool wear for clearances between 5 and 20% on a carbon steel (0.6% C), and suggested that a 10% clearance would minimize the shearing force and the tool wear. Hilditch and Hodgson [10] conducted trimming experiments on low-carbon steels and concluded that both the rollover and the burr height would increase at greater clearances, and that the depth of the rollover depended on both the clearance and the work-hardening behavior of the sheet material. Choi et al. [5] studied the effects of the clearance and of the trimming angle (i.e., the angle of the sheet relative to the trimming direction) on the sheared edge characteristics of the sheared DP980.
They found that the maximum trimming load decreased with an increase in the clearance, and that a negative trimming angle improved the edge quality and decreased the trimming load. Le et al. [11] investigated the effects of cutting clearance on longitudinal, transverse, and diagonal orientations of the trim line relative to the rolling direction on a broadly used aluminum alloy, 6111-T4. They found that for all the sheet orientations, an increase in the cutting clearance resulted in a substantial reduction in material stretchability along the sheared edge. By analysing the effect of the cutting angle on the stretchability, they observed that higher elongations occurred at cutting angles of 10° and 20° for the typical 10% clearance, compared to orthogonal (90°) cutting with an identical clearance.

Burrs formed during trimming decrease the edge quality of stamped parts as they are the sources of potential cracks in subsequent forming operations. The formation of a burr is usually related to the fracture mechanisms operating during shearing process. Hilditch and Hodgson [10] carried out trimming experiments on steel, aluminum, and magnesium alloys and found that different burr formation mechanisms were exhibited in the different classes of alloys. Rapid crack propagation and part-scrap separation occurred at a low punch penetration in both aluminum and magnesium alloy samples resulting in a curved fracture profile and “angle shaped” burr. Slow crack propagation occurred after crack initiation in the steel samples, and subsequently, part-scrap separation occurred at a significantly higher punch penetration, resulting in a straight fracture profile and a “vee shaped” burr. Choi et al. [5] found that an increase in the clearance (above 15.6%) caused an increase in the bending moment, which led to the crack initiating from the upper surface of the sheet, and a tensile hydrostatic stress generated in the sheared zone resulted in a tensile-type burr.

The clamping force that is applied to grip the sheet metal just prior to trimming has a significant impact on the sheared edge geometry. Thorough clamping of the sheet near the trim line is critical in order to reduce the strains and distortions of the sheared edges. Ideally, cracks will start from locations adjacent to each tool radius and meet near the mid-thickness of the sheet [12]. Gustafsson et al. [13] studied the effect of clamping force in shearing of steel sheets and found that the force required to shear the sheet increased if an additional clamping force was introduced from the bottom of the scrap side. However, published studies on robust trimming of high-strength steel sheets using sharp trim edges are difficult to find. Nevertheless, trimming high-strength steel sheet metal parts is a common, but critical, operation in the manufacture of lightweight automotive body parts. And while laser trimming is gradually gaining prominence, traditional mechanical trimming is still preferred because of decades of accumulated knowhow and greater cost effectiveness. Therefore, the optimization of the trimming process is very useful to autobody part manufacturers. This requires a comprehensive and systematic study of the process-dependent, deformation and fracture mechanisms that occur in the sheared parts.

The objective of this work was to observe the progression of damage processes that occur within the shear affected zone, SAZ of DP980 sheets subjected to both conventional and robust trimming tests using various clearances. This was achieved by conducting a series of partial trimming tests using a metallographic polishing method where the initiation of fracture and progression of crack propagation could be observed for different upper die penetration distances. Partial and full trimming tests were conducted by using a laboratory scale trimming press which allowed to monitor the variation of the trimming forces as a function of the depth of die penetration. The SEM observations made on pre-polished partially trimmed cross-sections revealed the differences in the crack propagation and deformation processes in SAZ for trimming tests performed with and without the scrap support at different clearances.

2 Experimental work

2.1 Description of trimming tests

A DP980 steel sheet with a yield strength of 775 MPa and a tensile strength of 999 MPa [14] was used. The microstructure of DP980 steel sheet consisted of martensite plates (70 area %) distributed uniformly within the ferrite (α-Fe) matrix [15]. The trimming experiments were performed by feeding a 10-mm wide galvanized DP980 sheet with a thickness of 1.0 mm into the press. An instrumented trimming press was used with an upper die speed of 50 mm/s, which approximates the trimming process typically used in the automotive industry. Schematic drawings of the trim die setup are shown in Fig. 1a, b. The upper and lower trimming blades are bolted to the die shoe. The clearance between them was adjusted to be uniform along the shearing line with an accuracy of about ± 0.01 mm. The clearance was adjusted by using shims positioned between the lower die block and the lower trimming blade. To prevent the clearance gap changing over time, a four-pillar die shoe was used to ensure the precision and stability of the trimming process. A load cell (FUTEK LCM375) with a 5-ton range was installed in the upper die block directly above the upper trim die insert and was used to measure the trimming force. A laser displacement sensor (Keyence LK-G Series) with an accuracy of ± 0.02% was installed on an isolated tripod beside the trimming press to measure the displacement of the upper die (Fig. 1a). A National Instruments Data acquisition system (DAQ-9178) was employed to record the force and displacement signals for post-processing of the experimental data.
The trim dies were made from uncoated AISI D2 high-carbon, high chromium cold work steel containing a bands of rounded primary carbides [15]. The lower and upper die inserts had hardness values of HRC $61 \pm 1$ and HRC $58 \pm 1$, respectively, reached by using the heat treatment methods specified by the automotive manufacturers. Both upper and lower trim dies had sharp trimming edges at the start of the trimming tests and a zero-degree trimming angle was maintained throughout the tests. The clearance was controlled and adjusted to 10%, 20%, and 30%. Conventional trimming tests shown in Fig. 1c were conducted at a rate of 30 strokes/min. A stressed spring ($k = 17$ lbs/mm) support pad placed under the scrap piece allowed to conduct “robust trimming” as shown in Fig. 1b, d under the same conditions as the conventional trimming.

### 2.2 Partial trimming tests

In order to observe the progression of deformation and fracture processes that occurred within the SAZ, partial trimming tests were conducted. The displacements of the upper die that were recorded by the laser sensor and used to determine the instantaneous penetration of the upper die into the sheet being trimmed. The trimming process was interrupted after a certain upper die penetration distance by a pneumatic control system that could stop the press cycle. In this way, the damage features within the SAZ were captured at different successive stages of a trimming of DP980 sheet. An important aspect of this method was the sample preparation for observations. Instead of the traditional way of analyzing the cross-section of sheet specimens by mounting, polishing, and etching.

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**Fig. 1** Trimming die set up used to study progression of damage during trimming of DP980 sheets: (a) general view of the setup, with the laser sensor used for displacement measurements, (b) transparent section view of the upper and lower blocks showing the location of the load cell, (c) schematic of the conventional trimming process, (d) schematic of the trimming process with scrap support (robust trimming). DP980 sheets are fed in the X-direction. The trimming direction and location of trim edge are also identified.
after the trimming test, the cross-sectioned plane of the undeformed sheet sample perpendicular to the trimming direction was polished (without epoxy mounting) prior to the trimming process. The polished cross-section of the partially trimmed specimen was etched for 8–12 s with 4% Nital, washed in water, and dried with compressed air. By avoiding post grinding and polishing damage features on the partially trimmed specimen cross-section were maintained. Therefore, metallographic preparation prior to trimming revealed evidence of plastic deformation and damage features within the SAZ during subsequent microscopic observations of the partially trimmed sheet cross-sections.

3 Results and discussion

3.1 Characteristics of load–displacement curves

A typical trimming force and upper die penetration curve for 10% clearance is shown in Fig. 2a. Qualitatively, five successive stages can be distinguished on a force–displacement curve as indicated in Fig. 2a. At the beginning of stage I, the upper trim die comes into contact with the sheet metal. The sheet is then subjected to elastic deformation and bending in stage II. When the magnitude of the compressive stress exceeds the yield strength of the sheet, plastic deformation occurs which is delineated as stage III, corresponding to the formation of the rollover and burnish zones that are shown in Fig. 2b. Cracks initiate and propagate within the SAZ, leading to the final fracture which occurs in stage IV. The sudden drop in force experienced in stage IV is accompanied by the separation of the scrap piece from the strip and the formation of the fracture surface and the burr. Finally, the reverse motion of the press causes elastic vibrations in the upper trim die, as seen in stage V.

3.1.1 Effect of clearance on load–displacement curves in conventional trimming

The typical curves displaying variations of the applied loads with the penetration of the upper die into the sheet during trimming for three different clearances are shown in Fig. 3a. It can be observed that the depth of penetration of the upper die at the onset of separation increased with increasing the clearance. Namely, an increase from 0.603 to 0.996 mm occurred as the clearance increased from 10 to 30%. Meanwhile, the peak load decreased from 4677.2 N to 4135.6 N as the clearance increased from 10 to 30%. At the lower clearance of 10%, the deflection of the sheet metal between the upper and lower trim dies was more difficult. Therefore, the initial increase in the trimming force was steeper (stage II) with a high slope of $2.72 \times 10^4$ N/mm. However, as the clearance increased, the constraints on the unsupported sheet in the gap decreased resulting in a force-penetration curve with a lower slope of $1.67 \times 10^4$ N/mm at 20% clearance, and $1.37 \times 10^4$ N/mm at 30% clearance. The increase in the clearance also affected the length of the deformed

Fig. 2 (a) A typical trimming load versus the die penetration curve. See the text for the description of the regions identified as I-V. (b) Different features of sheared edge profile labeled on an optical microscopy image (magnification ×50).
ligament (rollover and burnish zones) prior to fracture as the upper die penetration at the onset of fracture increased from 0.535 mm at 10% clearance to 0.889 mm at 30% clearance. This was due to the changes in the deformation and fracture processes with the clearance, as will be further discussed in Sect. 3.3. The amount of work done per trimming stroke with respect to upper die penetration was calculated by integrating the load vs. penetration curve for each clearance and plotted in Fig. 3b. The trimming work done increased as the clearance increased. The elastic and plastic components of the total work can also be distinguished from the graphs in Fig. 3a, b. The elastic work increased from 0.30 N.m at 10% clearance to 0.51 N.m at 30% clearance, and the plastic work increased from 1.52 N.m at 10% clearance to 2.28 N.m at 30% clearance. The main results arising from analysis of the force–displacement curves obtained at different clearances are summarized in Table 1, where the values shown are the averages of three different tests.

3.1.2 Effect of clearance on load–displacement curve-under robust trimming

For the robust trimming process, the variations of loads with the upper die penetration for different clearances are shown in Fig. 4a and total amounts of work done are shown in Fig. 4b. The main outputs obtained from the load vs. penetration curves are summarized in Table 2 for three different clearance percentages. The peak load decreased from 5928 to 5350 N as the clearance increased from 10 to 30%. Upper die penetration at the onset of sheet separation increased from 0.780 to 0.927 mm as the clearance increased from 10 to 30%. During robust trimming the clearance had less effect on trimming work done which increased from 3.14 N·m to 3.75 N·m when clearance increased from 10 to 30%. The introduction of the support pad under the scrap piece reduced the deflection of the scrap piece due to the increased clearance, and consequently the slope of the elastic stage (stage II) remained almost constant with changing the clearance. Namely a decrease from $2.93 \times 10^4$ N/mm at 10% clearance to $2.61 \times 10^4$ N/mm at 30% clearance was observed.

When compared with the conventional trimming process, a more rapid increase of trimming force was noticeable in stage II. The slopes obtained under robust trimming were greater than those for conventional trimming (Fig. 4a). In addition, the spring pad under the scrap piece made continuous contact with the upper die which allowed longer

| Clear ance | Peak load (N) | Upper die penetration at the peak load (mm) | Upper die penetration at the onset of fracture (mm) | Upper die penetration at the onset of sheet separation (mm) | Total work done during trimming (N·m) |
|-----------|---------------|---------------------------------------------|----------------------------------------------------|----------------------------------------------------------|---------------------------------------|
| 10%       | 4677 ± 19     | 0.321 ± 0.002                               | 0.535 ± 0.004                                      | 0.603 ± 0.002                                            | 1.82 ± 0.12                           |
| 20%       | 4371 ± 20     | 0.465 ± 0.001                               | 0.712 ± 0.003                                      | 0.766 ± 0.002                                            | 2.29 ± 0.15                           |
| 30%       | 4135 ± 18     | 0.544 ± 0.003                               | 0.889 ± 0.003                                      | 0.996 ± 0.001                                            | 2.79 ± 0.11                           |
displacement under higher peak loads (Fig. 4a) compared with conventional trimming (Fig. 3a). The peak load and the total work done measured at the selected clearances (10%, 20%, and 30%) are greater than those in conventional trimming (as plotted in Fig. 5a, d). At high clearances the onset of fracture was delayed for conventional trimming; the upper die penetrations at the onset of fracture for robust trimming (0.685 mm at 20% and 0.788 mm at 30% clearance) were lower than those of conventional trimming (0.712 mm at 20% and 0.889 mm at 30% clearance). However, for 10% clearance the die penetrations at the onset of fracture were comparable for conventional and robust trimming (Fig. 5c). This observation reveals that the introduction of the support pad under the scrap piece expedited the fracture of the sheet at clearances of 20% and 30% compared with conventional trimming and this observation will be further discussed in Sect. 3.4.

3.2 Effect of clearance and support force on sheared edge quality

Compared to the conventional process, robust trimming had the advantage of producing a smaller burr. Cross-sectional profiles of trimmed and scrap pieces obtained for different clearances using conventional and robust trimming tests are shown in Fig. 6a–f. It can be seen that conventional trimming at 10% clearance provided a sheared edge with no apparent burr. At 20% clearance, a small burr was observed on the conventionally trimmed part. For a clearance of 30%, the burr became significantly larger. For robust trimming, no burr was observed at 10% clearance, while at 30%, a small burr was visible. It should be noted that bending of the edge of the scrap (marked by the red dashed rectangles in Fig. 6a–c) was observed for the conventional trimming for all the clearances. The bending of the scrap piece resulted in additional tension near the upper trim edge and additional compression around the lower trim edge. However, no bending of the scrap piece was observed when the scrap support pad was used, (as marked by the blue dashed rectangles in Fig. 6d–f), and both the trimmed part and the scrap piece showed symmetrical profiles. Accordingly, the presence of a scrap support pad clearly affected the crack initiation process and crack propagation path and the formation as will be explained in Sect. 3.3.

Table 2 Summary of main results obtained from the load vs. penetration curves for robust trimming conducted at three clearance percentages. The values shown are the averages of three tests for each clearance shown

| Clearance | Peak load (N) | Upper die penetration at peak load (mm) | Upper die penetration at the onset of fracture (mm) | Upper die penetration at the onset of sheet separation (mm) | Total work done during trimming (N.m) |
|-----------|--------------|----------------------------------------|-----------------------------------------------|-------------------------------------------------|--------------------------------------|
| 10%       | 5928 ± 26    | 0.361 ± 0.003                           | 0.529 ± 0.004                                  | 0.780 ± 0.003                                     | 3.14 ± 0.15                          |
| 20%       | 5516 ± 25    | 0.566 ± 0.003                           | 0.685 ± 0.003                                  | 0.846 ± 0.003                                     | 3.54 ± 0.14                          |
| 30%       | 5350 ± 21    | 0.665 ± 0.002                           | 0.788 ± 0.002                                  | 0.927 ± 0.002                                     | 3.75 ± 0.11                          |
Figure 7a summarizes the characteristic features of the sheared edge of DP980 for conventional trimming. The height of rollover region increased with increasing the clearance due to the increase of the bending of the sheet at the trim edge. The height of burnish also increased as the clearance increased. In general, the height of the burnish zone has been observed to increase with increasing the clearance. It was indicated that for low clearance trimming a higher hydrostatic pressure was imposed in the SAZ, which improves the ductility of the sheet material [16]. It was also observed that the length of the fracture zone decreased at high clearances. For robust trimming (as shown in Fig. 7b), similar trends were observed compared with the conventional trimming, however, the introduction of a support pad reduced the burr height by 4.0, 4.6 and 16.3 times at 10%, 20%, and 30% clearance, respectively. It should be noted that the height of the burnish zone at 20% and 30% clearances was less than that of the corresponding clearances under conventional trimming. Thus, the height of the fracture zone decreased when the support pad was used, as indicated by Fig. 5c.

3.3 Effect of clearance on crack initiation and propagation

In order to investigate the effect of clearance on the fracture and burr formation processes during conventional and robust trimming, partial trimming tests were conducted. Figure 8 shows the cross-section of a sample subjected to partial shearing in conventional trimming with a 10% clearance. The trimming test during the first cycle was interrupted when the upper trim edge reached a penetration depth (P) of 20% of the sheet thickness (t). At this stage, the crack was more developed at the upper surface and less at the lower surface. Cracks (identified inside the red and blue dashed rectangles...
in Fig. 8a) were formed and these cracks are shown at higher magnification in Fig. 8b, c were found to have initiated from the upper and lower surfaces of the sheet.

Shearing induced plastic deformation in the SAZ was also apparent. Some horizontal cracks branching off the main crack can be observed in the region close to the upper surface (Fig. 8b). It can also be seen that a band of martensite islands, which was originally parallel to the rolling plane (normal to the shear plane) exhibited a tendency to bend as shown in Fig. 8b to accommodate the local strains, in the trimming direction. Also, decohesion occurred at the interface between the hard martensite and the soft ferrite matrix as evidenced by small horizontal cracks observed around the martensite islands. The initially polished cross-sectional surface (indicated within the white dashed rectangle in Fig. 8a) was scanned with an optical profilometer and a 3D image of the surface topography is shown in Fig. 8d. Since the
Fig. 8 SEM images of cross-sections of partially sheared (to 20% of thickness $t$, $P=20\%t$) in conventional trimming with 10% clearance: (a) low magnification cross-sectional view of shear induced plastic deformation zone, (b) crack initiation and propagation from the top surface of the sheet. The arrows indicate the displaced martensite islands in the trimming direction, (c) crack initiation and propagation from the lower surface of the sheet near the lower trim edge, (d) cross-sectional surface topography of the area within the area shown by the white dashed rectangle in (a). The sheet material near the upper trim edge was subjected to large plastic deformation. The damage pattern was symmetrical and exhibited similar levels of plastic deformation in the vicinity of the upper and lower trim edges.

Fig. 9 SEM images of cross-sections of partially sheared (to 30% of thickness, $P=30\%t$) in conventional trimming with 10% clearance: (a) low magnification cross-sectional view of shear induced plastic deformation zone, (b) crack propagation from the top surface of the sheet. The arrows indicate the displaced martensite islands in the trimming direction showing development of larger shear strains compared to 20% die penetration, (c) crack propagation from the lower surface of the sheet near the lower trim edge, (d) cross-sectional surface topography of the area within the white dashed rectangle in (a).
metallographic preparation has been completed prior to the partial trimming process, the surface topography can be used as an indicator to identify the level of plastic deformation within the SAZ. It is evident that the sheet material near the upper sharp trim edge was subjected to large plastic deformation. Moreover, the damage distribution was practically symmetrical. Qualitatively, similar levels of plastic deformation occurred in the vicinity of the upper and lower trim edges.

Figure 9 shows the damage on the cross-section of the partially trimmed sample observed at a die penetration depth of 30% sheet thickness in conventional trimming with a 10% clearance. At this further stage of partial shearing process, the cracks that were previously initiated from the upper and lower surfaces of the sheet (identified by the red and blue dashed rectangles in Fig. 9a) are seen to continue to propagate with increasing penetration as shown at higher magnification.

![Image](image_url)

**Fig. 10** SEM images of cross-sections of partially sheared (to 38% of thickness, P = 38%t) in conventional trimming with 30% clearance: (a) low magnification cross-sectional view of shear induced plastic deformation zone, (b) crack initiation and propagation from the top surface of the sheet, (c) no evidence of crack initiation from the lower surface of the sheet near the lower trim edge, (d) cross-sectional surface topography of the area within the white dashed rectangle in (a). At 30% clearance, the damage pattern was asymmetrical, showing different levels of plastic deformation in the areas near the upper and lower trim edges.
The displacements near the mid-plane of the trimmed sheet increased, as revealed by deformed matrix around the band of the martensite islands, as shown in Fig. 9b. The cracks that were likely initiated at the martensite-ferrite interfaces have increased in number and length (Fig. 9b). The damage distribution (Fig. 9d) remains nearly symmetrical, showing similar levels of plastic deformation in the vicinity of the upper and lower trim edges. Finally, it can be pointed out that the crack that was initiated from the upper corner of the sheet has propagated to a longer distance compared to the crack originated at the lower corner.

Figure 10 shows the partial shearing of the sheet when the die penetrated to 38% of the sheet thickness in conventional trimming. But this time a clearance of 30% was used. At this higher-level clearance, a crack (identified inside the red dashed rectangle in Fig. 10a and shown at larger magnification in Fig. 10b) initiated from the upper surface of the sheet at the location of contact with the upper trim edge, but no crack was visible at the lower sheet surface (Fig. 10c). The surface topography of this cross-section taken from the region indicated by the white dashed rectangle in Fig. 10a was examined by 3D profilometer and shown in Fig. 10d. The sheet surface around the edge of the upper die was subjected to larger (plane stress) plastic deformation than that near the lower die edge.

Figure 11 shows the cross-section of sample subjected to partial shearing at a die penetration of 45% in conventional trimming with a 30% clearance. At this more advanced stage of the trimming stroke, the crack (located in the red dashed rectangle in Fig. 11a and shown at higher magnification in Fig. 11b) that initiated from the upper surface of the sheet continued to propagate, while no crack has formed from the lower surface. The martensite band experienced a larger amount of displacement accompanied by the formation of many more small cracks (Fig. 11b). The plastic deformation zone (Fig. 11d) became increasingly localized to the region near the upper contact surface. As at higher clearances (i.e., 30%), bending of the scrap piece would create additional tensile stresses near the upper die edge and higher compression near the lower die edge, thus development of cracks at the upper trim edge are more likely compared to those at compressed area near the lower trim edge.
Effect of support force on crack initiation and propagation

The use of the support pad was shown to minimize the bending of the scrap piece during trimming, as pointed out in Sect. 3.2 and consequently resulted in different crack formation and growth patterns. Figure 12 shows the evolution of the deformation and fracture patterns within the SAZ of the cross-sectional profile of DP980 sheet at three different stages of a trimming stroke with a support pad and a 30% clearance. At an upper die penetration of 20% of sheet thickness, a crack initiated from the lower surface of the sheet as

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![Figure 12](image)

**Fig. 12** Evolution of the cross-sectional profiles of DP980 sheet subject to robust trimming with a 30% clearance and at increasing upper die penetration distances: (a) $P = 20\% \ t$, (b) $P = 30\% \ t$, (c) $P = 38\% \ t$, (d)–(f) cross-sectional surface topographies of the area within the white dashed rectangles in Fig. 12 (a)–(c).

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3.4 Effect of support force on crack initiation and propagation

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indicated by the blue rectangle in Fig. 12a, whereas no crack was observed at the upper surface near the upper trim edge. When the die penetration was increased to 30% of the sheet thickness, it can be seen that the crack at the lower edge continued to propagate upwards through the sheet, as indicated by the blue rectangle in Fig. 12b. Meanwhile, a microcrack initiated from the top surface of the sheet near the upper trim edge as identified by the red rectangle in Fig. 12b. When the penetration of the upper die increased to 38% of the sheet thickness, the upper and lower cracks continued to propagate toward each other and expected to meet in the mid-section of the SAZ. The plastic deformation zone (Fig. 12d–f) had an almost symmetrical pattern localized both at the upper and lower sheet edges except that the area near the lower edge was subjected to a slightly greater plastic deformation. This observation is consistent with the crack initiating from the lower trim edge earlier than that from the upper trim edge.

The use of a support pad affected the burr formation, as shown in Fig. 13. Figure 13a is an optical microscopy image of the profile of the DP980 sheet at the onset of the separation of the scrap piece during conventional trimming with a 10% clearance. Since the crack initiated from the lower surface of the sheet, the burr was of negligible size. Figure 13b shows the optical image of the sheet at the onset of separation in conventional trimming with a 30% clearance. The cracks started near upper trim edge and then propagated downward into the sheet metal until complete separation occurred. The bending of the scrap altered the plastic deformation and damage patterns. As the bending moment created a tensile stress near the upper surface and a compressive stress near the lower surface a tensile-type burr was formed. Figure 13c shows the sheet profile at the onset of separation in robust trimming with a 30% clearance. The mechanism of burr formation in this trimming configuration was different from that in conventional trimming. Since the bending of the scrap was prevented, the deformation and damage patterns remained symmetrical with respect to the path of crack propagation. The cracks started simultaneously from both the lower and upper trim edges and met in the mid-section of the SAZ. Once the shearing was complete, practically no burr was formed during the robust trimming of DP980 sheet with a 30% clearance.

The partial shearing tests with the presence of a scrap support pad confirmed that the main crack was first initiated from the bottom surface of the sheet near the lower trim edge, and then this was followed by the initiation of a crack from the upper trim edge. This led to practically no burr at the sheared edge. In conventional trimming, the bending moment had a significant effect on the deformation, damage distribution and crack initiation, and the bending moment increased with increasing the clearance. The bending of the scrap piece in the absence of a support pad applied additional stretching (tension) near the upper surface and additional compression near the lower surface, and therefore the crack initiated from the upper surface.

4 Summary and conclusions

In this work, the development of characteristic features of the sheared edge of DP980 sheets were investigated by conducting trimming tests using D2 type steel dies with or without the use of a scrap support pad and recording the corresponding force displacement diagrams. The development of burnish and fracture zones was examined at different clearances. Details of the plastic deformation and crack formation processes were studied using partial trimming experiments on pre-polished cross-sections of the sheets. In this way, damage events at different stages of a trimming stroke were observed. These observations contributed to the interpretation of the sheared edge...
features formed during trimming of DP980 sheets. On the basis of experimental results and observations, the main conclusions arising from this work are as follows:

1. The peak value of the trimming force decreased with increasing the clearance during both conventional and robust trimming tests due to the increasing bending moment within the SAZ. The upper trim die penetration at the onset of fracture and the total work done in a single trimming operation increased with increasing the clearance.

2. In conventional trimming with a 10% clearance, the shearing process proceeded by cracks propagating from both the upper and lower surfaces toward each other and meeting near the mid-thickness of the sheet.

3. The shearing process in conventional trimming changed as the clearance was increased to 30%: the main crack initiated from the upper surface and propagated through to the lower surface, resulting in a large, tensile-type burr.

4. As robust trimming with a 30% clearance prevented the bending of the scrap piece, the cracks first initiated from the lower surface of the sheet, and subsequently, other cracks were initiated from the upper surface, resulting in a sheared edge with practically no burr formation.

**Author contribution** Zeyuan Cui designed and carried out experiments and data analysis and drafted original manuscript. Dr. Daniel Green and Dr. Ahmet T. Alpas, as the Principal Investigators, secured funding and resources for the research, provided critical discussions, reviewed and revised the manuscript.

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