

Evaluation of wear-induced plastic deformation at the trimmed edge of DP980 steel sheets

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Abstract. In order to increase the use of advanced high strength steel (AHSS) for automotive light-weighting, the significant trimming-induced wear damage that AHSS sheets cause to the trim dies should be reduced so as to decrease die maintenance costs and deterioration of the quality of sheared edge. In this research, the wear characteristics in the upper AISI D2 die inserts used for trimming DP980-type AHSS sheets and the wear-induced plastic deformation at the sheared edges of DP980 were studied. Observation of wear profiles at the edge of the upper trim die revealed that material abrasion was the main damage feature. The trimmed edge quality of DP980 deteriorated with the number of strokes, as indicated by an increase in burr width. Plastic strains near the surface of the sheared edge estimated using the displacements of martensite plates, increased from 2.9 at 2.5 μm below the trimmed edge after 40,000th cycles, to 55 after 80,000th cycles. Micro-hardness tests performed to estimate the local flow stresses in the shear affected zone (SAZ) indicated that the flow stress at a distance of 4.5 μm below the trimmed edge increased with the number of trimming cycles to 1.73 GPa in the 80,000th trimmed part.

1. Introduction

The constant demand for vehicle weight reduction and improved crashworthiness is leading to increased usage of advanced high strength steel (AHSS) in the automotive industry because of their higher strength-to-weight ratio. The micro-constituents of AHSS are ferrite and martensite and possibly retained austenite and bainite; controlled combinations of these phases lead to higher strength compared to mild steel while still maintaining sufficient ductility [1]. The formability of AHSS is affected by variations in the percentages and distributions of the constituent phases. Dual phase (DP) steels, one of the most important AHSS grades, which consists of islands of martensite distributed in a ferritic matrix, are extensively used in the production of the automotive components [1-3]. Due to their greater strength and limited formability, AHSS sheets tend to create added manufacturing challenges such as controlling the dimensional accuracy of parts, wear of the dies, and wear-induced damage on the finished product [4, 5]. One of the manufacturing processes that have become very costly is the trimming operation, a shearing process that removes excess material from stamped parts.

During trimming, the high strength of AHSS parts imparts high contact pressures and stresses on the trim dies resulting in severe wear and galling (a combination of adhesive and abrasive wear) at the sharp edge of the trim dies [6-8]. Bhattacharya et.al [9] studied the wear behaviour on the upper and lower dies between 20,000 - 230,000 trimming cycles and showed that the wear at the trim edge of the upper insert progressively increased by the accumulation of plastic deformation and by means of material



removal by abrasion. They observed a chipped edge percentage of 45% on the lower insert at the end of 230,000 cycles. Consequently, the service life of trim dies is significantly shortened due to the severe wear that occurs at the trim edge. Furthermore, the effect of tool wear on the part edge quality is significant. Tool wear has been shown to cause the formation of burrs at the sheared edge, which tend to negatively affect subsequent forming operations when sheared edge stretching occurs such as in flanging and hemming [10-12]. Bhattacharya et.al [13] observed micro-cracks at ferrite/martensite interfaces in DP980 steel sheets that were subjected to cyclic trimming and suggested that this resulted from an increase in the depth of the deformation zone next to the sheared edge, possibly due to trimming with a chipped and blunted die edge. Moreover, the stretchability of the sheared edges decreases because of the severe plastic deformation induced by tool wear in the trimming process.

Extensive research has been carried out to optimize trimmed edge quality. The precise clearance and alignment between upper and lower shearing edges is required to obtain acceptable part quality [14], So et.al [15] investigated the sheared edge characteristics of automotive components made with high-strength steel (aluminum–silicon pre-coated boron–manganese alloyed steel 22MnB5). They found that the roll-over and burr height increased with increasing clearance. Choi et al. [16] studied the effects of process variables such as the clearance and the inclined angle of the die on the sheared edge characteristics of trimmed DP980 and tool failure. Through the experimental work and finite element analyses, a negative inclined angle was recommended for trimming of DP980 to achieve a high quality trimmed edge by reducing the burr height. Li [17] performed an experimental investigation on the trimmed surface and burr with respect to the clearance, sharpness of the tool, and trim angle, which demonstrated the micro-mechanisms of deformation and fracture in the trimming of aluminum alloys: firstly, cracks initiate and propagate well ahead of the moving tool tip regardless of the blade sharpness, then, following the formation and propagation of the localization zone, the initiation, growth and coalescence of microvoids occur far ahead of the macroscopic crack tip. Ultimately, at the locations where the fracture mode switches from “shear” to “shear and tear”, large second-phase particles are present which trigger the unsteady progress of the fracture process. Golovashchenko [18] performed numerical simulations and experimental work to study the effect of trimming conditions (edge radius and the clearance) on the quality of the sheared edge. Burr height can be reduced by incorporating an elastic support pad under the moving upper die insert to minimize bending, and also by dulling the upper trim edge.

The investigation into wear-induced plastic deformation at the sheared edge of DP steels, and furthermore, the link between the characteristics of the sheared edge and the consequent edge cracking of DP steels were not addressed in the previous studies. In addition, die wear mechanisms are yet to be explored in detail. Therefore, there is a need for detailed surface and subsurface microstructural analysis of the trimmed edge in order to correlate the die wear mechanisms with trimmed part edge damage. In this work, the evolution of the wear profiles at the edge of the upper die insert used for industrial-scale trimming of DP980-type AHSS sheets was recorded using a non-contact optical interferometer technique. Characteristics of shear affect zone (SAZ) at the trimmed edge (wear induced) was studied by estimating the equivalent strain.

2. Experimental

A 127-mm-wide coil of uncoated DP980 steel with a thickness of 1.4 mm was used in the trimming experiments. The yield strength of the as-received DP980 steel was 775 MPa, the tensile strength being 999 MPa. The total elongation at fracture was measured as 14.1%. The trimming experiments were performed in an industrial-scale semi-production facility that consists of a decoiler, a straightener/feeder and a mechanical press at a rate of 30 strokes/min. Upper and lower trim edges were sharp at the start of the trimming operation. The clearance between the upper and lower trimming inserts was maintained at 10% of the thickness of DP980 sheets (0.14 mm), [9, 13]. The trimming dies were made from uncoated AISI D2 tool steel with a hardness of HRC 61±1. The dimensions of the upper insert were 132 mm × 63

mm \times 19 mm, while those for the lower insert were 132 mm \times 57 mm \times 19 mm. The cutting angle was maintained at zero degrees.

The trim edges of the die inserts were observed using a non-contact surface profilometer, WYKO NT-1100, by means of scanning white light interferometry in the vertical scanning interferometry (VSI) mode. In the VSI mode, there is an alternating combination of bright and dark patterns resulting from splitting of the beam where one part is reflected against a smooth reference surface and the other against the die inserts. After reflection the beams are recombined in the interferometer and the resulting interference pattern is photographed by a CCD camera and transferred to a personal computer for analysis. The data acquired from a measurement is then used for generating 3-dimensional and 2-dimensional profiles of the surface. The WYKO software, Vision32, enables calculations of various surface parameters, including surface roughness and profile height measurements.

As-received DP980 trimmed samples were sectioned by a low speed diamond saw, cold-mounted by means of EpoFixTM resin and hardener (Struers), ground and polished by using standard metallographic sample preparation steps for metallographic investigation of their plastic deformation characteristics.

3. Results and Discussion

3.1 Observation of wear damage at the trim edge of D2 inserts

A co-ordinate system was created for systematic investigation of the wear that occurred on the surfaces of the inserts. It was assumed that DP980 sheets were fed between the upper and lower inserts which is perpendicular to YZ plane and trimming occurred along the Z-direction, as shown in figure 1. The YZ plane (starting from the trim edge) of the upper inserts were observed in as-received condition and after trimming for a specific number of cycles as shown in figure 1. Figure 1(a) is a 3-dimensional optical profilometry image that was obtained prior to the trimming tests. The trim edge morphologies after 40,000, 50,000, 60,000, 70,000 and 80,000 cycles were observed and shown in figures 1(b), (c), (d), (e) and (f), respectively. It can be seen that the material at the trim edge was plastically deformed and wear occurred gradually with increasing damage by abrasion. Other than plastic deformation, non-uniform microchipping-type fracture was observed at the trimmed edge. An increase in the size chipped was observed after 60,000 cycles, as can be seen in figure 1(d). The total length of chipped regions observed at 10 different locations on the YZ plane at the vicinity of the trim edges of upper inserts (normalized by the trim length) was plotted as a function of the trim cycles in figure 1(g). The chipped edge percentage of 5% was observed for upper insert at the end of 80,000 trim cycles. In summary, material abrasion and chipping were identified as the main damage characteristic at the trim edge of the upper die inserts. The trimming-induced wear damage at the upper insert is expected to affect the features of the DP980 sheared edge that will be discussed in the following sections.

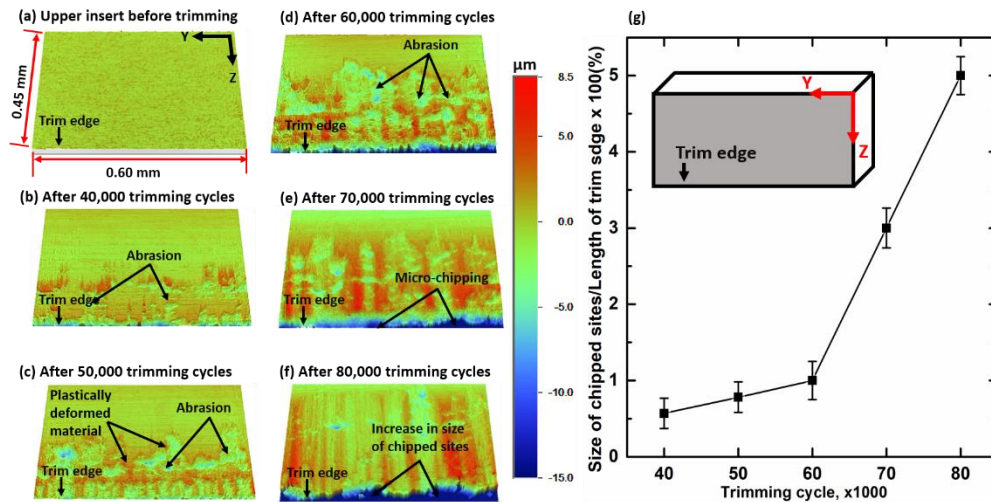


Figure 1. 3-dimensional optical profilometry images obtained from the YZ-plane of the upper insert (a) before trimming and after (b) 40,000, (c) 50,000, (d) 60,000, (e) 70,000 and (f) 80,000 cycles, (g) percentage of chipped die edge observed on the YZ plane in the vicinity of the trim edge of upper insert and normalized by the trim length, plotted as a function of the number of trimming cycles. The trimming clearance was 10% of the sheet thickness.

3.2 Measurement of Trimming-induced Equivalent Strain Gradients in DP980 sheets

The cross-sectional SEM images of a portion of the trimmed edge of DP980 sheets are shown in figure 2. It can be seen that the edge quality gradually decreased with the number of strokes from 40,000 (figure 2 (a)), 50,000 (figure 2 (b)), 70,000 (figure 2 (c)), and 80,000 (figure 2 (d)), which is evidenced by an increase in burr width which results from the accumulated tool wear on the upper insert. It can be seen that the martensite plates which were originally parallel to the rolling plane, tend to deform or bend downwards within the shear-affected zone (SAZ) as shown in figure 2 (a). The direction of the plastic flow at each point in the SAZ was represented by the orientation change of the deformed martensitic plates towards the trimming direction. In this work, the deformation angles (defined in Figure 2a) were measured by tracing the lines that followed the trajectories of the microstructural constituents that were subjected to plastic deformation during trimming. The selected lines are approximately located at a distance of 140 μm away from the bottom surface of the sheet (see in figure.2 (a)-(d)) which correspond to the fracture zone. The strain gradient could be calculated as discussed in the following section.

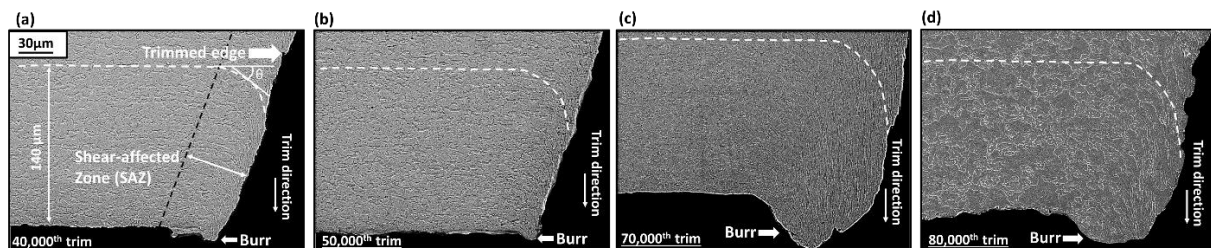


Figure 2. Cross-sectional SEM images of DP980 parts obtained after (a) 40,000, (b) 50,000, (c) 70,000 and (d) 80,000 trimming cycles. The samples were chemically etched using a solution consisting of 4 vol. % HNO_3 and 96 vol. % ethanol (Nital).

The generation of large strains in the SAZ was due to the deformation of the material layers adjacent to the die edge as a result of sliding contact at the interface between the part and the die. Cross-sectional SEM images of the subsurface region of the trimmed edge of DP980 sheets in figure 2 were investigated

to estimate the magnitude of the plastic strain gradients. The displaced martensite plates within the plastic flow field of ferrite phase (adjacent to the trimmed edge) were considered as the metallographic markers to measure the strain gradients. The estimation of plastic strain gradients in previous work was achieved by examining the metallographic features such as the displacement of second phase particles within plastic flow fields, and grain boundary displacement [19, 20]. The equivalent strain ($\bar{\varepsilon}$) of DP980 in the SAZ adjacent to trimmed edge was estimated using the following equation [21, 22]:

$$\bar{\varepsilon} = \frac{\sqrt{3}}{3} \tan \theta \quad (1)$$

where, θ is the deformation angle, as shown in figure 2(a). The variations in the equivalent strains after 40,000, 50,000, 60,000, 70,000, and 80,000 trimming cycles in the SAZ underneath the trimmed edge, calculated using Eq.1, are shown in figure 3. It can be seen that the amount of plastic strain close to the trimmed edge increased with the number of trimming cycles. For the part obtained after 40,000 trimming cycles, the equivalent strain was 2.9 at 2.5 μm from the trimmed edge, however, at the same depth, the strain was as high as 55.0 in the part obtained after 80,000 cycles. The strain decreased to a constant value of 0.45 at a distance larger than 35 μm , which also indicated the depth of the SAZ. A regression analysis indicated that the variation of $\bar{\varepsilon}$ after 40,000, 50,000, 60,000, 70,000, and 80,000 trimming cycles in the SAZ underneath the trimmed edge as a function of the distance from the trimmed edge, D , can be described as follows:

$$\bar{\varepsilon} = \bar{\varepsilon}_0 + \bar{\varepsilon}_s e^{(-D/t)} \quad (2)$$

where $\bar{\varepsilon}_0 = 0.45$ is the bulk strain as indicated previously, t is a fitted parameter for each number of trimming cycles based on the regression analysis. According to Eq. (2), the extrapolated plastic strain value ($\bar{\varepsilon}_s$) of the material adjacent to the trimmed edge after different numbers of trimming strokes was summarized in figure 3. It should be noticed that the positive proportional relation to the number of trimming cycles has also been observed on the estimated equivalent strain behaviour, which indicates that more plastic strain has been generated due to the accumulation of wear at the trim edge of the upper inserts, as shown in figure 1(g).

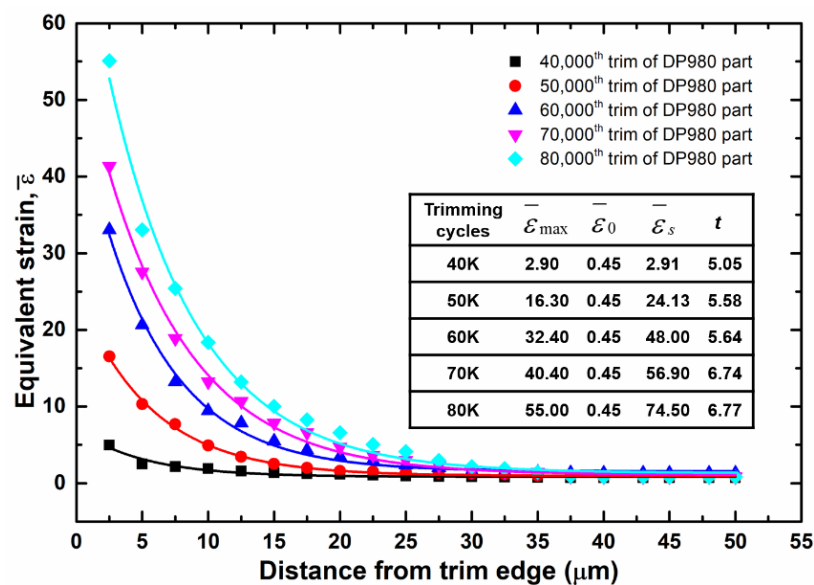


Figure 3. Variations in the equivalent strains after different numbers of trimming cycles in the SAZ underneath the trimmed edge.

3.3 Variation of Flow Stress of DP980 sheet with Depth beneath the trim edge

In order to estimate the local flow stresses in the SAZ just below the surface of the sheared edge, Vickers micro-hardness tests were performed, using a load of 25 gf and a dwell time of 15 s. The microhardness of the DP980 ahead of the SAZ was measured at regular intervals of 3 μm in parallel lines normal to the trimming direction. As the microhardness of the material in the SAZ underneath the trimming edge varies from one location to another, so does the flow strength of the material. Flow stress values were estimated from the measured microhardness values using the following relationship [23, 24].

$$\bar{\sigma} = \frac{H}{C} \quad (3)$$

where, σ is the equivalent flow stress, H is the hardness, and the constant factor, $C = 3.0$. Although this expression is an approximation, it has been commonly used to evaluate the strength of worn surfaces in materials in which plastic strains are large and/or work hardening is low [25, 26]. The variations in flow stress after 40,000, 50,000, 60,000, 70,000, and 80,000 trimming cycles in the SAZ underneath the trimmed edge, calculated using Eq. (3), are shown in figure 4. Each point represents an average of at least three measurements made at the same depth with standard deviation less than 20% of the mean. It can be seen that the flow stress close to the trimmed edge increased with the number of trimming cycles. For the part obtained after 40,000 trimming cycles, the flow stress was 1.30 GPa at a distance of 4.5 μm below the trimmed edge, however, at the same depth, the flow stress was as high as 1.73 GPa in the part obtained after 80,000 cycles. The flow stress decreased to a constant value of $\bar{\sigma}_o = 0.99$ GPa at a distance larger than 35 μm (depth of the SAZ).

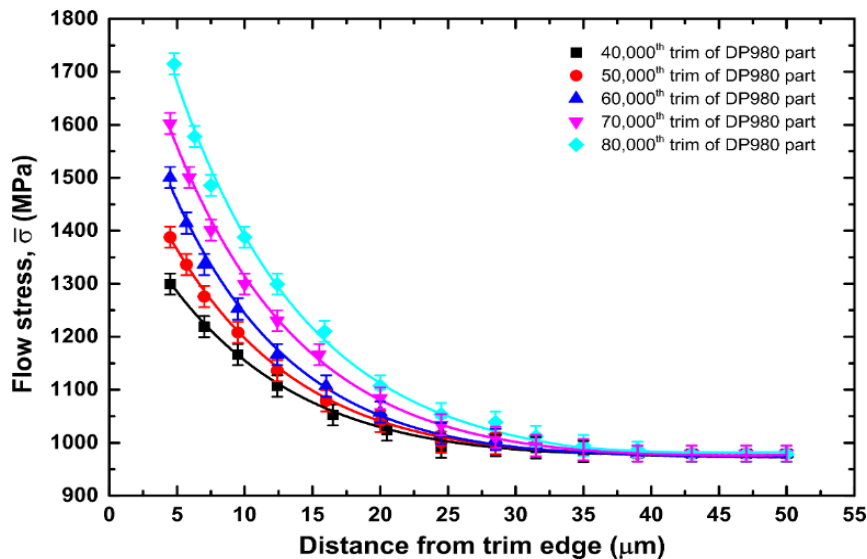


Figure 4. Variations in the flow stress after different numbers of trimming cycles in the SAZ underneath the trimmed edge.

4. Conclusions

In this work, DP980 steel sheets having a thickness of 1.4 mm were continuously trimmed at a rate of 30 strokes/min up to 80,000 cycles using die made from AISI D2 tool steel with a clearance of 10% of the thickness of the sheets. The progression of wear in the upper die used for trimming of AHSS sheets was observed using white-light optical interferometry techniques. Trimming-induced equivalent strain and flow stress were estimated after 40,000, 50,000, 60,000, 70,000, and 80,000 trimming cycles in the SAZ underneath the trimmed edge. The main conclusions arising from this work are as follows:

1. Material abrasion was identified as the main damage characteristic at the trim edge of the upper die inserts, and chipped edge percentage of 5% was observed for upper insert at the end of 80,000 trim cycles.
2. The morphology of the sheared edge of DP980 sheets depicted a depreciation of the edge quality with the number of strokes from 40,000 to 80,000, indicated by an increase in burr height resulting from the accumulated wear on the upper die insert.
3. The equivalent strain, estimated using displacements of the martensite plates within the SAZ underneath the trim edge, increased from 2.9 for the DP980 sheets obtained after 40,000 cycles, to 55 in the 80,000th trimmed part.
4. Local flow stress values were estimated from the microhardness measurements. The flow stress at a distance of 4.5 μm below the trimmed edge increased with the number of trimming cycles from 1.30 GPa for the part obtained after 40,000th trimming cycles, to 1.73 GPa in the 80,000th trimmed part.

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