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Review of the Shearing Process for Sheet Steels and Its Effect on Sheared-Edge Stretching

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Failure in sheared-edge stretching often limits the use of advanced high-strength steel sheets in automotive applications. The present study analyzes data in the literature from laboratory experiments on both the shearing process and the characteristics of sheared edges. Shearing produces a surface with regions of rollover, burnish, fracture, and burr. The effect of clearance and tensile strength on the shear face characteristics is quantified. Higher strength, lower ductility steels exhibit an increase in percent fracture region. The shearing process also creates a zone of deformation adjacent to the shear face called the shear-affected zone (SAZ). From an analysis of data in the literature, it is concluded that deformation in the SAZ is the dominant factor in controlling failure during sheared-edge stretching. The characteristics of the shear face are generally important for failures during sheared-edge stretching only as there is a correlation between the characteristics of the shear face and the characteristics of the SAZ. The effect of the shear burr on shear-edge stretching is also related to a correlation with the characteristics of the SAZ. In reviewing the literature, many shearing variables that could affect sheared-edge stretching limits are not identified or if identified, not quantified. It is likely that some of these variables could affect subsequent sheared-edge stretching limits.

Keywords piercing, shear-affected zone, sheared-edge stretching, shearing, trimming

1. Introduction

Advanced high-strength sheet steels (AHSS) exhibit strengths between 600 and 1000 MPa often with either a dual-phase or complex-phase microstructure. The use of AHSS with their excellent strength-to-mass ratio is an important contribution to reducing vehicle mass. However, failure in sheared-edge stretching during part production can significantly reduce the use of AHSS. Improvements in the understanding of shearing process and the behavior of the sheared edge during stretching can increase the use of AHSS in automotive applications. The present study analyzes data from the literature to examine the effect of the shearing process on the characteristics of the shear face and the adjacent material that extends into the bulk region of the sheet, called the shear-affected zone (SAZ).

Trimming is a shearing process that results in the separation of the sheet into two pieces. Trimming is used to produce cutouts on parts such as automotive side panels where the cutouts become window openings as well as the initial stage in producing flanges. Piercing is also a shearing process which produces one or more holes. In either process, there is a sheared edge (or shear face) and a SAZ on each of the separated pieces.

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Data from both trimming and piercing are used in this study, although only the trimming process is described in detail.

When a sheared edge is stretched, failure occurs at strains that are less than would be expected from a forming limit diagram (Ref 1). Sheared-edge stretching is normally evaluated in the laboratory by expanding a hole with a conical, flat, or spherical punch until a through thickness crack is produced in the sheet. The quantitative engineering measure of edge stretchability usually is percent hole-expansion, which is determined from the initial and final diameters of the hole. When the value for percent hole-expansion is converted to true strain, it can be used as a limit strain. The limit strain is used in FEA analysis to determine the occurrence of failure.

The features on the shear face are generally considered to have the primary effect on the edge stretchability of sheet steel. However, the analysis in this study indicates that deformation and resulting damage in the SAZ is the primary factor affecting limit strain in sheared-edge stretching.

While control of shearing operations in a stamping plant is limited by a variety of manufacturing constraints, it should still be possible to improve sheared-edge stretchability by using an improved understanding of the shearing process. A better understanding of shearing can also be used to improve the effectiveness of experimental work designed to understand the interactions between metallurgical and shearing variables that affect sheared-edge stretchability.

The next three sections of this paper describe: (1) the shearing process; (2) the shear face (sheared edge); and (3) the SAZ. In the first section, basics of the shearing process are described. In the second section, data from the literature are used to understand and quantify the features on the shear face. In the third section, the deformation conditions in the SAZ are described. The discussion that follows the third section provides the rational for concluding that the SAZ controls sheared-edge stretchability.

2. Overview of the Shearing Process

2.1 Tooling

Shearing in production operations is very rapid, with the deformation occurring in the time needed to penetrate the sheet thickness. As a result, the strain rate in production operations is very high with substantial deformational heat. Figure 1 shows the elements of the shearing process.

As Fig. 1(a) shows, the shear blade and die are offset by a gap that is described as the clearance. The clearance is usually a percentage of the sheet metal thickness. The shear blade and the die have radii, which typically increase with wear.

Figure 1(b) shows the trim angle, which represents the relationship between the motion of the shear blade and the plane of the sheet metal. The trim angle affects the geometry of the shearing process, but its effect on the process remains to be determined.

The forces due to shearing are distributed over some increment of press motion by the angle at which the top blade impacts the work material. The angle of the blade with respect to the sheet is the shear blade angle as shown in Fig. 1(c). The purpose of the blade angle is to reduce maximum press load due to shearing. When analyzing the effect of the blade angle, note that initiating shearing at one location while adjacent metal in the sheet is not being sheared could cause tensile stress components parallel to the free edge. Such stress components could affect the deformation pattern caused by the shearing process and the damage accumulation in the SAZ.

As Fig. 1(a) shows, a trim die typically includes a pad that applies a normal force to the sheet. This normal force is distributed over an area and produces pad pressure that restrains flow as the metal is pulled into the tooling gap where shearing occurs. The clearance and the radii on the shear blade and die also influence the flow of material into the shear gap. Pad location relative to the radius of the shear blade and lubrication are other variables that can affect deformation in the shear region. Pad pressure, pad location, and lubrication are generally not reported in studies in the literature.

From the preceding overview, it is clear that clearance, shear blade angle, trim angle, pad pressure, pad location, and lubrication could affect deformation in the shearing process and ultimately the limit strain for sheared-edge stretching. In general, clearance is the only reported process variable reported in the literature.

3. The Sheared Edge

Figure 2 provides a schematic of sheet steel during various stages in a shearing process. The initial contact between the tool and the sheet causes deformation in the sheet that is described as rollover. The tool then makes an impression in the sheet that causes a burnished surface. Finally, fracture occurs across the remaining ligament of the sheet. A burr is observed at the end of the fracture region.

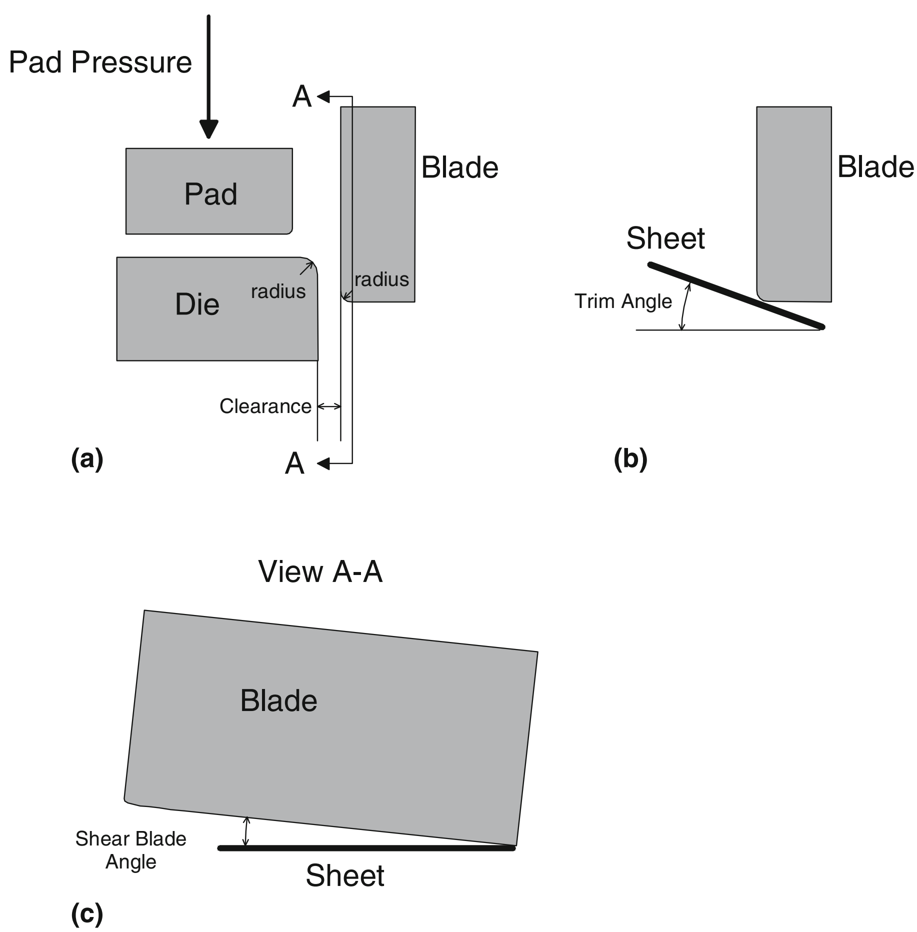

Fig. 1 Process variables in shearing. (a) Shear blade, die, pad and clearance, (b) trim angle, (c) shear blade angle

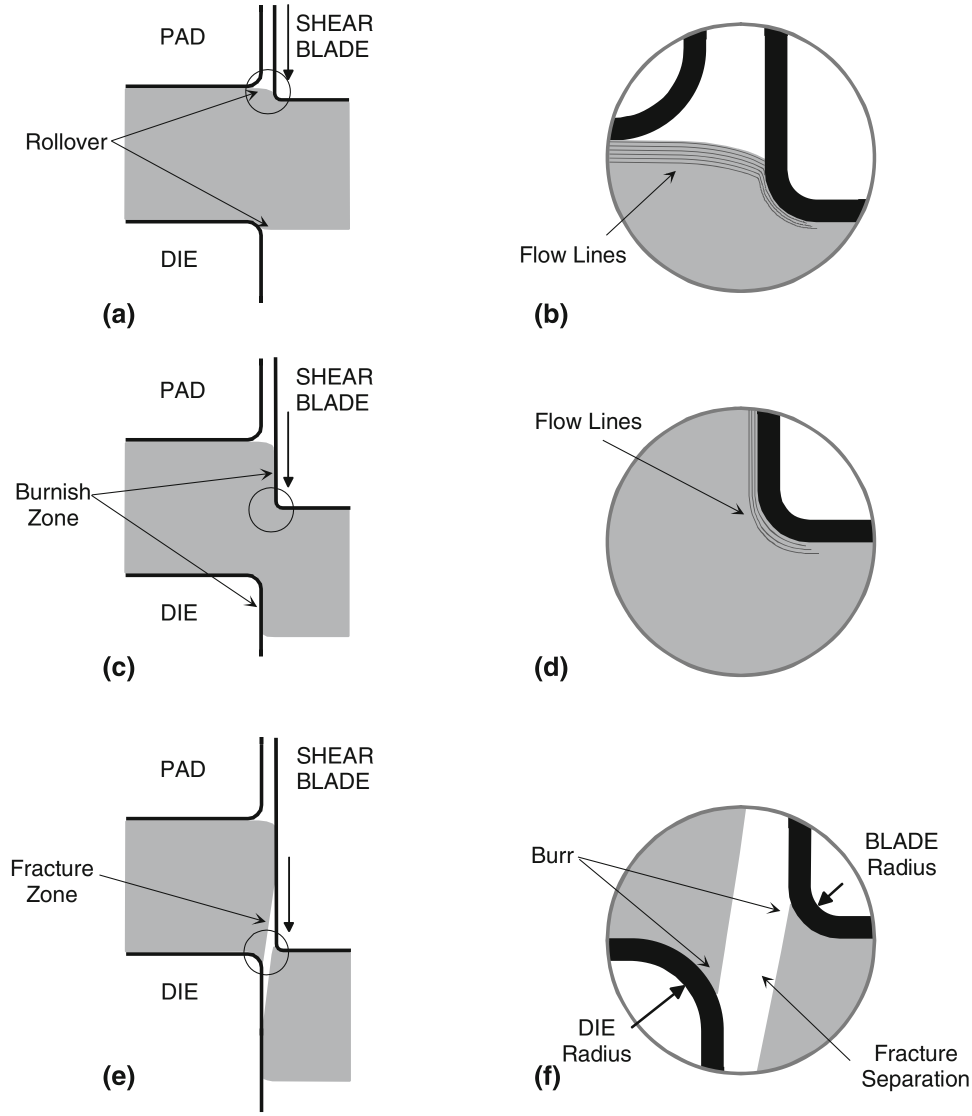

Fig. 2 Schematic illustrating steps in the shearing process. (a) The rollover phase of shearing, (b) an expanded view of rollover with the flow lines indicated, (c) the burnishing phase of shearing, (d) expanded view of burnishing with the flow lines indicated (e) the fracture phase of shearing, and (f) an expanded view of the initiation of fraction and location of the burrs

The quantitative data examined in the present study are taken from figures in the references by scanning the figures, scaling the plots, and digitally locating the data points. Data on rollover, burnish, and fracture are available from Konieczyny and Henderson (Ref 2) and Nakata et al. (Ref 3). The Konieczyny and Henderson data are for 1.4 mm 50XK, 590R, DP590, DP780, DP980, and TRIP780 steels. The samples were produced using a pierce die with clearances of 1.1, 6.4, 13.5, and 20.8% of the sheet thickness. The data from Nakata et al. are for steels identified as 270, 440, and 970 MPa. Samples were produced with both a pierce die and a trim die with clearances of 6, 8, 19, and 25% of the sheet thickness.

In each of the experimental data sets, clearance is the only shearing process variable that is identified. In analyzing the data from Konieczyny and Henderson (Ref 2), the sum of percent rollover, percent burnish, and percent fracture was determined. If the sum did not equal approximately 100%, these data were not used in the present analyses. For data of Nakata et al. (Ref 3), percent fracture was calculated by subtracting the sum of percent rollover and percent burnish from 100%.

3.1 Rollover

Figure 2(a) shows the tool position for rollover. As the shearing process begins, the shear blade that is moving down pulls metal from the top surface of the sheet into the gap between the radii of the shear blades. The position of the pressure pad can also affect the flow of metal. The abutting material and pad pressure restrain movement toward the gap between the shear blades. Figure 2b shows the expected flow lines for rollover. The existence of such flow lines has been confirmed by photomicrographs (Ref 2). For the bottom surface, the same rollover process is operative.

The rollover data were analyzed using regression analysis to quantify the effect of clearance and tensile strength (TS).

$$\text{Rollover}\ (\%) = a_0 + a_1 \cdot \text{Clearance}\ (\%) + a_2 \cdot \text{TS} \qquad \text{(Eq 1)}$$

For the Konieczny and Henderson data, $a_0 = 8.52 \pm 1.03$, $a_1 = 0.570 \pm 0.029$, $a_2 = -0.0061 \pm 0.0013$, and the square of the correlation coefficient, R^2, equals 0.95. The sample size is 23, and the deviations from the regression equation are reasonably random. The difference between predicted and actual percent rollover is less than 1.3% for 22 of 23 test conditions. The remaining difference is 2.4%. After measurement uncertainty is considered, the regression result is considered an excellent representation of the experimental data.

For the Nakata data, $a_0 = 8.62 \pm 2.70$, $a_1 = 0.777 \pm 0.121$, and $a_2 = -0.0134 \pm 0.0031$ with R^2 equal 0.87. The sample size is 12, and the deviations from the regression equation exhibit a small amount of systematic bias. From inspection of the data in the Nakata et al. paper (Ref 3), it can be seen that the results for the trim and pierce dies are somewhat different, probably because of inherent differences in process variables for trimming and piercing. The results from the Nakata and Konieczny and Henderson data indicate that there are other shearing process variables besides clearance that can have some effect on percent rollover.

Figure 3 shows the relative effect of clearance and tensile strength on rollover for the Nakata data and the Konieczny and Henderson data. Figure 3 and the regression results indicate that for both of these studies, clearance and, to a lesser extent, tensile strength determines percent rollover in either a pierce die or a trim die. The effect of clearance is due to its effect on the gap into which the sheet initially flows. The effect of tensile strength is related to its effect on the restraining force that inhibits the flow of the sheet into the gap. Figure 3 also indicates that the difference between the Konieczny and Henderson data and the Nakata data is more pronounced for the high tensile strength steels.

As demonstrated by fine blanking, increasing pad pressure including the use of stingers and a pad location close to the blade radius can reduce or eliminate rollover (Ref 4, 5). Thus, tensile strength, clearance, and pad variables affect percent rollover. Although other variables may affect percent rollover, no data are available to assess their importance.

3.2 Burnishing

Figure 2(c) shows the tooling position during burnishing. As the shear blade continues to penetrate the sheet, a wall is formed and deformation proceeds by a shear process. The face of the burnish region is smooth and striations in the direction of metal movement are also observed. These striations indicate metal-tool contact, so friction is also a factor.

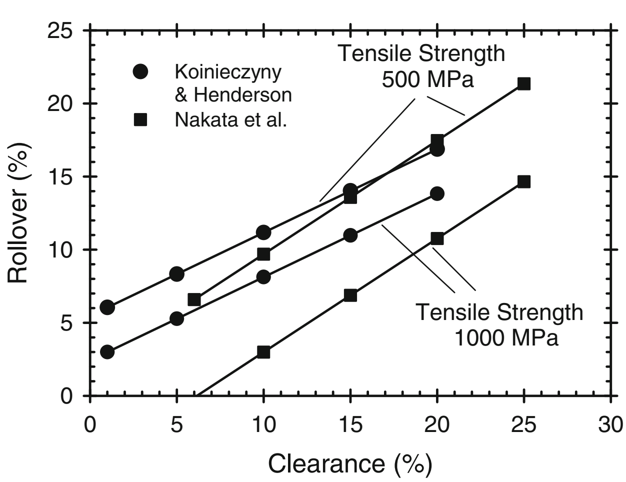

Fig. 3 Effect of percent clearance and tensile strength on rollover

Figure 2(d) is based on photomicrographs that show the flow pattern in the burnished region (Ref 2, 6, 7). The amount of grain elongation increases due to the increase in the vertical stress component as burnishing progresses. This explanation is consistent with the experimental observations of Milosevic and Moussy (Ref 8), who showed that the maximum strain is located at the transition from the burnish region to the fracture region.

In a finite element analysis study, Scheib et al. (Ref 9) have shown that the strain in the burnish region increases with depth, reaching a maximum at the transition from the burnish region to the fracture region. Their simulation work is consistent with the experimental observations.

Figure 4 shows the effect of percent clearance on percent burnish. Figure 4 indicates that as the tensile strength increases, the percent burnish decreases, although the TRIP780 is an exception for which there is no explanation. Since the ratio of fracture strength to tensile strength normally decreases as tensile strength increases, the decrease in percent burnish with increasing tensile strength is expected because burnishing ends when fracture initiates on the surface.

Figure 4 also shows that there is a general trend for percent burnish to decrease as percent clearance increases. This trend is probably a result of the observation by Milosevic and Moussy (Ref 8) and Hambli and Richer (Ref 10) that as percent clearance increases, deformation in the SAZ increases. If the amount of deformation increases, less burnish depth is required to initiate ductile fracture. The size of the burnish region depends on the mechanical properties of the sheet, clearance, pad related variables, and friction.

Since the strain at the end of burnishing must generate a stress state of sufficient magnitude to start ductile fracture, it is hypothesized that if percent rollover is increased, percent burnish should decrease. Thus, for a given material, the sum of percent rollover and percent burnish should be approximately constant.

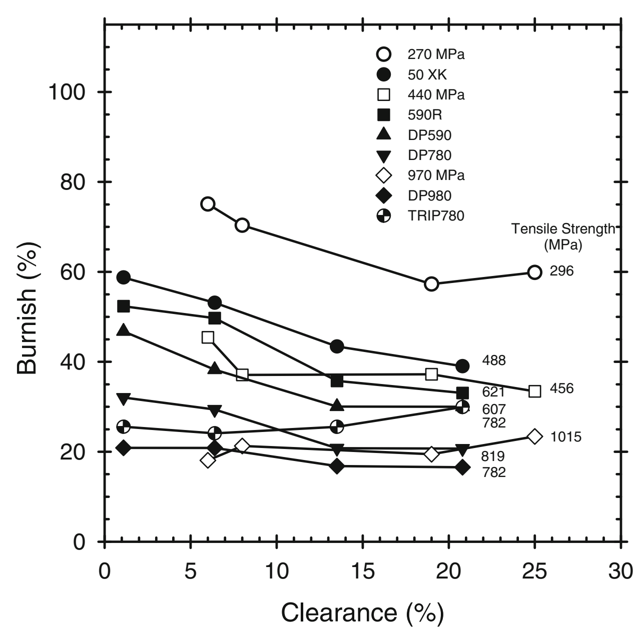

Fig. 4 Effect of percent clearance and tensile strength on percent burnish. Open symbols—data from Nakata et al. [2]. Closed symbols—data from Koinieczyny and Henderson [3]

3.3 Fracture

Figure 2(e) shows the tooling position just after complete fracture. When the stress generated during burnishing reach a critical value, fracture begins. As shown in Fig. 2(f), fracture during shearing begins at the end of the burnish region at the top and bottom surfaces of the sheet and propagates at an angle to the sheet surface. For other shearing conditions, the two cracks can propagate at different angles, and the cracks must jog to meet (Ref 2, 11, 12). When the cracks meet, the sheet separates.

If the sum of percent rollover and percent burnish are approximately constant, the stress to initiate ductile fracture should be approximately independent of clearance. This reasoning is confirmed by Fig. 5, which shows that effect of percent clearance has little or no effect on percent fracture.

Figure 5 also shows that as tensile strength increases, percent fracture generally increases. Figure 6 shows the estimated fracture at 10% clearance as a function of tensile strength. With the exception of one outlier, there is a reasonable linear relationship between increasing tensile strength and increasing percent fracture at 10% clearance. It can be seen that Fig. 5 and 6 are consistent with the prior observation that increasing tensile strength decreases the amount of rollover and burnish that is needed to initiate fracture.

3.4 Shear Burr

Murakawa (Ref 5) has shown that "a burr will never be generated if cracks occur both from the exact edge points of a pair of shearing tools". In reality, cracks occur from a point located slightly away from the cutting edge (Ref 5, 12).

Figure 2(f) is an expanded view of sheet fracture. Following the logic of Murakawa (Ref 5) and Golvanshcenko et al. (Ref 12), Fig. 2(f) shows that a shear burr is formed due to the intersection of the fracture surface and the surface of the sheet in contact with the tool. There is a shear burr on each side of the sheet. Using the geometry shown in Fig. 2(f), the height of the shear burr depends in part on the arc of contact around the blade radius at the start of fracture.

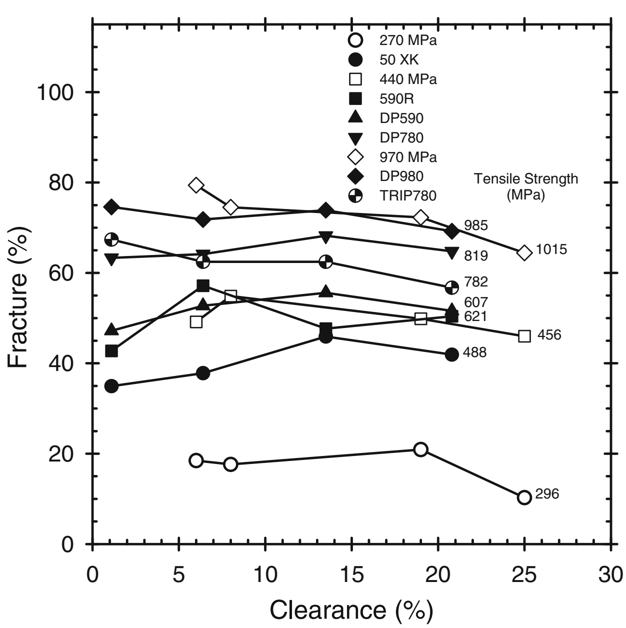

Fig. 5 Effect of percent clearance and tensile strength on percent fracture for a range of steels. Open symbols—data from Nakata et al. [2]. Closed symbols—data from Koinieczyny and Henderson [3]

Production experience indicates that as trim dies wear, both the trim die radii and burr height increase, which is consistent with the effect of trim die radius on burr height (Ref 5, 13). The wrap angle around the blade radius is thought to depend on the mechanical properties of the sheet. In particular, it would seem that increasing strength and decreasing ductility should reduce metal flow that in turn should result in a reduced wrap angle.

However, other factors affect burr height in production shearing processes. Nakata et al. (Ref 3) have shown the importance of the geometry that controls how the "cut" piece falls away from the remaining blank. In addition, Golovashenko et al. (Ref 12) have shown how clearance and difference in radius on the top and bottom trim dies can be used to eliminate burr on the work piece and shift the burr to the discard piece; i.e., the piece that falls away. Their study found that bending with a relatively small ratio of tool radius to thickness, a tight bend radius, and a smaller radius on the bottom die and a larger radius on the top die can be used to eliminate the burr on the work piece (Ref 12). From these observations, it is clear that shearing variables have a complex effect on burr height.

In quantifying experimental results for burr height, accurate experimental measurement of burr height is thought to be difficult. Since quantitative data for many shearing process variables that contribute to burr formation are not available, it is expected that the available data on burr height as a function of clearance should exhibit substantial variation.

Data are available for the following steel grades: 50XK, 590R, DP590, DP780, DP980, and TRIP780 (Ref 2); 270, 440, and 970 MPa (Ref 3); and DQSK, BH210, and DP590 (Ref 14). In general, there is a consistent trend for burr height to decrease with increasing tensile strength.

Adamczyk and Michal (Ref 15) have shown that removing the burr from early-generation HSLA and recovery anneal steels did not have a significant effect on increasing the failure strain in sheared-edge stretching, which indicates that the burr is not a critical factor in initiating failure in sheared-edge stretching.

A discussion of the effect of burr position on limit strain in shear-edged stretching is presented in Appendix A.

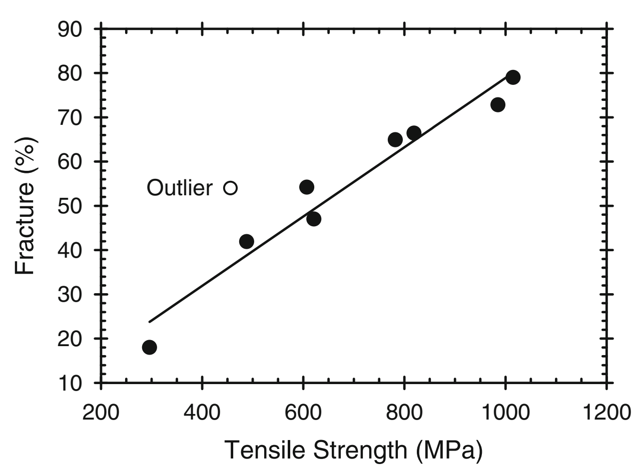

Fig. 6 Effect of tensile strength on estimated percent fracture at 10% clearance

4. The Shear-Affected Zone (SAZ)

4.1 Depth of SAZ

The depth of the SAZ can be determined by several methods: (1) the distance from the shear face to where the hardness has not increased due to the shearing process, (2) the distance from the shear face where the sheared-edge stretching limit equals that of the surrounding material, or (3) the distance from the shear face where the shearing has not increased the major strain component.

Davies (Ref 16) used heat treatment to determine the hardness increase from piercing 1.25 mm thick SAE 940 and an early version of rare-earth-treated 1.25 mm thick DP 600. The depth of the SAZ was determined to be approximately 0.3 mm from the sheared edge with the hardness in the SAZ progressively decreasing as the distance from the sheared edge progressively increased. For these two steels the SAZ depth is approximately 25% of metal thickness.

Davies (Ref 16) also determined the depth of the SAZ for approximately 1.25 mm thick SAE 950 steel by progressively reaming the shear face of a pierced hole, followed by hole-expansion testing to determine the failure limit. As material was progressively removed from the sheared edge, the limit strain progressively increased. In his study, the criterion for the depth of the SAZ was for the limit strain to equal the limit strain of the surrounding material. Using this criterion, the depth of the SAZ was about 0.4 mm, about 33% of metal thickness.

Held et al. (Ref 17) examined the depth of the SAZ for 3 mm thick S480MC using a precision measuring system for small strains. There results show a depth of SAZ of 2 mm with a rapid drop-off in major strain at about 0.8 mm, which is 67 and 27% of metal thickness, respectively.

Unpublished work by one of the authors (Levy) evaluated the depth of the SAZ using Knoop hardness with a 500 g load. The steel was a 0.87 mm continuously heat-treated, non-micro-alloyed high-strength steel with a yield strength of 396 MPa, tensile strength of 509 MPa, n value of 0.19, and a total elongation of 24%. Piercing was done with several negative clearances. The depth of the SAZ ranged from 0.30 to 0.46 mm or from 34 to 52% of metal thickness.

Milosevic and Moussy (Ref 8) used microhardness measurements on cold-rolled and hot-rolled AISI 1008 steel of unknown thickness that was pierced using a range of clearances to show the depth of the SAZ. For all conditions, the reported depth of the SAZ was about 1 mm. It was also reported that "the strain-hardened volume and the average strain hardening increase with increasing clearance".

Hambli and Richer (Ref 10) in a study on fine blanking have shown that the depth of the SAZ increases with increasing clearance.

Milosevic and Moussy (Ref 8) also reported that there is a small region of voids in the SAZ near the sheared edge. The size of this region with voids increases with clearance. The maximum depth from the shear face of these voids is 0.2 mm at 20% clearance. However, the authors also report that annealing increased the limit strain to values close to that of a machined hole. Annealing removes the deformation due to shearing, but does not affect voids. It appears that deformation due to shearing has a greater effect on sheared-edge stretching limits than do voids.

In analyzing the quantitative data from the literature, the depth of the SAZ ranges from 25 to 67% of metal thickness. If the criterion for the depth of the SAZ were reduced to strain equal to 50% of the maximum, the depth of the SAZ for the Held data would be 33% of metal thickness. It can be concluded from the available data that the effective depth of the SAZ is less than the thickness and probably less than half the thickness with variations due to differences in shearing conditions.

4.2 Maximum Strain

Milosevic and Moussy (Ref 8) used microhardness to delineate the region of maximum hardness and maximum strain for the AISI 1008 steels in their study. It was found that the region of maximum hardness appears to be in the transition from the burnish to fracture zones. Hardness was converted to strain using cold-rolled samples of the steel, microhardness testing, and establishing a calibration curve. The zone of maximum hardness indicated a maximum effective true strain of 1.65. For comparison, 80% reduction is equivalent to a true strain of -1.61.

Lee et al. (Ref 7) have determined shear strain in the SAZ from the angle of the grain rotation, where the shear strain equals the tangent of the angle between the plane of the sheet and the direction of the elongated grains. The measured shear strains were 14.7 for a low carbon steel, 6.57 for a HSLA, 2.67 for a TRIP590, 2.06 for a DP590, and 1.61 for a TRIP780. The strain for the low carbon steel is very much larger than for the AISI 1008 steel determined by Milosevic and Moussy (Ref 8). A possible explanation for this difference is that after some amount of shear strain, there is little or no increase in hardness. It can also be seen from data of Lee et al. (Ref 7) that material properties affect the magnitude of the shear strain in the SAZ.

Kalpakjian (Ref 11) has shown that the maximum temperature is at a punch penetration of about 50% of sheet thickness. Although the sheet metal is not identified, the location of the maximum temperature is at the mid-thickness of the work material, which is consistent with the hardness measurement results of Milosevic and Moussy (Ref 8).

It can be seen that the shearing process produces high strains at rapid strain rates that results in substantial deformation heat. The strains, strain rates, and temperature increases in shearing are much greater than those produced in tension testing or bulge testing. Since available stress-strain relationships do not describe deformation in shearing, experimental verification is essential for any finite element simulation of shearing.

4.3 Effect of SAZ

Davies (Ref 16) has shown that progressively removing a sheared edge results in progressively increasing the limit strain. This result clearly shows the importance of the SAZ in reducing the sheared-edge limit strain compared to as-received material.

Milosevic and Moussy (Ref 8) have shown for cold-rolled and hot-rolled steels, ranging in yield strength from about 160 to 600 MPa that machining a hole to remove the SAZ significantly increases the limit strain in sheared-edge stretching with a Fukui test. For the more ductile steels, the data from Milosevic and Moussy also show that annealing is less effective than reaming in increasing limit strain in sheared-edge stretching, which indicates that voids have some effect on reducing the failure strain in sheared-edge stretching.

Konieczny and Henderson (Ref 2) evaluated the effect of the SAZ on the failure strain in sheared-edge stretching for 50XK, 590R, DP590, TRIP780, DP780, and DP980 using both a conical and a spherical punch. The failure criterion was a through thickness crack. In their study, the SAZ was removed by reaming. It was found that reaming significantly increased the failure strain in subsequent sheared-edge stretching. It was also found that the improvement due to reaming is significantly less for TRIP780, DP780, and DP980 compared to the more ductile steels in the study, 50XK, 590R, and DP590.

Lazaridis (Ref 18) examined the effect of reaming a pierced hole on limit strain in sheared-edge stretching with a flat punch. The four steels in his study were either micro-alloyed or early versions of dual-phase steels. In comparing limit strain for as-sheared and reamed holes, it was shown that reaming significantly improved limit strain for all four steels. Lee (Ref 6) has also shown that removing the SAZ by machining increases the failure strain for two dual-phase steels and a low carbon martensitic steel.

In contrast, Comstock et al. (Ref 19) have shown that for ferritic stainless steels removing the sheared edge has little or no effect on improving limit strain. However, for austenitic stainless steel there is a large increase in limit strain when the sheared edge is removed by machining. It should be noted that the reported transverse n values for the ferritic stainless steels ranged from 0.180 to 0.230 while the reported n value for the single austenitic stainless steel was 0.406.

5. Discussion of Results

5.1 The Shear-Affected Zone (SAZ)

It has been shown that the SAZ has the dominant effect on sheared-edge stretchability for plain carbon steels. The importance given to the characteristics of the shear face in the literature is probably the result of correlation between the characteristics of the shear face and the nature of the SAZ.

The data from the literature indicate that deformation from shearing in the SAZ has a significant effect on reducing the limit strain for sheared-edge stretching, but there is also evidence that voids and related damage in the SAZ also contribute to the reduction. The importance of deformation in the SAZ is thought to be its affect on limiting the subsequent damage that can be tolerated when a sheared edge is stretched.

It has also been shown that material properties affect the results from shearing. More attention should be given towards understanding how shearing conditions affect the SAZ and on how microstructures interact with the stresses and the strains resulting from the shearing.

5.2 Shear Burr

The analysis of the SAZ and the data of Adamczyk and Michal (Ref 15) suggest that the shear burr itself may not have a direct effect on crack propagation when a sheared edge is stretched. Rather, the observed effect of the shear burr is due to the relation of the shear burr to a region of the SAZ subject to maximum internal damage. This hypothesis presupposes that as the size of the shear burr increases the internal damage in the adjacent region of the SAZ increases. The following analysis is in terms of the shear burr, but it is thought that the determining factor is the internal damage in the region of the SAZ adjacent to the shear burr.

It has been shown that with a conical punch, the position of the shear burr affects limit strain in hole-expansion tests. In contrast with a flat or hemispherical punch, the position of the shear burr has no effect on limit strain. With a conical punch, the strain on the sheared edge during stretching is highest for the top surface of the sheet. When the shear burr is on the top surface of the sheet, it experiences a higher strain than if it were on the bottom surface of the sheet. This strain difference accounts for the burr-effect on the sheared-edge limit strain. Since there is no significant strain gradient through the thickness of the sheet with a flat or hemispheric punch during hole-expansion, the position of the shear burr has no affect on limit strain.

Most stretching conditions during production are similar to expansions with a flat or a hemispherical punch. Production experience indicates that increasing the size of the shear burr decreases sheared-edge stretchability. In production, the size of the shear burr increases as dies wear. The increased size of the shear burr with wear is associated with rounding of the radii on the shear blades, which is equivalent to increasing clearance. It has been shown that increasing clearance increases hardness and probably the size of the SAZ. Thus, the effect of larger shear burrs is probably due to the changes in the characteristics of the SAZ due to an increase in effective clearance.

6. Summary

As a result of a review of the literature, the following is concluded.

- The SAZ controls limit strain for sheet steels in sheared-edge stretching. Deformation in the SAZ is the dominant factor in reducing the failure limit for sheared-edge stretching, while voids and microcracks have a secondary effect.
- The depth of the SAZ is less than the sheet thickness and is probably less than half the sheet thickness. Shearing variables and material properties affect the depth of the SAZ.
- The transition from burnish to fracture regions on the shear face occurs when the stress becomes sufficient to initiate a failure crack. As tensile strength increases, the percent fracture on the shear face increases, with a subsequent decrease in the rollover plus burnished regions.
- The effect of shear burr on sheared-edge limit strain is due to a correlation with the hardness and possibly size of the SAZ. The effect of other characteristics of the shear face on the sheared-edge limit strain is thought to be due to correlation with characteristics of the SAZ.
- In studying sheared-edge stretching, more detailed analysis of the SAZ would be desirable. Such studies should include the effect of shearing variables on the characteristics of the SAZ, and the effect of microstructure on deformation of the SAZ.

Acknowledgments

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Appendix A: Effect of Shear Burr Position on Failure During Stretching

Shear burr position (up or down) is generally thought to affect limit strain in sheared-edge stretching. The burr up position indicates that the burr is on the top surface of a sheet relative to the punch, while burr down represents the opposite condition. The purpose of this appendix is to show the conditions for which shear burr position affects limit strain in sheared-edge stretching.

Data on limit strain in sheared-edge stretching using circular holes are available for the burr up and burr down conditions for conical and spherical punches (Ref 1). The steels that were investigated are 1.4 mm thick 50XK, 590R, DP590, DP780, DP980, and TRIP 780. Prior to edge stretching, 10 mm holes were pierced at 1.1, 6.4, 13.5, and 20.8% clearance.

The experimental data on limit strains is subject to experimental variation. Comparing the difference between limit strains in the up and down positions increases experimental variation. Thus, in analyzing the effect of burr position, the differences in limit strains for the up and down positions are averaged for all clearances for each of the steels in the experiment.

The averaged difference values for a spherical and conical punch are shown in Table A1. Table A1 shows that for the spherical punch, there is no consistent effect of burr position on limit strain. In contrast, for a conical punch the data show that limit strain for burr in the up position is consistently less than for burr in the down position and that the difference decreases as tensile strength increases.

Regression analysis is used to quantify the effect of burr down minus burr up on limit strain determined using a conical punch.

$$\delta = b_0 + b_1 \cdot \mathrm{TS} \qquad \text{(Eq A1)}$$

where δ is the difference in limit strain for burr down minus burr up and TS is tensile strength in MPa, $b_0 = 0.204 \pm 0.027$, and $b_1 = -0.000184 \pm 0.000036$. The R^2 value is 0.86, the sample size is 6, and deviations from the regression line are reasonably random.

Equation A1 can be explained using the following logic. As a hole is expanded with a conical punch, the plane of the sheared edge moves from the vertical plane toward the horizontal plane. In the horizontal plane, the burr up position is on the outside surface. Once the free edge is vertical, the circumferential strain component on the outer surface can be 20 to 40% greater than that on the inner surface. While the strain gradient between the inner and outer surface decreases as testing progresses, there will still be a significant strain gradient from the outer to the inner surfaces. This analysis is supported by experimental observations that fracture initiates on the outer edge of a hole expanded with a conical punch (Ref 20).

In contrast, with a spherical punch, the free edge remains nearly in the horizontal plane, and strain gradients between the top and bottom surfaces are minimal. Thus, the position of the shear burr is only important when there is a significant strain gradient between the top and bottom surfaces of a sheet. In production operations, the strain gradient between the top and bottom surfaces is minimal for flanging or for expanding an interior cutout such as the window openings on a body side outer. In contrast, for extruded holes, strain gradients between the top and bottom surfaces of a sheet can be significant.

It should also be noted that the International Organization for Standardization (ISO) test for hole-expansion uses a conical punch. Thus, the effect of burr position can be observed in hole-expansion tests using the ISO test.

Table A1 Effect of burr position on stretching a sheared edge with a conical or a spherical punch

Steel grade	Tensile strength, MPa	Average difference in true limit strain for burr down minus burr up	
		Spherical punch	Conical punch
50XK	488	−0.033	0.114
590R	621	0.055	0.109
DP590	607	−0.019	0.082
TRIP780	782	0.024	0.037
DP780	819	0.035	0.056
DP980	985	0.021	0.032

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