Development of a 2-stage shear-cutting-process to reduce cut-edge-sensitivity of steels

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Abstract. The edge cracking sensitivity of AHSS and UHSS is a challenging factor in the cold forming process. Expanding cut holes during flanging operations is rather common in automotive components. During these flanging operations the pierced hole is stretched so that its diameter is increased. These flanging operations stretch material that has already been subjected to large amounts of plastic deformation, therefore forming problems may occur. An innovative cutting process decreases micro cracks in the cutting surface and facilitates the subsequent cold forming process. That cutting process consists of two stages, which produces close dimensional tolerance and smooth edges. As a result the hole expanding ratio was increased by nearly 100 % when using thick high strength steels for suspension components. The paper describes the mechanisms of the trimming process at the cut edge, and the positive effect of the 2-stage shear-cutting process on the hole extension capability of multiphase steels.

1. Introduction

In recent years, the automotive industry has been increasingly driven, both through political and also societal demands and expectations, to conserve resources and to reduce fuel consumption and, with this, pollutant emissions [1]. To meet these demands, reducing the total weight of the vehicle has been a primary objective. Reducing the vehicle weight by 100 kg reduces fuel consumption by approximately 0.5 l/100 km with a corresponding reduction in CO₂ emissions [2]. For developing innovative lightweight designs, high-strength and ultra-high-strength steel grades are currently being used more and more. This development represents an enormous challenge especially for metal working. As the strength of a material increases, its ductility and thus its ability to be shaped usually decreases [3]. Series production of high-strength and ultra-high-strength sheet-metal materials has shown that these materials have an increased sensitivity to edge cracks. The problem appears to be especially pronounced when the material is first cut by a shear cutting process and then subjected to a cold working process.
2. State of the art

2.1. Shear Cutting

2.1.1. Cutting process

Shear Cutting is the most common process used in sheet-metal processing. Almost every sheet-metal product undergoes one or more shear cutting operations at some point in its manufacturing process [4]. The shear cutting process is divided into five phases in the literature [5]:

In phase 1, the sheet metal is clamped between the die and blank holder. The punch contacts the sheet surface at a defined speed [5]. In phase 2, the effect of the applied compressive forces produces a bending moment \( M_b \) that leads to an elastic deformation of the sheet metal. The compressive force transmitted by the punch \( F_S \) and its reaction force \( F_S' \) lead to stress in the material in the area of the later cut surface. When the maximum shear stress \( \tau_{\text{max}} \) in the material reaches the shear yield stress, the material will undergo plastic deformation as per the shear stress hypothesis of Tresca and Mohr [5]. When the maximum shear stress in the material reaches the shear fracture limit, in phase 4 the ability of the material to deform is exhausted and incipient cracks are formed in the material. If the punch and die cutting edges have the same shape, according to [6] the crack usually originates from the die cutting edge, because on the bottom side of the sheet metal, the tensile stresses from the material stretching and the sheet-metal bending add together. The total load on the sheet metal side facing the punch is less, because there the tensile stresses from the material stretching are partially compensated by compressive loading from the sheet-metal bending. Therefore, cracks form here at a later time [6, 7]. After the sheet metal is separated (phase 5), elastic stresses are released that cause the material to spring back in the area of the cut surface. This causes dimensional and shape changes to the cut surface.

2.1.2. Work hardening of sheared edges

In the shear cutting process, the cutting punch penetrates into the sheet metal blank and generates a plastic flow of the material in the shear zone until the material separates. With increasing travel of the cutting blade, the very localized deformation causes strong cold work hardening of the cut edge. Sheared edges are often further loaded in the subsequent processes, in order, e.g., to form flanges or to expand cut holes. Especially when high-strength and ultra-high-strength materials are used, e.g., dual-phase and complex-phase steels, cracks starting from the sheared edges increasingly appear in these downstream processes. This sensitivity to edge cracks represents, in addition to the generally low ability to deform and the higher required shaping forces, a challenge in the use of high-strength materials [8].

2.2. Collar drawing

As per DIN 8584, collar drawing or plunging is a tensile-compressive forming process, which is defined as the creation of closed edges (collars) on cut-out openings with a punch and drawing die. Collar drawing is widely used in industrial practice, e.g., as extruded holes for threaded connections, as brackets for joints and bushings, or as a stiffening element for large surface area sheet-metal components [9].

2.2.1. Description of the method

In collar drawing in flat sheet metal, the sheet metal segment lying over the drawing die opening is bent around the edges of the drawing die and the drawing punch. During this forming, the diameter of the pilot hole is increased while the thickness of the sheet metal is simultaneously reduced. In contrast, the changes in shape in the radial direction are minimal, so that the length of the free bending leg remains approximately the same. The process is completed when the punch edge has passed the pilot hole edge and the bending leg contacts the cylindrical part of the punch. In practice, a blank holder is usually used, which prevents material from flowing out from the flange area [10, 9].
2.2.2. Limits of the method

The limit of the method for collar drawing is characterized by the occurrence of radial cracks at the collar edge, which can cause the component to become unusable. A crack initiates when the tangential tensile stresses caused by the widening process at the collar edge exceed the tensile strength of the material. Crack formation is generally introduced by previously created constricted sections which have to be considered as a failure case due to the associated partial wall thickness reduction, depending on the use purpose of the collar [11, 12].

A characteristic parameter for describing the method’s limit is the maximum achievable widening ratio \( V_{A, \text{max}} \). This parameter is defined as the quotient from the punch diameter \( d_{St} \) and the pilot hole diameter \( d_0 \), at the point just before cracks are formed (see equation 1):

\[
V_{A, \text{max}} = \frac{d_{St}}{d_0}
\]  

Cut pilot holes always contain an area of cold work hardening even under optimal cutting conditions, a burr of some size, an area with score marks running perpendicular to the main deformation direction in the burnish zone, and a rough fracture zone. All of these factors promote the formation of cracks on the collar, which results in significant worsening of the maximum widening ratio compared with drilling [11, 13]. Because these factors overlap and cannot be separated, it is difficult to clarify which factor is the main reason for the worse deformation behavior of cut pilot holes. Studies by [13] have shown that both turning the burr side toward the drawing die and also deburring generate only minimal improvements in the maximum achievable widening ratio. In contrast, removing the rough fracture zone and the cold-work-hardened area by shaving has a significantly greater effect. From this information, [14] draws the conclusion that the limit of the method for collar drawing with cut holes is determined primarily by the low residual ability of the cut surfaces to deform and less by the formation of burrs. [11] and [15] were able to experimentally confirm this conclusion. For example, [11] showed that after eliminating the cold work-hardened area by an annealing process, larger widening ratios could be achieved. In the research by [15], the cut pilot holes were reground. In these tests as well, it was determined that the greatest influence on the limit of failure resulted from the cold work hardening. [15] therefore noted that a sufficiently large portion of the hardened cut surface (approximately 0.65 mm) must be removed to achieve a noticeable improvement in the widening ratio.

3. Test systems, material, and execution

3.1. Cutting and collar drawing tool

The shear cutting and collar drawing tests are performed with a modular test tool developed and built at the Chair of Metal Forming and Casting at the Technical University of Munich. The test tool can be converted from a cutting configuration to a collar drawing configuration by swapping just a few modules in a short amount of time.
3.2. Test materials
The complex-phase steel HDT780C (material number: 1.0957) with a nominal thickness of 3.5 mm is used as the material for the test series. To ensure uniform sheet metal quality, all test samples are taken from blanks from the same batch.

3.3. Shear cutting tests
All shear cutting tests were performed on a hydraulic press and with the test tool (see figure 1). The size of the test blanks was 160 mm x 200 mm for the collar drawing tests. The outer shape of the blanks was formed by laser cutting. The rolling direction was always equalled in the direction of the longer side. The shear cutting operations were performed using Multidraw St300 lubricant made by Zeller + Gmelin, Eislingen, Germany.

3.4. Collar drawing tests
To optimize the trimming allowance with respect to the deformation ability of the cut edge, the trimming allowance is varied in a systematic manner between $z_{abs} = 0.35$ mm and 4 mm with a constant cutting gap ($u_k = 12.5\%$), and the maximum achievable widening ratio $\lambda_{max}$ in each case is determined. The maximum widening ratio $\lambda_{max}$ of conventionally cut samples is also determined as a reference.

4. Results

4.1. Increase in the maximum widening ratio by optimizing the trimming allowance
All of the trimming samples achieved significantly higher widening ratios than the conventionally cut samples. The highest widening ratio ($\lambda_{max} = 85\%$) is achieved for a trimming allowance of $z_{abs} = 1$ mm. Increasing the trimming allowance tended to reduce the widening ratios. For $z = 2$ mm, a widening ratio of $\lambda_{max} = 70\%$ could be achieved; for $z = 4$ mm, a widening ratio of $\lambda_{max} = 65\%$ could be achieved. Reducing the trimming allowance to $z_{abs} < 1$ mm reduced the maximum achievable widening ratio significantly. However, it was still above the values that could be achieved by conventionally cut samples (see figure 2).

Figure 1: Test tool in the (a) cutting configuration and (b) collar drawing configuration
Figure 2: Maximum achievable widening ratio as a function of the trimming allowance (material: HDT780C, $s = 3.5$ mm, relative cutting gap $u_S = 12.5\%$)

4.2. Process considerations and model setup

To clarify the results, the processes and their effects on the trimming process are examined below in comparison with conventional shear cutting. The process evaluation is realized with the help of cut start tests, because optical measuring devices cannot be used due to the high cutting speed and the compact tool construction.

4.2.1. Cutting process: plastic deformation

The compressive force transmitted by the punch and its reaction force lead to stresses in the material in the area of the cutting edges. When the stresses exceed the shear yield stress, the material begins to deform plastically, resulting in the formation of the edge roll-over zone and burnish zone on the cut part. Figure 3 shows this phase for the trimming process and conventional shear cutting. The trimming allowance and the cutting method that are used produce significant differences in the deformation behavior. For a trimming allowance of $z_{abs} = 1$ mm, the material displaced by the punch (punch penetration depth $x = 620\mu m$) is moved completely in the radial direction; no material is pressed into the die channel (see figure 3). In contrast, for conventional shear cutting, the displaced material only performs a translational movement in the direction of the punch movement (axial); radial flow is not possible due to the geometrical conditions. For the trimming allowances $z_{abs} = 2$ mm and $z_{abs} = 4$ mm, a mixed form of the two processes occurs. Part of the displaced material flows in the radial direction, the other part flows in the axial direction. This behavior can be explained by the increased stiffness of the rings to be separated compared with $z_{abs} = 1$ mm. The resistance against radial flow is greater here; dissipating the compressive stresses through radial flow is therefore possible only to a limited extent. The trimming process with an allowance of $z_{abs} = 0.35$ mm is a special case. Here, rather a chip-producing behavior occurs.
Figure 3: Plastic deformation during the cut start tests as a function of the shear cutting method (material: HDT780C, $s = 3.5$ mm)

The deformation behavior of the material has a significant effect on the size of the edge roll-over zone that is formed. This can be illustrated by a model on the conventional shear cutting process according to [5] and [16] on the conventional shear cutting process (see figure 4). When the punch penetrates by the displacement $x$, sheet-metal material of volume $V_1$ is displaced. From the geometrical conditions it can be derived that the need for material in the die channel ($V_1 + V_2$) is greater than volume $V_1$ displaced by the punch. The volume difference $V_2$ is compensated by the flow of sheet-metal material into the cutting gap. This process forms the edge roll-over zone.

For trimming with $z_{abs} = 1$ mm, the material volume $V_1$ displaced by the punch is moved only in the radial direction; no material is pressed into the die channel ($t = 0$), so that no differential volume is produced here ($V_2 = 0$). For trimming with $z = 2$ mm and 4 mm, a part of the displaced material volume ($V'_1$) is pressed into the die channel; the other part ($V''_1$) flows in the radial direction. Therefore, $0 < t < x$, so that here a greater differential volume $V_2$ is produced than for $z = 1$, but a smaller one than for conventional shear cutting ($t = x$). A reduced differential volume is associated with a smaller edge roll-over zone, because less material flows into the cutting gap.
For trimming with $z_{\text{abs}} = 1$ mm, the material volume $V_1$ displaced by the punch is moved only in the radial direction; no material is pressed into the die channel ($t = 0$), so that no differential volume is produced here ($V_2 = 0$). For trimming with $z = 2$ mm and 4 mm, a part of the displaced material volume ($V_1'$) is pressed into the die channel; the other part ($V_2'$) flows in the radial direction. Therefore, $0 < t < x$, so that here a greater differential volume $V_2$ is produced than for $z = 1$, but a smaller one than for conventional shear cutting ($t = x$). A reduced differential volume is associated with a smaller edge roll-over zone, because less material flows into the cutting gap.

4.2.2. Cutting process: crack formation

When the maximum shear stress in the material reaches the shear fracture limit, the ability of the material to deform is exhausted and incipient cracks are formed in the material. In trimming, the crack forms at the punch cutting edge in all cases considered. For $z = 1$ mm, the crack is formed at a punch penetration depth of $x = 980$ $\mu$m, for $z = 2$ mm at $x = 1229$ $\mu$m, and for $z_{\text{abs}} = 4$ mm at $x = 1216$ $\mu$m. In contrast, in conventional shear cutting, at a punch penetration depth of $x = 1385$ $\mu$m, a crack is formed in the material on the die side. The crack formation in conventional shear cutting and in trimming shall be explained with the help of the following model (see figure 5).
4.2.3. Cutting process: crack propagation

With increasing punch penetration depth, the incipient cracks propagate in the direction of the opposite cutting edge until the material cohesion is completely annihilated. Figure 6 shows this phase for the trimming process and conventional shear cutting.

In conventional shear cutting, shortly after the crack is created at the die cutting edge, the ability of the material to deform is exceeded at the punch cutting edge, so that cracks are also formed there. This fact supports the assertion that the additional tensile stresses induced at the die cutting edge from the sheet metal deflection ($\sigma_{Bt}$, $\sigma_{Ba}$) are relatively small. The incipient cracks run from the cutting edges into the shear zone and connect with other cracks there. This separating process takes place abruptly. According to [16], the crack propagation is unstable and causes an explosive-like brittle fracture. In trimming, the material separation is realized by a one-side propagation of the crack outward from the punch cutting edge. This can be traced back to the greater penetration depth of the punch cutting edge into the material, in comparison with the die cutting edge, and the additional tensile stresses from the bending moment $M_A$. In addition, due to the bending moment $M_A$ on the die cutting edge, steady compressive stresses are induced.
Figure 6: Crack propagation during trimming and conventional shear cutting (HDT780C, sheet metal thickness $s = 3.5$ mm, rel. cutting gap $u_S = 12.5\%$)

For the considered trimming allowances ($z = 0.7$ mm, 1 mm, 2 mm, 4 mm), the crack runs towards the die cutting edge. The crack propagation takes place slowly; the crack can be stopped at any time by removing the load. This is an indication that the crack is in a stable propagation stage [16]. This behavior is also exhibited in the force-path-time curve. In figure 7, the curves for the normal cutting and the different trimming parameters are shown. Due to the changed stiffness of the circular cutting and the thus changed flow behavior it can be seen that also the occurring maximum cutting force is reduced. The maximum cutting force $z_{rel} = 10\%$ is approximately 60 kN and approaches, with increasing allowance, the normal cutting force $F_{max} = 180$ kN. With reduced trimming allowance, both the transition from elastic to plastic deformation and the end of the plastic deformation is reached significantly earlier. In agreement with the determined reduction of the burnish zone for trimmed samples, it can be seen that the final fracture is introduced earlier. It is also evident that for normal cutting, this fracture takes place very quickly in time, while in trimming, this fracture takes place rather slowly due to the induced die-side compressive stresses during trimming. Trimming with an allowance of $z_{rel} = 10\%$ is again an exception. Due to the chip-forming sliding of the material in the radial direction, this leads to significantly lower cutting forces.
4.2.4. Cutting process: effects of the modified process

In the model representation of the trimming process, it could be shown that for trimming, in comparison with normal cutting, only a smaller portion of material is drawn into the die channel; see figure 7. The edge rollover width decreases to the minimum value of \( b_E = 490 \, \mu m \) for a trimming allowance of \( z_{rel} = 30 \% \). With smaller trimming allowance, the edge rollover width increases again, although the ring stiffness decreases further due to the smaller cross section (see table 1).

Table 1: Edge rollover widths as a function of the shear cutting method (material: HDT780C, \( s = 3.5 \) mm)

| Material: HDT780C \( s = 3.5 \) mm | Shear cutting method |
|-------------------------------------|----------------------|
|                                     | Normal Cutting |
|                                     | absolute trimming allowance \( z_{abs} \) [mm] |
|                                     | (relative trimming allowance \( z_{rel} \) [%]) |
|                                     | 0.35 (10) | 0.7 (20) | 1 (30) | 2 (57) | 4 (114) |
| Edge rollover width \( b_E \) [\( \mu m \)] | 1 644 | 1 027 | 869 | 490 | 1 087 | 1 246 |

This result is because, in this case, a process superimposed with the pre-cutting is produced (see figure 8). Depending on the size of the selected trimming allowance, it is then possible that this area produced by the pre-cutting process is not completely separated. It can be seen that only starting from a trimming allowance of \( z_{abs} = 1 \) mm (\( z_{rel} = 30 \% \)) and above, the work-hardened edge zone is almost completely removed or only a very minimal residual rollover zone is present.
5. Summary and outlook
To reduce the edge crack sensitivity, a 2-step shear cutting process (pre-cutting, trimming) was developed in a joint project between the Chair of Metal Forming and Casting at the Technische Universität München and Volkswagen AG.

To optimize the process parameters with respect to the ability of the cut edge to deform, the trimming allowance was systematically varied. Then the maximum achievable widening ratio for the collar drawing was determined. The test results show that for a pilot hole diameter of $d_0 = 50$ mm, the widening ratio can be increased by the trimming process by up to 350%. The highest widening ratio is achieved with a trimming allowance of $z = 1$ mm and a cutting gap of $u_s = 12.5$ %. The trimming process leads to a bending of the ring-shaped cutting. The effective bending moment leads to additional tensile stresses on the punch cutting edge, wherein these tensile stresses are added to the tensile stresses at that location from the material stretching. The ability of the material to deform is therefore exceeded earlier in trimming than in conventional shear cutting. As a consequence, the burnish zone is smaller for the trimmed test samples. In cut start tests, it could be further shown that the material separation takes place through stable crack propagation for the trimming. In contrast, in conventional shear cutting an unstable crack propagation occurs, which results in brittle fracture.

6. References

[1] Wurm A 2007 Ermittlung umformtechnischer Verfahrensgrenzen und Potenzialbewertung neuer hochfester Karosseriestähle Dissertation (Freiberg)
[2] Buchmayer B 2007 Innovative Beiträge in der Umformtechnik zum Leichtbau von Kraftfahrzeugen BHM vol 152 p 136
[3] Doege E and Behrens B-A 2007 Handbuch Umformtechnik Springer Verlag (Berlin)
[4] Fritz A-H and Schulz G 2010 Fertigungstechnik Springer Verlag (Berlin) vol 9
[5] Cammann J 1986 Untersuchungen zur Verschleißminderung an Scherschneidwerkzeugen der Blechbearbeitung durch Einsatz geeigneter Werkstoffe und Beschichtungen Dissertation (Darmstadt)
[6] Timmerbeil F-W 1957 Untersuchungen des Schneidvorganges bei Blech, insbesondere beim geschlossenen Schnitt Dissertation (Hannover)
[7] Schmidt R-A 2006 Umformen und Feinschneiden: Handbuch für Verfahren, Stahlwerkstoffe und Teilegestaltung Carl Hanser Verlag (München)
[8] Held C, Liewald M and Sindel M 2010 Erweiterte Werkstoffprüfverfahren zur Charakterisierung von Leichtbauwerkstoffen im Hinblick auf die Kantenrissempfindlichkeit MP Materials Testing (München: Carl Hanser Verlag) p 596
[9] Lange K 1990 Umformtechnik, Handbuch für Industrie und Wissenschaft, Band 3
Blechbearbeitung *Springer Verlag* (Berlin) vol 2

[10] Hentrich C 2002 Untersuchungen zum Aushalsen von Rohren mit starrem Werkzeug unter besonderer Berücksichtigung der Vorlochgeometrie *Dissertation* (Magdeburg)

[11] Schlagau S 1988 Verfahrensverbesserung beim Kragenziehen durch Überlagern von Druckspannungen *Dissertation* (Darmstadt)

[12] Otto M 2003 Erweiterung der Umformgrenzen beim Tiefziehen und Kragenziehen durch Nachschieben von Werkstoff *Dissertation* (Magdeburg)

[13] Wilken R 1957 Das Biegen von Innenborden mit Stempeln *Dissertation* (Hannover)

[14] Dannemann E 1980 Overflächen und Randzonenbeeinflussung durch Umformen und Schneiden *Technische Mitteilungen* vol 73 p 893

[15] Petzold W and Hentrich C 1984 Untersuchungen zu den Verfahrens- und Werkzeugkenngrößen beim Aushalsen von Rohren *EFB-Forschungsbericht* (Hannover) vol 59

[16] Hoogen M 1999 Einfluss der Werkzeuggeometrie auf das Scherschneiden und Reißen von Aluminiumblechen *Dissertation* (München)