Improvement of shear cutting process by stress superposition via cross-elastic partholder

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Abstract. High quality requirements for shear-cut workpieces made of advanced sheet metal materials nowadays pose highest demands on cutting technologies. In this context, stress superposition in shear zones represents a common approach to adjust cutting surface quality or reduce trim load, but usually requires sophisticated process technologies. For example, fine blanking technology allows to increase clean-cut portion, but requires advanced tool and press technology. Given this background, the present paper deals with a novel, low-cost and straightforward approach of stress superposition in conventional shear cutting processes and tools. For this purpose, the partholder was geometrically modified to achieve vertical and horizontal force transmission into the blank. Presented investigations with implemented Z-shaped partholder and its cross-elasticity show a significant impact on cutting surface quality. The results were obtained by a numerical study using the FEA-Software DEFORM 2D, wherein geometry and process parameters were varied. By superposing compressive stresses, clean-cut portion could be increased up to 43 % compared to conventional shear cutting of DP600 having a sheet thickness of 1 mm. Additionally, rollover height was significantly reduced by up to 50 % due to the transversal forces of the cross-elastic partholder, while burr height could be kept constant.

1. Introduction

Material separation by shear cutting technologies is commonly used in production processes. Many technical products made of metal are separated or pierced by shear cutting at least once in its production chain [1]. Here, the most frequently used method in metal forming industry is the conventional shear cutting, which can be performed on single-acting presses. Those separation processes with stroke rates up to 3,000 strokes per minute offer considerable cost advantages, particularly in large-scale production of sheet metal components [2]. Nowadays, the quality requirements of manufactured parts with regard to the cutting surface are constantly increasing and process results of conventional shear cutting are often no longer sufficient [1]. High-quality cutting surfaces, which can be used without additional rework, are characterized by a small rollover, high clean-cut portion and marginal burr heights [3]. With ordinary shear cutting tools and processes, however, only a clean-cut portion of up to 50 % is achievable [4], [5]. Therefore, for producing parts with higher quality requirements, subsequent reworking or finishing steps are necessary, which reduce the overall economic efficiency of the production chain.

For this reason, various special cutting tools and processes have evolved over the last decades. Two-stage shear cutting, for example, combines conventional shear cutting with a subsequent trimming operation to produce precise and functional part contours [6], [7]. Counter cutting avoids burr formation and improves cutting surface quality by a two- or three-stage, counteracting embossing and shearing
process [8]. These multi-stage shear cutting processes may increase part contour quality, but are accompanied by high demands on multiple axes tool design, part positioning issues, tooling cost or multiple acting presses. Therefore, single stage shear cutting technologies are more likely implemented to reduce complexity and cost of the manufacturing tools and processes. For example, conventional cutting of high-strength steels shows a tremendous reduction of clean-cut portion where a compressive stress superposition in the shear zone can counteract and again extend the formability of the material [9]. In this context, Senn et al. [10] investigated the impact of a new sheet metal cutting tool design using a concave nose punch geometry to superpose compressive stresses and thus increase the clean-cut portion up to 73 % for various steel grades. However, filigree punch edges reduce tool life in series production. In general, fine blanking technology is commonly applied to achieve highest part contour quality and precision [11]. This cutting process is characterized by a minimized cutting clearance, a special partholder geometry with a vee-ring indented along the cutting contour of the blank and an additional counter-acting pad. Due to this, the tool and process design of fine blanking generates a beneficial stress state in the shear zone and prevents an early fracture of material, which leads to clean-cut portions up to 100 % [12]. However, the complex and multi-acting tool and press design, lower stroke rates and a reduced tool life make fine blanking a cost-intensive process compared to conventional shear cutting.

Against this background, the present paper deals with a new approach for stress superposition in shear zones via a cross-elastic partholder geometry. Supported by numerical results, the proposed and new partholder design transforms the vertical load of the press into a horizontal and vertical load towards the blank, which superposes stresses in the cutting area and improves shear cutting processes.

2. Concept of cross-elastic partholder
In general, this paper pursues the research hypothesis of using a geometrically controlled blankholder deformation in combination with tool material elasticity for a simultaneous reversible horizontal and vertical partholder force transmission on blanks. Herein, the lateral contraction of elastic-plastic material, described by Poisson’s ratio [13], is used to generate a force transmission in the sheet metal plane with the help of static friction. Simultaneously, the vertical force transmission still provides the general functionality of a partholder with positioning and lift-off prevention of the blank. This tool setup is shown in figure 1 a) as a cross section for piercing rectangular or circular cut-outs.

![Figure 1](image_url)

**Figure 1:** a) Concept of a cross-elastic partholder in shear cutting tools and derived design variants with one- or double-sided Z-shaped partholders for b) compressive and c) tensile stress superposition.

However, a symmetrical vertical force transmission on the blank by a lateral material contraction \(F_{-x} = F_{-x}\) would not sufficiently impact the stress state in the shear zone. One solution for this is the concept of a Z-shaped partholder, derived from a single spring winding and shown in figure 1 b) and c). It enables a geometrically controlled and targeted cross-elasticity in a desired lateral working direction. Thereby, the diagonal alignment of the Z-shaped element defines the deformation and working direction of the partholder. If the diagonal points top down towards the punch, a horizontal compression force on the blank is transferred and leads to a compressive stress superposition in the shear zone. As explained
in the introduction, such a compressive stress superposition can increase the cutting surface quality. Here, it is conceivable to use one Z-element, only acting on one blank side, or a double-sided solution with two horizontally symmetrically located Z-shaped partholders (see figure 1 b). If the diagonal points top down away from the punch, a horizontal tensile force on the blank is transferred and leads to a tensile stress superposition. In particularly, this is important for mechanical separation processes of high-strength steels to decrease cutting forces [14]. Likewise, this can be realized by one Z-shaped partholder or a double sided-solution (see figure 1 c)). The numerical results presented in this paper deal with the approach of compressive stress superposition to increase cutting surface quality, measured by a high clean-cut portion and a minimum of rollover height.

3. Numerical study on a partholder design for compressive stress superposition in shear zones

The virtual tool design presented in this paper was carried out using the FEA-Software DEFORM 2D. All numerical investigations and simulations refer to the dual-phase steel DP600 with a thickness of \( t = 1 \) mm. For the blank, an elastic-plastic material model was chosen, whose material properties were determined by means of tensile tests in previous work of authors (see figure 2) [10]. Damage modelling used, refers to the normalized Cockcroft & Latham criterion with a cumulative real-time value \( C_{\text{normC&L}} \). This criterion is commonly applied in shear cutting simulation and integrates the ratio of maximum principal stress and the equivalent stress up to the limit fracture strain. Thereby, critical limit of plastic work \( (C_{\text{crit}}) \) is locally considered by deleting adjacent mesh elements. The determination of the critical limit of plastic work was done by conventional shear cutting experiments and an afterwards iterative calibration of \( C_{\text{crit}} = 2.8 \) of simulated cutting surface quality. Here, conventional shear cutting simulation with a cutting clearance of 10 \%, a standard partholder geometry and rigid tools with sharp punch and die radii (0.05 mm) were used and served additionally as a valid reference for the new partholder design. All other settings like mesh sizes and boundary conditions are described in the following and were kept constant to ensure comparable results. The implemented elastic-plastic and damage modelling led to a simulated clean-cut portion of 27 \% and a rollover height of 0.08 mm, which is in a good agreement with the experimental data (see figure 2 a)).

![Figure 2](image_url)

**Figure 2:** a) Validation of simulated surface quality for conventional shear cutting of DP600 and b) corresponding stress-strain curve and damage modelling of selected material.

3.1. Modelling approach of shear cutting with cross-elastic partholder

A parametrized 2D FE-model of shear cutting with cross-elastic partholder was built with DEFORM 2D Software in an integrated pre-processor. To reduce computational time, plane strain symmetric boundary conditions were applied to model shear cutting of rectangular cut-outs, see figure 3 a). The 2D finite elements were extruded in Z-direction with a thickness of 1 mm. The elastic-plastic modeled blank was discretized by 15,000 elements with an adaptive meshing and refinement towards the shear zone, limited by a minimum edge length of 0.006 mm. The nominal Z-shaped partholder geometry and its dimensions were conceptually designed and also discretized by 2D finite elements and an elastic tool steel material model (AISI-D2) was assigned. For calculation, punch and die were defined as rigid bodies and friction coefficients were set locally for blank and partholder at \( \mu = 0.2 \) and globally at \( \mu = 0.1 \).
Figure 3: a) 2D FE-model with plane strain symmetry and b) dimensions of Z-shaped partholder with c) the cross-elastic deformation for nominal simulation setup.

For the initial assumed design, the principal mechanism of the targeted cross-elasticity by Z-shaped partholders and two-dimensional force transmission on blanks can be illustrated by the total nodal displacements of the respective elements, see figure 3 c). The vertical applied partholder force $F_{PH}$ of 5,000 N compresses the Z-shaped component and results in a lateral deformation of the partholder towards the shear zone at its contact area with the blank. These minor elastic deformations of the Z-shaped partholder towards the downward moving punch do result into an improved cutting surface quality compared to conventional shear cutting, see figure 4. Even for the initial process design with a reduced cutting clearance and comparable partholder forces, the rollover height was reduced by 50 % due to the lateral stress superposition. Furthermore, the clean-cut portion increases from 27 % to 47 %. Regarding the fracture surface of conventional and shear cutting with Z-shaped partholder, the fracture height and fracture angle was reduced because of the stress superposition together with a smaller cutting clearance (6 %) of initial simulated design. In contrast, a slight increase of the burr height from 0.01 mm to 0.03 mm was numerically predicted when cutting with Z-shaped partholder.

Figure 4: Comparison of simulated surface quality for cutting with nominal Z-shaped partholder and conventional shear cutting.

3.2. Sensitivity analysis
With this 2D FE-model, a numerical sensitivity analysis was carried out regarding the influence of the Z-shaped partholder geometry, the cutting clearance $u_S$ and the partholder force $F_{PH}$ on the cutting surface quality. The initial designed geometries and tool setup is shown in figure 3 b) together with the varied parameters. In addition, the nominal settings as well as the considered parameter space are given
in table 1. The sensitivity analysis, presented in the following, based on a Latin-Hypercube (LHC) parameter sampling with more than 50 runs and different parameter combinations.

**Table 1:** Summary of investigated process and geometry parameters.

| Parameter   | \( b_1 \) | \( b_2 \) | \( r_1 \) | \( r_2 \) | \( h \) | \( u_s \) | \( F_{PH} \) |
|-------------|-----------|-----------|-----------|-----------|-------|--------|----------|
| Initial     | 10        | 8         | 0.5       | 1         | 12    | 6      | 5        |
| LHC-interval | 8 - 12    | 6 - 10    | 0.3 - 0.7 | 0.8 - 1.2 | 10 - 14 | 1 - 11 | 3 - 7    |

In the course of the sensitivity analysis, the Z-shaped partholder geometry, the cutting clearance \( u_s \) and the partholder force \( F_{PH} \) were varied using a LHC parameter sampling. This enabled the determination of the impact of these parameters on the cutting process and the cutting surface quality, represented by estimated linear correlation coefficients \( \rho \). Due to an internal and dependent scaling of the Z-shaped partholder geometry parameters by DEFORM 2D software, all varied dimensions could be summarized as one geometry parameter. Subsequently, correlations between this geometry parameter as well as the other input parameters with the cutting surface quality (burr, clean-cut, rollover and blank imprint) and process conditions (cutting surface and partholder stress) were identified. These correlations are shown in figure 5 a). Here, a positive value \( \rho \) of up to 1 indicates a rise of result variable when the input parameter is increased, and vice versa (-1 ≤ \( \rho \) ≤ 0).

Due to the dependent scaling of the Z-shaped partholder geometry size within narrow boundaries, only minor correlations can be directly observed in cutting quality. It shows a certain tendency, that increasing the size of the partholder reduces the burr formation, increases the clean-cut portion, requires more cutting force but reduces the stress of the partholder itself. The elaborated correlation between a reduced cutting clearance, an enhanced surface quality and increased process loads are in a good agreement with the state of the art for conventional shear cutting [1]. It is thereby confirmed that a minimized cutting clearance increases the clean-cut portion, reduces burr and rollover height but requires significantly higher cutting forces.

![Figure 5: a) Estimated correlation coefficients for varied parameters on surface quality and shear cutting process. b) Correlation between partholder force and clean-cut portion due to cross-elastic partholder.](image)

In general, it can be stated that the Z-shaped partholder geometry enables the partholder force as an influencing factor on cutting surface quality and process. Compared to a partholder or stripper of conventional shear cutting tool design, which only serves as a rigid blank fixture or lift-off prevention, the new partholder design impacts the cutting surface quality and the process parameters. Due to the cross-elastic behaviour of Z-shaped partholder, an increase of partholder force tremendously enhances the
cutting surface quality. It directly impacts the clean-cut portion and reduces burr formation and rollover height. It is limited by the formation of blank imprints (< 0.001 mm) at the contact zone between partholder and blank surface to ensure an overall sufficient part quality for cut-outs. It also affects the load on partholder, represented by an evaluation of maximum partholder stress, which is discussed in the following section.

3.3. Best-case design of DoE

Within the investigated parameter space (see table 1) and the total of 50 simulation runs, a best-case design of the Z-shaped partholder was selected. This selection was made by taking into account the maximum achievable clean-cut portion and a marginal imprint of the partholder on the blank surface. The resulting partholder dimensions are shown in figure 6. In addition, the partholder stress distribution occurring and the achievable cutting surface quality are depicted in this figure. Thus, with the presented geometry, a cutting clearance \( u_c \) of 1 \% and a partholder force \( F_{PH} \) of 5.1 kN, a clean-cut portion of 67 \% and a neglectable blank imprint is obtained. However, the improvement of cutting surface quality is accompanied by a critical effective stress for tool steel \( (\sigma_{max} = 2,600 \text{MPa}) \) at the lower radius \( (r_2 = 1 \text{ mm}) \). On contrary, selected high carbon and chromium steel AISI-D2 exhibits a compressive strength up to 2,500 MPa and a bending strength up to 4,000 MPa [15]. Thus, even for static failure evaluation, critical loads on Z-shaped partholder geometry can be stated. In terms of an application with cyclic loading by thousands of strokes and a considerably reduced fatigue limit (~ 1,000 MPa) [16], current design shows an extensive risk of premature fracture. This needs to be tackled in a future redesign work to reduce the notch effect in respective area and increased tool strength with improved material properties by surface or heat treatment [16], [17] and later on verified in experimental endurance tests.

**Figure 6:** Numerical results for a) effective stress on selected best-case Z-shaped partholder geometry with corresponding dimensions and b) simulated cutting surface quality.

4. Classification of shear cutting results

In the following chapter, the cutting results obtained with the devised best-case design of the Z-shaped partholder is numerically compared to those of a conventional shear cutting tool design as well as a state of the art fine blanking setup, but without utilizing a counter-acting pad. The comparability is ensured by defining the same cutting clearance, material, simulation settings as well as punch and die radii. In this context, figure 7 shows the mean stress distributions obtained with the three different shear cutting processes, each at a punch intrusion depth of 0.3 mm. For conventional shear cutting (figure 7 a)), the formation of tensile stress bands can be observed, which provoke an early failure of material. On contrary, the other two process variants (figure 7 b) and c)) show a fully compressive stress coverage at the shear zone, which supports an extended plastic material flow and thus high clean-cut portions.
Figure 7: Mean stress distribution at a punch intrusion of 0.3 mm for a) conventional shear cutting, b) cutting with Z-shaped partholder and c) fine blanking.

Figure 8 shows a comparison of the cutting surfaces obtained with the three investigated shear cutting methods and illustrates the resulting formations of rollover, clean-cut, fracture and burr. Additionally, these numerical results show the emerging damage in the cutting area, which represents the edge hardening and provides information of the formability in subsequent forming operations. Here, conventional shear cutting reveals the lowest cutting surface quality with a clean-cut portion of 47% and severe edge hardening along more than 50% of blank thickness. Simulation results for the new approach using the Z-shaped partholder offers an increased clean-cut portion of 67%, reduced rollover and burr height as well as minor edge hardening phenomena. At current state of work, fine blanking still provides highest cutting surface quality (73% clean-cut portion) with lowest material damage in shear zones. Nevertheless, rollover and burr formation are found at the same level as cutting with Z-shaped partholder.

Figure 9 presents numerically determined force-stroke curves for conventional cutting (black), fine blanking (blue) and cutting with Z-shaped partholder (grey). The calculated forces relate to the 2D-FE-model at a section depth of 1 mm. For all processes, maximum cutting force occurs at a punch intrusion depth of 0.1 mm at the end of the elastic deformation phase of blank material. Here, maximum cutting force of conventional and fine blanking amounts to 442 N and a slightly higher force (453 N) is required for cutting with Z-shaped partholder. The subsequent plastic deformation phase leads to a decrease of cutting forces for all three investigated tool designs. It can be stated, that fine blanking and cutting with Z-shaped partholder do exhibit same flow behavior whereas conventional
shear cutting shows a slightly higher decrease of forces. The abrupt force drop marks the separation of material when the shearing stress finally exceeds its shear fracture limit. This correlates with the calculated clean-cut portions of all three tool designs (figure 8). After material separation, the push-phase proceeds at different constant force levels. Here, the compressive stress superposed by fine blanking and cutting with Z-shaped partholder leads to an increased contact pressure between cutting and lateral punch surface and thus to marginally increased push forces.

Figure 9: Numerically calculated cutting force curves for conventional shear cutting, cutting with Z-shaped partholder and fine blanking.

5. Conclusion and outlook
In the numerical study presented in this paper, a new design of a cross-elastic partholder was analysed to superpose stresses in shear cutting zones. First, suggested Z-shaped partholder geometry for compressive stress superposition was modelled in DEFORM 2D FE-software and a parametric shear cutting simulation was set up. The numerical sensitivity analysis revealed correlations of the partholder geometry, cutting force and clearance on the process and the cutting surface quality. Due to the targeted cross-elasticity of Z-shaped partholder, clean cut-portion could be controlled by normally applied partholder force. Second, the best-case design of the Z-partholder, leading to the highest achievable clean-cut portion (67 %), was compared to the numerical results of conventional shear cutting (47 %) and fine blanking (73 %).

These first prospectful results for stress superposition via cross-elastic partholder geometry to enhance cutting surface quality by minor tool and process modifications of a conventional shear cutting tool motivates for future research work. Currently, a topology optimization of partholder geometry with wider boundaries and different target options such as cutting surface quality or tool load is set up to achieve multiple geometries for both tensile and compressive stress superposition. Furthermore, physical implementation of new partholder design into a prototype tool and an experimental verification of the numerical results is necessary. Here, partholder geometry and cutting process have to be analysed in terms of static and fatigue strength as well as achievable cutting surface quality.

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