Numerical investigation of a new sheet metal shear cutting tool design to increase the part quality by superposed compression stress

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Abstract. Nowadays, a major criterion for the quality of shear cut workpieces is characterised by a smooth final cutting surface. Normally, this surface only can be manufactured by using fine cutting or trimming technology. Major disadvantage of these processes is the complex tooling design caused by a double-acting press and corresponding tool layout. Content of this numerical study is to investigate the impact of a new sheet metal cutting tool design to increase the clean-cut portion in conventional shear cutting of high strength steel (DP600). Using FEA-Software DEFORM 2D, the models of fine cutting, conventional cutting and cutting with new tool design were mapped by comparing cutting surface results and stress distribution in the shearing zone. The main criterion of the optimization of tool design focuses on an enlarged clean-cut area along the cutting surface compared to conventional shear cutting. This study is based on the design of experiments (DOE) using Latin-Hypercube-Variation of the factors cutting clearance, die radius, punch radius, punch velocity, part holder force and special geometry designs to identify and to optimise new tool geometry. New tool design shows a significant increase of clean-cut surface up to 73% compared to conventional cutting surfaces disclosing 35% when using tools according to standard design rules. Using this new punch design, it is possible to shear high strength steels revealing a noticeably performed shearing surface quality.

1. Introduction

Shear cutting is a widely used mass production process, in which almost every technical product in its production chain is processed at least once. Conventional shear cutting is the most frequently used method in industry. This process can be realized on single-acting presses and is characterized by a high achievable number of units due to 3,000 strokes per minute [1]. Due to increased quality requirements for shear cut components with regard to the cutting surface, the cutting results in normal cutting are often no longer satisfactory. High quality functional surfaces are characterised by a small roll-over process, a high smooth cut and a low burr height. With normal cutting, however, only a smooth cut portion of up to 50 % is generated [2], [3], [4]. Therefore, post-processing procedures are necessary to obtain the desired cutting surface quality. Nevertheless, this has a negative effect on the economic efficiency of the entire production process. In order to meet the high demands on the cutting surface, fine blanking, counter cutting and re-cutting are used today [5], [6], [7], [8], [9], [10]. This process enables the production of precision components with smooth cuts of up to 100% without any reworking. A special part holder geometry, an additional counter-acting pad and the adjustment of the cutting parameters can promote an advantageous stress state during the cutting process in such a way that no
premature breaking of the material along the cutting edge occurs. The punched parts can be used directly after cutting without a subsequent milling process. However, due to the more complex tool design, lower stroke rates and relatively short tool life, fine blanking is a much more cost-intensive process compared to normal cutting. A mass production process that combines the advantages of conventional shear cutting and fine blanking for the production of functional components with a high percentage of smooth cut and at the same time a manageable process effort is currently not known. Thus, this paper investigates the impact of modified cutting tool shapes to increase the clean-cut percentage in conventional cutting. Normally, a high clean-cut area (CCA) could only be achieved by using fine cutting. The major disadvantage of this process is its complex sequence caused by multiple-acting presses or multiple axes tool design. This paper gives an overview of the simulation setup and its results of a new shear cutting tool design with a concave nose punch design to increase part quality of shear cutted parts.

2. Modelling approach and simulative setup

In this paper, a new sheet metal shear cutting tool was designed to increase the part quality by superposed compression stress, applied along outline of punched part. Besides, an optimization of shear cutting parameters was performed here to increase the smooth cut zone up to a maximum, using Software DEFORM 2D. The numerical investigation is based on criteria like amount of clean cut area, stability of simulation, state of stress in the shear zone and technical feasibility. The new tool design, here called concave nose punch, is shown in Figure 1. The purpose of this concept is to locally increase the superposed compression stress in the shearing zone, which enables a high clean cut zone. The small punch nose can penetrate the metal sheet from both sides and this results in a better stress state during the cutting. To analyze the significant parameters with the greatest influence on the clean-cut area (CCA), a DOE with 100 runs (Latin-Hypercube sample) is executed. The CCA of all simulations is measured with the ‘measure tool’ of the DEFORM 2D software.

![Diagram of parameters](image)

Figure 1: Parameters of concave nose punch design

| Varying parameters | LHC-interval |
|--------------------|-------------|
| Web width $b_{Web}$ [mm] | 0.1 – 0.5 |
| Web angle $\gamma_{Rsa}$ [°] | 10 – 90 |
| Punch cutting edge $R_s$ [mm] | 0.01 – 0.1 |
| Cutting clearance $\mu_s$ [-] | 0.5 – 15 % |
| Part holder force $F_{Ph}$ [kN] | 0 – 30 |
| Die cutting edge $R_d$ [mm] | 0.01 – 0.2 |
| Punch velocity $v_5$ [mm/s] | 5 – 300 |
| Distance part holder – punch $l$ [mm] | 0.05 – 2 |

Table 1: Summary of investigated process and design parameters

The investigated sheet metal material D600 having a thickness of $t = 1$ mm was finely meshed with solid elements and an elastic-plastic material law was chosen, based on tensile test. To reduce calculation errors, the Newton-Raphson method was chosen. It reduces errors by adding an internal stiffness iteration for each load step. All other components such as the punch, part-holder and the die in calculation were defined as rigid. In this simulation, the normalized Cockroft & Latham criterion was used for damage modelling. This caused a local failure of a mesh element as soon as the cumulative real-time value $C_{normC&L}$ of the plastic work reached a critical limit of $C_{crit} = 2.8$. This value was calibrated by comparing the smooth cut zone of the simulation and experiment. For this several damage values were simulated for conventional cutting and then the cut surfaces were compared with the real part in simulation. According to [11], two to five adjacent elements must fail before the program starts deleting extremely deformed elements. Element deletion is a method of modeling ductile material failure from crack initiation and expansion to global fracture. It is known as the "Normalized Cockroft & Latham" criterion and formulated as follows:
The first main stress $\sigma^*$ refers to the equivalent stress $\sigma_v$. This is a common model, mainly used in the simulation of shear cutting.

3. Results of DoE - Sensitivity analysis

Increase the part quality of stamping parts is the reason for development of the new investigated concave nose punch design. The objective of the numerical investigation is to examine to what extent it is possible to obstruct the material flow by penetrating the punch on the side facing away from the cutting edge in the resulting slugs and thus increase the smooth cut portion. The possible penetration depth is assumed to be 1 mm sheet metal thickness and 0.3 mm web width. The opening angle of 70° is intended to stabilize the punch nose. By simulating this concept with the cutting clearance of 1%, 5% and 15%, it can be determined that the punch nose can penetrate deeper into the blank with a larger cutting clearance. In this case, a higher compressive stress state is located below the punch face than when cutting with conventional punch geometry. Highlighted parameters in Table 1 are those indicating a significant influence on the clean cut area (CCA). Furthermore, there is a smaller influence of the tool edge radii. Due to the dominance of the highlighted parameters, this can only be proven by analyzing all 100 runs carefully. The results of all measured CCA depending on all 100 simulation runs are shown in Figure 2. Compared to conventional shearing, all measured smooth cut portions are above the measured 35% of normal cutting. CCA values range from 40% to 84%, depending on the parameter combination investigated. The highest CCA is shown with the parameter combination in run 92 (marked red in Figure 2).

Figure 3 shows a comparison of two DOE-runs of the concave nose punch design with different web widths. If the web width is very small as in P92 design, the punch nose can penetrate into the sheet metal from both sides. This reveal a high influence on the stress state during the cutting process. The penetration causes an increased compressive stress state, which suppresses cracking, resulting in a higher amount of CCA. The wider the web width, the more the process behaves like a conventional cutting process. Only the larger edge radii are responsible for the delayed crack formation. The graph in Figure 3 shows the point at which the critical damage value has been reached and cracking is initially simulated. The highest amount of CCA with the normal cutting model is possible with a very small clearance, e.g. 1%. In comparison, the two DOE-runs show better results because of the facts mentioned above. Especially with the P92 design, a high clean-cut area can be achieved with the small web width and the

![Figure 2: Clean cut area DOE-results for 100 runs of the concave nose punch design](image)

![Figure 3: Concave nose punch design: Influence of the nose height and nose width on clean-cut area](image)

![Figure 4: Comparison of penetration depth of three DOE-runs; punch stroke 0.6 mm](image)
resulting high penetration depth. Results of numerical investigations also show that a higher clearance between punch edge and cutting die edge has a positive effect on the clean-cut area (CCA). This is very untypical for a shear cutting process. A larger clearance simplifies the penetration process of the punch nose on its inner side and the results of the sensitivity analysis show that the CCA rises when the penetration depth is increased. The penetration depth correlates with the size of the web width and the web angle. In Figure 4, this fact is shown. Run 83 has a small web width like P92 but also a small web angle. With a small angle, the contact surface of the punch nose highly increases and the process looses the ability of penetrating into the sheet metal. With a large nose width, the web angle looses his significance because the punch cannot penetrate the sheet metal at inner site of punch (P97).

4. Results of Optimization and metamodel building

For a prediction of an optimal solution, the optimization software needs a metamodel based on DOE data and sensitivity analysis. A metamodel is a data construct that refers to information from one or multiple existing models. This means that the test points generated in the defined parameter space can be approximated on the basis of the DOE simulations [12]. In order to evaluate the quality of the approximation of the metamodel to DOE data, the programme code optiSLang determines a forecast value, the so-called CoP, which indicates the quality of the model. This measure determines how well the predicted optimization results match with a subsequent simulation. The CoP of the smooth cut metamodel of the concave nose punch design is 84 %. Figure 5 shows a three-dimensional metamodel of the smooth section, which is able to approximate the 100 test points in the form of a plane. The metamodel can map the results of all simulated test points with regard to the smooth cut portion. The parameter space stretched by LHC sampling comprises the two most significant parameters of the model, the web width and the web angle. To maximize the clean-cut area, the optimal parameter combination must be found. On the basis of the DOE-results and the sensitivity analysis, an optimization analysis is run for this concept with the software ‘optiSLang’ for the concave nose punch design. Table 2 shows the setup and the result of the calculated optimal parameter combination for a maximum clean-cut area value. With a very small web width and a maximal angle of the punch nose, the CCA can reach up to 0.85 mm.

Table 2: Optimized parameters of the concave nose punch design

| Parameters                  | Setup                        | Result |
|-----------------------------|------------------------------|--------|
| Web width $b_{\text{Web}}$ [mm] | 0.1                          |        |
| Web angle $\gamma_{\text{Web}}$ [°] | 90                           |        |
| Punch cutting edge $R_{S}$ [mm] | 0.05                         |        |
| Cutting clearance $\nu_{S}$ [-] | 12 %                         |        |
| Part holder force $F_{\text{NH}}$ [kN] | (3)                         |        |
| Die cutting edge $R_{M}$ [mm] | 0.13                         |        |
| Punch velocity $v_{S}$ [mm/s] | (100)                        |        |
| Distance part holder – punch $l$ [mm] | (0.5)                      |        |

Figure 5: Metamodel of concave nose punch design—optimized clean cut area
Due to the very small width of the punch nose, there is a high risk for tool failure caused by fracture. To evaluate the mechanical strength of the punch nose, a die stress study is conducted according to the DEFORM manual. Afterwards, a complete simulation is carried out with an elastic punch. With this simulation it is possible to identify the maximal effective von Mises stress at the punch nose, as shown in Figure.

Figure 6: Graph of max. von Mises stress on the elastic simulated concave nose punch during piercing of sheet metal material DP600

The die stress analysis shows that a very small web width like 0.1 mm is not a reasonable solution for a new punch geometry. To control the result of the optimization process, it is possible to set limit values for the calculated optimal parameter combination. The following lists show the limit values for the new optimization to control the effective stress during the piercing by use of the concave nose punch design.

- web width: 0.2 mm ≤ web width ≤ 0.3 mm
- web angle: 45° ≤ web angle ≤ 75°

Table 3 lists the new parameter combination and shows the new setup of the optimized tool concept. With this punch geometry, the maximum of the affecting stress is only about 2000 MPa. The value of the clean-cut area is 73% of the cutting surface. Compared to the normal cutting, this is still a significant improvement. This optimization is only valid for the investigated sheet metal material DP600 having a sheet thickness of 1 mm, but nevertheless the wear behaviour and fatigue behaviour of the punch nose must be investigated in a further study. For this reason, a special tool design and experimental wear tests are planned.

Table 3: Parameters and setup of the new optimized concave nose punch design after setting limited geometry values

| Parameters                      | Setup |
|---------------------------------|-------|
| Web width $b_{\text{web}}$ [mm] | 0.2   |
| Web angle $\gamma_{\text{web}}$ [°] | 71    |
| Punch cutting edge $R_b$ [mm]   | 0.06  |
| Cutting clearance $\mu_s$ [-]   | 15 %  |
| Blank holder force $F_{\text{NH}}$ [kN] | (3)   |
| Die cutting edge $R_d$ [mm]     | 0.1   |
| Punch velocity $v_S$ [mm/s]     | (100) |
| Distance Blank holder – punch $l$ [mm] | (0.5) |
5. Comparison of the cutting surfaces

Figure 7 shows the final comparison of the cutting surfaces for both basic simulations (normal and fine cutting) and the new concave nose punch design. Compared to normal cutting, piercing with concave nose punch design, shows very good results in the size of the clean-cut area along the cutting surface. Especially the high cutting clearance makes this process easy to manufacture and is a good progress in shear cutting. Now experimental tests must be carried out to verify the simulated results of the new geometries.

6. Conclusion

Having a local normal pressure transmitting zone, the concave nose punch design is able to penetrate the sheet metal material and thus improve compression stresses in the shearing zone. The cutting parameters were analysed with regard to their influence on the clean-cut portion, the roll-over and the penetration depth of the punch inner side. In addition to the dimensions of the concave nose punch, the cutting edges and the cutting clearance have been also proven to be significant. First solution was simulated by an initial optimization based on sensitivity analysis data, which achieved a high percentage of smooth cut area, but would lead to a failure of the punch due to very high loads on the punch nose in the experiment. For this reason, boundary conditions were defined for the punch geometry, which were taken into account by the optimization solver, when searching for a new optimal parameter combination. A further stress analysis of the improved solution confirmed a purposeful concept, which doubles the target size in comparison to normal cutting with a clear cut percentage of approx. 70%.

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