Influence of tool elasticity on process forces and joint properties during clinching with rotational tool movement

Maria Hiller, Tim Benkert, Simon Vitzthum and Wolfram Volk
Chair of Metal Forming and Casting, Technical University of Munich, Walther-Meissner-Strasse 4, 85748 Garching, Germany
maria.hiller@tum.de

Abstract. Clinching as a joining method for sheet metal components offers various advantages. Therefore, the process optimization using finite element simulations is continuously increasing. For translational clinching, the use of rigid tools results in a good prediction of process forces and joint properties. In case of roller clinching, the lateral forces acting on the punch lead to significant elastic tool deformation during the process. This paper focuses on the effects of the tool elasticity on the joining forces, the tool deformation and the joint formation during roller clinching. The results are obtained using the finite element tool Abaqus. To evaluate whether higher simulation costs in form of elastic tools are necessary, the obtained clinchpoints are compared to experimental data.

1. Introduction
Clinching is a joining method which uses plastic deformation. The result is a form and force closed joint without any auxiliary parts. Therefore, clinching supports the combination of tailored materials without increasing the weight by the joining process. The main advantages of clinching are the maintenance of coatings, the possibility to join different material combinations and that neither heating nor preparation before joining are needed. [1]

Roll forming is a continuous bending of coiled sheet material using several roller pairs. Thereby, open and closed profiles are obtained for many construction purposes. [1] For roll forming, there is a trend towards process integration like surface treatment, blanking or joining processes [2]. Next to welding, clinching is an increasingly used joining technology to close roll formed profiles. Roller clinching allows the direct integration of the clinching process in roll forming systems.

Roller clinching combines the advantages of clinching and roll forming by mounting the clinching tools on tool rolls. This allows to continuously feed the sheet materials through the tool rolls and to join them at the same time. Besides the advantages of the continuous tool movement and the possibility of direct integration in the roll forming process, the change from translational to rotational kinematic leads to challenges concerning joint strength and tool load. In translational clinching, the axes of punch and die always remain aligned to each other and perpendicular to the sheets. Deviations in these parameters lead to a non-symmetric joint formation [3]. The same is observed for roller clinching. During the roller clinching process, the tools are not aligned to each other except for their bottom dead center. This results in a highly asymmetric joint formation with anisotropic joint properties. This was observed for steel-steel [4–6] and steel-aluminum material combinations [7,8]. Due to the not perpendicular contact of tools and sheets, the tools are charged with lateral forces.
Finite element simulations in conventional clinching consider the clinching tools mainly as rigid bodies [9–14]. [15] uses also rigid tools, but investigates the influence of the C-frame’s stiffness on the joint formation. [16] employs rigid tools for the evaluation of the joint formation and linear elastic tools to investigate the tool load during thick sheet clinching. [17] and [18] employ an elastic punch to investigate the maximum punch loads during clinching, but the influence of elastic tools on the joint formation has not been investigated yet. Therefore, the aim of this paper is to obtain an understanding of joining forces during the roller clinching process. The influence of the normal and lateral forces on the tool deformation and joint formation is of special interest. Joining forces, tool deformation and clinchpoint geometry are analyzed for rigid and elastic tools.

2. Roller clinching process

Figure 1 (left) shows the roller clinching setup which basically consists of a punch and a die roll. The punch roll includes the punch itself as well as a blank holder, which fixes the sheets before joining and strips the clinchpoint from the punch afterwards. Cavities on the die roll carry the dies. Rolling radii of punch \( r_p \) and die \( r_d \) can be adapted using washer plates to achieve the desired joint bottom thickness of \( x = 0.55 \) mm and to investigate the effects of different rolling radii on the clinchpoint formation [6]. The distance of the tool roll center points is fixed at \( d = 286.48 \) mm. Because of the elasticity of the tool setup, \( r_p + r_d + x \neq d \) to obtain a joint bottom thickness of \( x = 0.55 \) mm.

Sheets are continuously fed through the tool rolls with a constant velocity \( v \). Angular velocity of punch and die roll are set to \( \omega = \frac{r_r}{v} = 1 \) deg/s with a reference radius of \( r_r = 143.5 \) mm. The blank holder is spring-suspended and the resulting force at the bottom dead center is 800 N. To ensure an exact positioning of the sheets, they are clamped between a linear drive and a decoiler with a holding force of \( F = 500 \) N. More details can be found in [6].

![Figure 1: Roller clinching setup (left) [8] and tool geometries (right).](image)

### Table 1: Material parameters of the used steels.

| Material type | E-module in N/mm² | Yield strength in N/mm² | Tensile strength in N/mm² | Poisson ratio | Density in g/cm³ |
|---------------|-------------------|-------------------------|---------------------------|---------------|-----------------|
| DC04          | 210000            | 159                     | 292                       | 0.3           | 7.85            |
| PM-steel      | 218000            | -                       | -                         | 0.3           | 7.78            |
Figure 1 (right) depicts the geometries of punch and die. The die is rigid without lamellas and the punch has a flat tip. Punch and die are made of a powder metallurgical (PM-) steel. The mild steel DC04 with a thickness of 1 mm is the investigated sheet material. This steel is often found in the automotive industry for parts which require a good material formability. Material parameters of both steels are presented in table 1.

3. Simulation setup

The finite element simulations are carried out with the finite element software Abaqus 6.12-3. Because of the complex contact situations and the high deformations, the explicit integration scheme is used [5]. In contrast to conventional clinching, the process necessitates a 3D simulation model (figure 2). Only the symmetry in the x-y-plane allows to reduce simulation costs by modelling just a half model. Thus, symmetry boundary conditions in all deformable elements in z-direction are necessary (not depicted in figure 2). Modelling only the elements of the experimental setup, which are directly involved in the joint formation, using mass scaling and increasing loading rates reduces simulation time. Mass scaling and loading rates are chosen to values which neither effect the joint formation nor the process forces.

Blank holder and sheet support are both rigid bodies. Punch and die are modelled either rigid or linear elastic. Both sheets are defined using an elastic-plastic material model for DC04 (table 1).

Figure 2: Simulation setup with rigid tools and corresponding boundary conditions.

In reality, the tool rolls rotate and the sheets translate. However, in the simulation model the tool rolls rotate and translate while the sheets stand still. This inversion of the kinematics simplifies the model omitting unwanted dynamic effects in the sheets caused by accelerations. Punch and blank holder move translationally along the negative x-axis and rotate counter clockwise around the punch roll centre RP_p in the x-y-plane. The blank holder has an additional degree of freedom along the punch axis with the stiffness of the springs c used in the experimental setup. Die and sheet support rotate clockwise around the die roll centre RP_d and move translationally along the negative x-axis. The sheets are positioned by a line load corresponding to the experimental setup. To be able to describe the formed clinchpoint
properly, the arbitrary Lagrangian-Eulerian (ALE) method is used in the forming zone. Using shell elements in the area without high deformation allows to reduce simulation time as well as to apply boundary and contact conditions correctly.

For modelling the friction between the contact partners, the coulomb friction model was used in combination with a shear stress limit of $1/\sqrt{3}$ yield strength [19]. The friction coefficient between tools and sheets were determined in a stripping test to 0.15. The same value is also used for the sheets’ contact.

4. Experimental Design

To investigate the influence of the tools’ elasticity on the joining forces as well as on the joint formation, three different numerical and one real experiment are carried out (table 2). Numerical experiments contain one case for elastic tools (no. 1) and two for rigid tools (no. 2 and 3).

To compare loads and clinchpoint geometries between rigid and elastic tools, the joint bottom thickness has to be equal in both cases (no. 1 and 2). Therefore, the distance between punch and die in the bottom dead center is reduced for deformable tools. This is done by increasing the die rolling radius. For the analysis of the elastic tools’ deformation compared to their rigid counterparts, the same rolling radii are chosen (no. 1 and 3). This leads to a reduced joint bottom thickness in case of rigid tools.

To evaluate the simulation’s accuracy, the simulated clinchpoints’ geometries are compared to experimental data (no. 0). Four cross sections gained by the experiments are used to analyze the clinchpoints’ characteristics neck thickness and undercut as proposed in [6].

| Experiment number (no.) | Method       | Tool elasticity | Punch rolling radius $r_p$ in mm | Die rolling radius $r_d$ in mm | Joint bottom thickness $x$ in mm | Deformation in normal direction in mm |
|-------------------------|--------------|-----------------|---------------------------------|-------------------------------|---------------------------------|--------------------------------------|
| 0                       | Test rig     | Deformable      | 143.25                          | 142.90                        | 0.55                            | 0.22                                 |
| 1                       | Simulation   | Deformable      | 143.25                          | 142.82                        | 0.55                            | 0.14                                 |
| 2                       | Simulation   | Rigid           | 143.25                          | 142.68                        | 0.55                            | 0.00                                 |
| 3                       | Simulation   | Rigid           | 143.25                          | 142.82                        | 0.41                            | 0.00                                 |

5. Results

Figure 3 shows the joining forces depending on the tools’ elasticity for a constant joint bottom thickness. The punch angle (figure 2) is zero at the tool’s bottom dead center and positive after the tool’s bottom dead center. Forming forces are determined at the reference point RP, located in the center of the punch roll (figure 2). The joint formation can be divided by the joining force in normal direction into five phases analogous to translational clinching [20,21]: offsetting (1), upsetting (2), flow pressing (3), load relief (4) and punch retraction (5).

During the offsetting (1) and the upsetting phase (2), the clinching forces are irrespective of the tools’ elasticity. There are some oscillations visible for the deformable punch prior to the sheet impact because of the dynamic explicit approach. In flow pressing phase (3), differences in the lateral forces between rigid and deformable tools occur. Lateral forces for rigid tools increase stronger than for deformable tools. This trend intensifies during the load relief phase (4). At the lateral force peak, the force of rigid tools doubles the one of deformable tools. The normal force of rigid tools slopes down stronger than the one of deformable tools. When the punch is retracted (5), there are still lateral forces acting on the punch, but no normal forces. In the case of rigid tools, lateral forces disappear earlier than in the case of deformable tools.
Figure 3: Influence of deformable (def.) and rigid (rig.) tools on simulated joining forces normal (nor.) and lateral (lat.) to the punch axes depending on punch angle for a constant joint bottom thickness (table 2, no. 1 and 2).

Figure 4: Displacement of deformable tools compared to rigid tools for equal tool rolling radii depending on punch angle (table 2, no. 1 and 3).

To get a deeper understanding of the different behaviors of rigid and deformable tools, the tools’ positions (figure 4) are compared for the angles marked in figure 3. The lateral force during offsetting (1) and upsetting (2) phase moves the punch in negative x-direction. During flow pressing (3), the lateral force changes from negative to positive, which results in a displacement of the deformable punch in
positive x-direction. Because of the big lever arm, lateral forces of 3.0 kN result at the punch tip corner in a displacement of 0.14 mm during load relief at an angle of 2.6 deg. The maximum normal force of 36.2 kN leads to a displacement of 0.11 mm at the middle of the punch tip at an angle of -1.2 deg.

Compared to the punch, there is no visible deformation of the die in lateral direction during the whole clinching process. In normal direction, there is a slight compression of the effective volume when the normal force reaches its maximum at an angle of -1.2 deg.

**Figure 5:** Comparison of clinchpoint geometries between experiment and simulation for a constant joint bottom thickness (table 2, no. 0, 1 and 2).

To evaluate the influence of the tools’ elasticity on the geometry of the clinchpoints, figure 5 compares the experimental data to the one gained for deformable and rigid tools at a constant joint bottom thickness. The clinchpoint obtained with deformable tools, shows a very good accordance with the experimental results. Neck thicknesses as well as the undercut at the impact side are similar (figure 6). Joints obtained with rigid tools show higher deviations from the experiment. Punch and die geometries are not reproduced accurately. Furthermore, deviations at the neck thickness at the retraction side are visible and the undercuts are significantly smaller compared to the experiment (figure 6).
The displacement of the punch due to normal and lateral forces changes the punch geometry as well as the kinematics during the clinching process. This becomes especially clear during impact and retraction of the punch. Although the simulation with deformable tools shows very good accordance with the experiments, the undercut at the retraction side still exhibits small deviations. As especially the lateral forces are affected by the elasticity of the tools, the deviations at the retraction side of the clinchpoint can be explained by the additional overall elasticity of the test rig.

In contrast to the simulation with deformable tools, the test rig has additional elasticities in the tool rolls and the roll bearings. The elasticity of the test rig in normal direction results in a deflection of the tool rolls of 0.22 mm while the deflection in the simulation with a deformable punch is 0.14 mm. The difference of 0.08 mm is a result of the elasticities of the tool rolls and the roll bearings. Because of the missing knowledge on the lateral stiffness of the test rig, it is hard to include this additional elasticity in the simulation of the roller clinching process to increase its accuracy.

6. Conclusion
While in finite element simulations of translational clinching, rigid tools deliver good accordance with the experimental results [22,23], the modelling of the tools’ elasticities has significant impact on the quality of the simulation results for roller clinching. Because of the high lateral forces during the roller clinching process, the punch tip is bent, which leads to different contact situations while forming the sheets. Thus, the resulting joining forces, especially the lateral forces, differ between rigid and deformable tools. The quality of the simulative prediction of the clinchpoint geometry is clearly increased by using deformable tools.

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