Numerical and experimental investigation of the transmission moment of clinching points

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Abstract. In clinching, the combinations of requirements, materials, component dimensions and tools influence the resulting joint geometry and the resulting bonding mechanisms. These in turn affect the property profile of the joint. For example, it is possible to use different tools to flexibly adapt clinching points to the respective required load regime. Clinching points dimensioned in this way can be geometrically similar, but have different mechanical stress states, which leads to different properties in terms of load-bearing behavior. Within the scope of this work, the clinching process with different tools in optimal and compromise design and its effect on the force and form-closure component, is investigated in a torsion test of the clinched connection. Clinched steel sheets with two thicknesses and joining directions are analyzed. Virtual experiments are carried out using finite element analyses (FEA) of the joining process and are followed by a springback simulation. Subsequently, the surface pressure between the two joining partners in the clinching points is calculated on the basis of the results from the FEA and the transmittable moment of the connection, as an indicator for the force-closure component, is determined. Finally, the experimental and simulated data are compared and discussed.

1. Introduction and state of current research

The versatility of a process chain requires joints with specifically adjustable mechanical, thermal [1], chemical [2] and/or electrical [3] properties. Increased demands on the products, the use of new materials and multi-material design [4] are leading to the increased use of known or further developed joining compounds [5] produced by forming technology. In contrast to the widespread use of welded or bolted joints, for which a large number of selection, design and layout methods exist [6], the knowledge of clinching points is usually only intuitive. A few approaches regarding design and dimensioning [7], predictions of mechanical properties [8] and robustness evaluations [9] of form-fitted joints are currently used.

Joints can be classified according to their bonding mechanisms: form-, force- and material-closure [10]. The form-closure is created by establishing mechanical contact between the joining surfaces of the components to be joined. Neither a physical bond nor chemical interactions between atoms or molecules take place. The force-closure is established via the joining surfaces in mechanical contact through a constant interaction of forces due to elastic deformation. Material-closure occurs through material unification as a result of adhesion or cohesion bonds [11]. Mechanical joints are dominated by form- and force-closure. The selection and design of formed joints is mainly dependent on empirical knowledge, which has been acquired through trials for specific applications, such as clinching of coated
semi-finished products [12], clinching of multilayer joints [13] or die-casting materials [14]. Knowledge repositories are design catalogs [15], data sheets [16] and exemplary manufacturer data [17]. The quality standards only define geometrical characteristics (undercut, neck thickness, bottom thickness) of the form-closure [7]. The frictional connection has not yet been quantified and is therefore not included in the design [9]. A traceability of the properties of the mechanical joint connections to the binding mechanisms acting at the connection point is not yet known.

The predominant approach to defining the manufacturing parameters for the production of mechanical joints is experimental or experience-based. It must be ensured that the shape (e.g. joining surfaces, space requirements, undercut) and number of joining points specified by the design can be realized without damaging components [18]. A comprehensive investigation of the relationships between the bonding mechanisms present in the clinching point and the resulting properties has not yet been the subject of research.

Coppieters et al. demonstrated the suitability of FEA for the investigation of the clinching process. In combination with the experimental work on the design of clinching points, the FEA can be used for process design. It was shown that numerical simulation can reduce the number of tests when designing clinching points. [19]

The selection of a suitable tool geometry combination for the clinching process can be done by FEA [20]. In addition to the geometric information of the joining point, the FEA results also provide information on the plastic strain or the stress conditions in the joining point. This information can be used to calculate the transmissible moment of a clinching point. The results of process simulations are primarily verified by comparison with the test results regarding the resulting geometric parameters like neck thickness and undercut. Hence, only the form-closure component is taken into account while the existing force-closure component due to springback is neglected. The following investigations were carried out with the goal of the detection of this force-closure component.

2. Design of clinching points
The tests are based on a single-stage round clinching point without cutting component manufactured with a closed die (Figure 1) and a nominal diameter of $D_m = 8$ mm. The closed die produces a geometrically rotationally symmetrical clinching point (Figure 2). It is characterized by the geometric and quality-determining parameters neck thickness, undercut and bottom thickness. A dual phase steel HCT590X+Z with zinc coating and thicknesses of $t = 0.8$ mm and $t = 1.5$ mm as joining partners is used for the experimental investigations. These different thicknesses are arranged at punch side and/or die side positions. Table 1 gives an overview of the investigated clinched connections. In addition to the component thickness (Table 1, Series 1 - 4), the variation of tool geometries was also investigated (Table 1, Series 3 - 4). The zinc surface of all joining partners was cleaned with isopropanol before clinching. This surface preparation should minimize influences of residual lubricants or other surface contamination to the tribological system.

Figure 1. Metallographic cross section of a clinching point

Figure 2. Die side view of rotationally symmetric clinching point
Due to the possibility of an optimum and compromise design of clinching points with regard to their primary load type or manufacturing requirements, these clinching points have different mechanical properties based on different stress states. For the design and evaluation criteria, the neck thickness directly correlates to the shear tensile strength and the undercut directly correlates to the peel or head tensile strength. These areas form the primary bonding mechanism form-closure and the secondary bonding mechanism force-closure between the joining partners via the tool geometries. Due to springback, after removal of the tools, a change in the force component occurs. The use of defined, application-related surface conditions of the joining surfaces enables the formation of different form-closure and force-closure conditions via the different friction forces between the joining partners. The existing form-closure component can be quantified by geometrically measuring the clinching point using micrographs. However, the force-closure component cannot be measured directly. For rotationally symmetrical clinching points, torsion testing is one method of detecting and quantifying the frictional component due to stress relief and can also be used to distinguish the effect of different surface conditions on the tribological system.

Material-closure can be ruled out for the steel clinching points both in the neck area and in the bottom area, since the sufficient conditions for the effect of cold welding (relative movement, surface pressure and surface activation) are not met for these materials during the clinching process.

The tool selection for clinching in influenced by the materials to be joined, their component thicknesses and (their component) arrangements. First, the joining partner with the greater thickness is arranged on the punch side (Table 1). Quality control is performed by measuring the dimensions for undercut and neck thickness on the basis of metallographic cross sections. The surfaces are etched with 3 % HNO₃ to visualize the parting plane of the two joining partners and to measure the quality-relevant parameters. Due to the galvanized surfaces tₓᵧ = 8 µm, a gap is created between the joining partners only at the surface by the effect of the etchant.

This arrangement is the preferred variant for identical materials. The largest formed zone is located in the neck area of the clinching point. To achieve complete clinching, the greater component thickness in this arrangement is advantageous. The material can be deformed without crack formation to the required clinching depth. A conical punch geometry with a punch diameter of 5.8 mm is used to form the neck thickness and undercut. This is necessary to provide sufficient material volume under the projected face of the punch for undercut formation after penetration of the die-sided joining partner. The thinner die-sided joining partner is formed into the die contour. To enable the die-side mating partner to be fully inserted, a die with a depth of 1.6 mm (BD8016) must be used so that the undercut can be formed underneath the die-side joining partner. When changing the joining direction and thus the punch-side arrangement of the thinner joining partner, a die with a shallower depth of 1.2 mm (BD8012) must be used to avoid neck breakage. The die depth selection depends on the thinner joining partner on the punch side.

| Sheet thickness in mm | Micrograph | Tools | Neck thickness tₜ in mm | Undercut tᵤ in mm | Bottom thickness t₃ in mm |
|----------------------|-----------|-------|------------------------|------------------|------------------------|
| **Series 1**         |           | A - Punch AC58100 | 0.56 ± 0.01 | 0.14 ± 0.01 | 0.88 ± 0.01 |
| t₁ = 1.5             | BD8016    | B - Die        |            |                |                        |
| t₂ = 0.8             |           |                |            |                |                        |
| **Series 2**         |           | A - Punch AC58100 | 0.25 ± 0.01 | 0.16 ± 0.01 | 0.84 ± 0.01 |
| t₁ = 0.8             | BD8012    | B - Die        |            |                |                        |
| t₂ = 1.5             |           |                |            |                |                        |

Table 1. Metallographic cross sections of the examined clinch points
In the design of Series 3, a stepped punch is used in addition to the die from Series 1 (same punch-side material). This punch has the advantage that it has two punch diameters with a distance of 2 mm. This makes it possible to achieve a large neck thickness, caused by a small first punch diameter of 4.8 mm. The second larger punch diameter of 5.2 mm (offset by 2 mm) prevents further stretching during the clinching process and at the same time to achieve an improved surface contact (enlargement of the friction surface) in the punch insertion area between the joining partners.

In order to demonstrate the versatility of the clinching joining process, this joining task can also be realized with another tool set (Series 4). In this case, a modified punch geometry (conical punch with a tip diameter of 5.0 mm) is used with the same die (BD8016), which enables identical formation of the undercut when the same base thickness is set as in Series 3.

The clinch points designed in this way were subjected to a torsion test to qualify the force-closure portion or to detect changes in the portion of the force-closure binding mechanism.

3. Numerical analyses of the clinching process
Parallel to the experimental joining tests, numerical simulations were carried out for the presented joining points. The simulation of the clinching process using a 2D-axisymmetric-model with x-axis of symmetry is performed using MSC Marc with an implicit solver. An elastic-plastic material behavior with a Young’s modulus of 210,000 MPa, a Poisson’s ratio of 0.30 and tabulated flow curve based on the results of tensile tests is used. The flow curve for dual phase steel HCT590X+Z is extrapolated with the Swift approach. A remeshing function with a characteristic element size of 0.05 mm is used. Remeshing is always performed after a punch displacement of 0.1 mm. The calculation time is about 20 minutes. The general setup of the simulation as well as the material data used are based on the work of Bielak et al. [21]. The principal setup of the process simulation is shown in Figure 3. The tools were adapted to the respective clinching point. After the simulation of the clinching process, a springback simulation is performed. The simulations were performed exemplarily for Series 3 and Series 4 and the results were compared afterwards.

Figure 3. Exemplary setup of the simulation of the clinching process of Series 3 using punch ABY482052 and die BD8016
4. Analysis of the transmittable moment of the clinching point based on stress analysis

The determination of the transmittable moment is based on the results from the FEA. The path of the contact segments for the calculation of the moment is shown in Figure 4. The normal contact force is exported from the FEA results. The Coulomb’s law with a friction coefficient of $\mu = 0.15$ is used for the calculation. The normal contact force is multiplied by the radius to obtain the specific moment transmissible by the elements. Because the simulation uses an axis-symmetrical formulation, the specific torque must then be integrated in the direction of the circumference. After summation of every element contribution, the total transmissible moment is obtained.

5. Experimental setup and results

The form-closure component can be determined by measuring the neck thickness and the undercut. A test method to identify the force-closure component as a result of different mechanical stress states by using different tool geometries for rotationally symmetrical clinch points is the torsion test method. It can also be used to distinguish the effect of different surface conditions on the tribological system. The test set-up consists of a tightening spindle with integrated torque - angle of rotation detection (Figure 5). The test result is the breakaway torque, which is measured during the rotation of the joined components against each other (Figure 6).

The breakaway torque correlates directly to the force-closure component induced during the joining process. The higher the breakaway torque, the greater the force-closure component in the clinching point. The form-closure component of the undercut does not contribute to the load bearing capacity in this test and therefore does not affect the test result. By comparing the mean values of the resulting torque measurements (Figure 7), it is evident that each series results in a different breakaway torque. The entered error indicator marks the minimum and maximum value.
Figure 7. Influence of a different force-closure component on the breakaway torque of clinching points, mean value of the breakaway torque with the minimum and maximum value as error indicator

It can be seen, comparing Series 1 with Series 2, that a loss of testing torque is detected when arranging the thinner material as the punch side layer. This indicates a larger force-closure component between the two joining partners at the contact area, due to the higher deformation of the material in Series 1 as a result of the deeper die. The comparison of these results to Series 3 showed that the breakaway torque is still increasing by the combination of the two 1.5 mm thick sheets. A look at the comparison of Series 3 and Series 4 shows a significant difference in the breakaway torque. The significantly reduced breakaway torque indicates a significantly reduced force-closure component. The form-closure, on the other hand, is identical in both series as the geometrical measurements indicate (Table 1). By changing the punch geometries, the binding mechanisms force-closure can be varied in their proportions.

The geometric parameters neck thickness, undercut and bottom thickness from the micrographs are used to validate the simulations. The experimental data are compared with the simulated data in Table 2. In the simulations, the geometric parameters from the experiments could be reproduced in general. The geometric parameters in the connection Series 4 could be reproduced with a good accuracy. For the connection Series 3, the undercut could not be completely achieved due to the modelling of the friction in the simulation. This should be taken into account in further investigations.

| Series  | Experimental geometry | Simulative geometry |
|---------|-----------------------|---------------------|
|         | Neck thickness $t_n$ in mm | Undercut $t_u$ in mm | Bottom thickness $t_b$ in mm | Neck thickness $t_n$ in mm | Undercut $t_u$ in mm | Bottom thickness $t_b$ in mm |
| Series 3 | 0.47  | 0.18  | 0.67  | 0.44  | 0.12  | 0.68  |
| Series 4 | 0.38  | 0.18  | 0.67  | 0.38  | 0.17  | 0.68  |

The contact normal forces determined by FEA for the Series 3 and Series 4 connection are shown in Figure 8. When comparing the two variants, the contact between the joining partners occurs in different areas when using different tools with similar geometric parameters of the clinching point. While in the combination with the conical punch Series 4 the contact exists mainly in the area of the undercut, see Figure 8 b), the contact is distributed over a larger area when using the stepped punch in Series 3, see Figure 8 a). It could be shown that only the examination of the standard geometric parameters neck thickness, undercut and bottom thickness does not provide any information about the force-closure of the clinching point, since different contact areas are formed in the joint due to the different tool geometries.
The results of the transmissible moments calculated using the contact normal forces are compared with the experimentally determined moments in Table 3. The transmittable torques could be calculated in a comparable order of magnitude to the experimentally determined values. In further steps, a quantitative comparison of the transferable moments is required. It also seems useful to investigate different friction models, since these influence the force-closure of the clinching point.

Table 3. Comparison of the measured and calculated transmissible moments of the clinched connection

| Series | Average breakaway torque in Nm | Calculated moment in Nm |
|--------|-------------------------------|-------------------------|
| Series 3 | 4.06                          | 4.29                    |
| Series 4 | 2.52                          | 4.53                    |

6. Summary and outlook
It is possible to use different tools to flexibly adapt clinching points to the respective required load regime. The clinching points can be geometrically similar, but have different mechanical stress states, which leads to different properties in terms of load bearing behavior. The experimental clinching process was carried out with different tools in optimal and compromise design. Thereby, the effect on the force and form-closure component could be shown and more importantly the respective influence on each joining mechanism could be analyzed separately. The clinched connections of steel sheets with two thicknesses and joining directions are investigated in a torsion test. The experimental work was accompanied by FEA of the joining process of two exemplary connections and was followed by a springback simulation. Subsequently, the normal contact force between the two joining partners in the clinching point from the FEA was used for the calculation of the transmittable moment of the clinched connection, as an indicator for the force-closure component. By changing the punch geometries, the binding mechanisms force-closure can be varied in their proportions. The transmittable moments could be calculated in a comparable order of magnitude to the experimentally determined values. Quantitative reconciliation of the results is still pending. In further studies, it could be useful to investigate alternative surface conditions and friction models to the Coulomb’s law.

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