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Experimental and Numerical Investigation on Manufacturing-Induced Pre-Strain on the Load-Bearing Capacity of Clinched Joints

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Abstract. Background. Clinching is a conventional cold forming process in which two or more sheets can be joined without auxiliary parts. A pre-forming of the parts to be joined, which is introduced by previous manufacturing steps, has an influence on the joining result. When considering the suitability for joining with regard to the formability of the materials, the influence of the preforming steps must be taken into account. The influences of strain hardening and sheet thickness on the joining properties must be investigated. In this context, a Finite Element Method (FEM) based metamodel analysis of the clinching process was carried out in [1] to investigate the robustness of the clinching process with respect to the different material pre-strains. In [2], the method was extended to the load bearing simulation.
Procedure. The metamodel from preliminary work based on various FE models, which predicts the load-bearing capacity of a clinched joint influenced by pre-straining, is compared here with experimental data and the accuracy of the metamodel prediction is discussed. For this purpose an experimental procedure was further develop which allows the preforming of metal sheets from which joining specimens can be separated with a certain degree of unidirectional deformation. In the study, the procedure for preparing the joint specimens and the results of the loading tests are presented. Different possible relevant pre-strain combinations are investigated and compared with the simulation results, to validate the FE models and choose suitable metamodel.

Introduction

The production of sheet metal components involves several production steps that influence the resulting component properties. For metal constructions, such as body-in-white, components are usually deep-drawn for the following processes. This pre-forming influences the joinability in relation to the formability of the materials and must be taken into account when designing joints. Conventional clinching (classified as "joining by forming" (DIN 8593-5)) is a mechanical joining process that is becoming increasingly important in multi-material lightweight construction. The joining process is characterized by two or more overlapping sheets, tubes or profiled parts by cold forming without auxiliary joining elements. A punch and a die are used to create an inseparable form-fit and force-fit connection. The clinched joint created after joining process is shown in sectional view in Fig. 1 with geometrical characteristics.

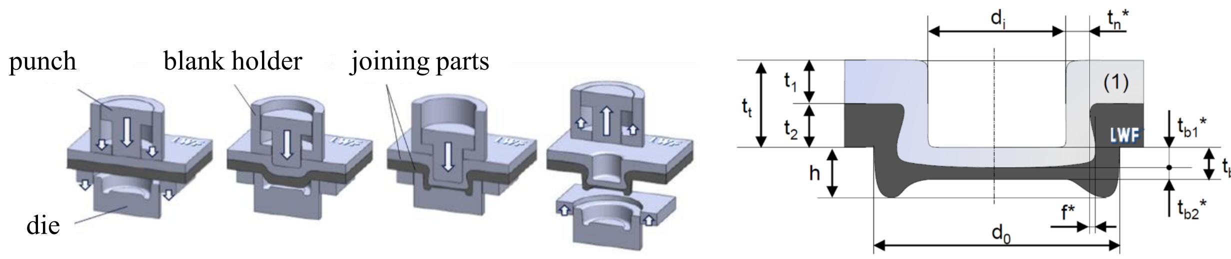


Figure 1: Tool design and sequence for clinching with closed die and geometric parameters of a clinched joint [3]

Particularly the geometrical characteristics bottom thickness t_b, interlock f* and neck thickness t_n* are considered relevant to quality aspects of the joint [3]. The interlock f* and the neck thickness t_n* directly influence the failure modes of a clinched joint and thus its load-bearing capacity. Both correlate with the bottom thickness t_b, which can be utilized as a non-destructive evaluable, quality-determining parameter if the tool and process parameters are known.
In clinch joining, the materials on the punch and die side are penetrated and radially expanded [3]. The resulting high plastic strains limit the joinability of the material-geometry combinations depending on the formability of the materials [4].
The forming history of the parts to be joined (previous degrees of transformation or thinning) has an influence on clinched joints, this is described in detail in [5] for steel and in [6] for aluminum. The preforming of the punch-side material has a greater influence on the joining parameters than the die-side material. For both materials it could be shown that the energy absorption of a shear-stressed joint is significantly reduced (approx. 70 %) if the punch-side sheet is pre-deformed to uniform elongation. In addition, the maximum load that can be applied decreases significantly (approx. 15 %). In [1], the influence of forming before the joining process on the joint quality was investigated with a numerical Method. The influences of strain hardening and sheet thickness variation on the joint properties were analyzed. In this context, a metamodel-based analysis of the clinching process is carried out to evaluate the robustness of the clinching process based on quality-relevant geometric parameters. A non-linear correlation between pre-straining in combination with pre-hardening and the normalized maximum cutting force could be determined in [7]. The influence on the clinching process was investigated by sensitivity analyses. In addition to the pre-hardening, the change in joining part thicknesses was identified as a significant influencing factor. There is a negative correlation between the neck thickness and the interlock, whereby the sheet thickness reduction has a stronger influence on the neck thickness and the interlock than the pre-strengthening due to the pre-strain. In [8], a significant decrease in the load-bearing capacity of the connection (approx. 20 %) was also found at a pre-strain of 5 % (uniaxial plastic strain in the tensile direction). Further analyses of the influence of the forming history on clinched joints is described in [9]. A FE simulation of clinching process has been investigated in [10]. In [11] the finite element method was used to design an efficient development process. In [12] the suitability of numerical simulation for the investigation of the clinching process is investigated. The reasons were reported due to combined effect of hardening and pre-damage. A development to analyze the influence of forming processes before clinching is also presented in [2]. The setup of the required FE simulations for the joining process as well as for the shear load tests without pre-deformation is presented and validated by experimental investigations. The sequential calculation of the prepared models enables the calculation of a large number of coupled FE models. Quality-relevant parameters of the clinched joint as well as the maximum transmittable force under shear load is determined. Correlations between the pre-strain and quality-related parameters were compared with the maximum shear force, using the metamodels developed from the FE models. The aim of this study is to present and investigate a method for validating the numerical approach already presented. For this purpose, the experimental procedure and the results are presented. These are compared and discussed with the numerical results from the study in [2].

Experimental

Materials. The investigations in this study were carried out using a dual phase steel HCT590X with a sheet thickness t = 1.5 mm. According to the manufacturer's data sheet the chemical compositions and the mechanical properties of the investigated materials are shown in Table 1.

Table 1: Chemical compositions mechanical properties of investigated HCT590X [13]

	HCT590X (wt.-%)		
		Min.	Max.
Chemical composition	C		0.15
	Si		0.75
	Mn		2.5
	P		0.04
	S		0.015
	Al	0.015	1.5
	Cr+Mo		1.4
	Nb+Ti		0.15
Physical properties	Yield strength	330 – 430 MPa	
	Ultimate tensile strength [MPa]	590 – 700 MPa	
	Elongation A80	≥ 20 %	

In order to obtain higher experimental strain values to evaluate a flow curve for the numerical investigation, a layer pressure test according to DIN 50106 was carried out with two 3D DIC systems [14]. The experimental setup is shown in [15] in more detail. Figure 2 shows the flow curve extrapolated with the Hockett-Sherby approach used in this work to describe the material plasticity in the numerical model.

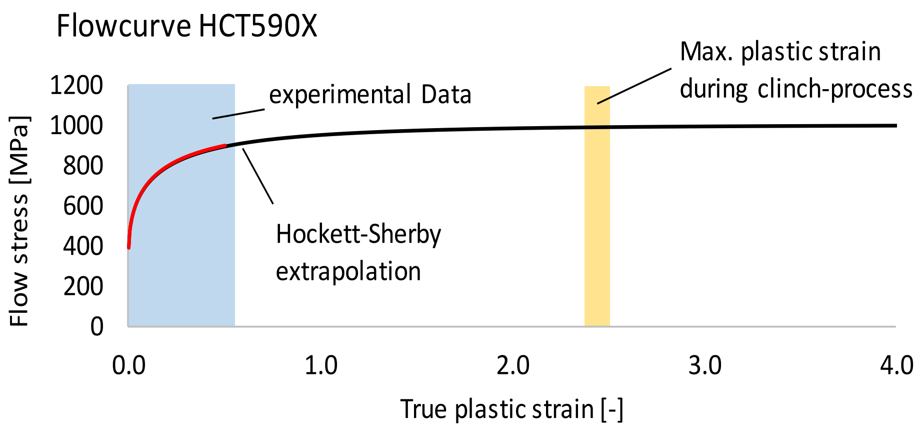


Figure 2: The flow curve used in this work was determined using the layer compression test and extrapolated according to the Hockett-Sherby approach.

Clinching. The clinched joints for the presented study were produced on a TOX® PRESSOTECHNIK clinching system type TZ-VSN. A joining speed of 2 mm/s and a blank holder force of 785 N was used. All clinched joints were made with the same punch TOX® A50100, which means that it has a diameter of 5.0 mm and a conical shape. This study is confined to a non-cutting round clinching process using a closed die TOX® BD8016. Sampling was carried out on specimen sections with dimensions of 45 x 45 mm. The joining parameters were previously determined on undeformed specimens and kept the same for all joints and pre-deformation conditions.

Load-bearing capacity tests. In order to investigate the influence of plastic pre-strain of the joining parts on the load-bearing capacities, shear tensile tests were conducted. Specimen for the shear tensile tests had the dimensions 105 x 45 mm, see Fig 3. The overlap length was 16 mm and the free clamping length was 95 mm. All load-bearing capacity tests were performed on a Zwick Z100 tensile-compression testing machine with a test rate of 10 mm/min. These specifications are based on the guideline DVS 3480-1 [16].

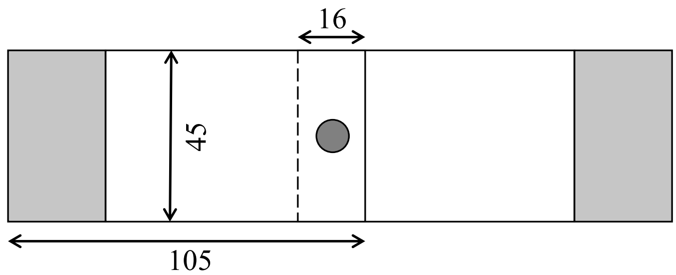


Figure 3: Specimen for shear tensile tests according to DVS 3480-1 [10]

Plastic pre-deformation. In order to induce a defined plastic deformation in the parts to be joined, they are pre-formed by means of uniaxial elongation. This is carried out in a primary specimen with dimensions 140 x 500 mm, in accordance with [16]. This is subsequently used to extract secondary specimens for sampling joints and shear tensile specimens. Fig. 4a) shows the dimensions of the initial primary specimen (blue) and the plastically deformed specimen with the secondary specimens to be extracted. In order to be able to determine the exact elongation of the primary specimen for a defined plastic pre-strain and its homogeneity over the entire specimen area, the elongation process was first investigated by a 3D simulation model (Fig. 4b)), using LS-DYNA implicit solver (smp d R11.1.0). The effective degree of plastic deformation and the resulting irreversible elongation of the specimen compared to the experiment is to be investigated. For this reason, a spring back was calculated after the forming process, by giving the displacement a death time.

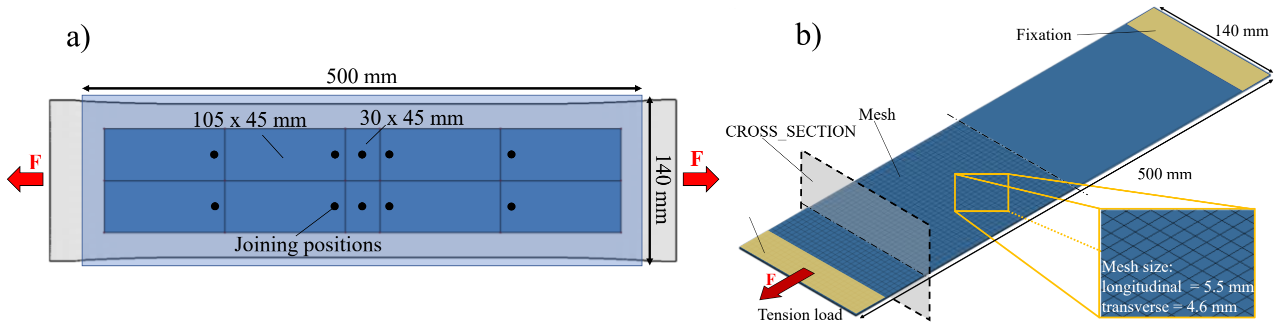


Figure 4: a) Initial primary specimen and plastically deformed specimen with secondary specimens for sampling and shear tensile tests; b) Setup of the FEM simulation of the elongation process.

The displacement is applied one-sided via a node constraint (*NODE_SET) over a displacement condition (*PRESCRIBED_BOUNDERY_SET). The clamped surface is fixed by locking the nodes against translational and rotational displacements in the *SPC_SET setting. The model fixation is set according to the experimental setup. For the elongation process, the primary specimen is clamped in a special mounting. In the simulation model, this mounting is represented with this substitute fixation. The model was calculated with 5 solid elements across the thickness. The mesh sizes can be seen in Fig. 3b), which shows the numerical model as well as features such as cross sections, node quantities (boundary conditions) and the loading direction of the displacement. Due to the relatively large mesh, the low degrees of deformation and the slow loading velocity, the model is calculated in whole geometry without any simplifications due to symmetry. The force acting during the forming process is measured via a cross-section plane (*CROSS_SECTION). A von Mises plasticity model is used, which assumes the independence of the strain rate. The LS-Dyna material card is MAT_224 is used to describe the material elastic-plastic behaviour. Figure 2 shows the material flow curve used in this study. Thermal effects or damage are not taken into account.
Fig. 5 shows the numerically predicted distribution and homogeneity of plastic deformation over the surface of the primary sample. If the specimen is elongated to a length l_1 = 545.3 mm, a uniform degree of deformation of $\varphi = 0.1$ is obtained over most of the surface. The values vary between $\varphi = 0.096$ and $\varphi = 0.104$. It can be seen that eight secondary specimens can be extracted from the primary specimen for shear tensile tests, in which a degree of deformation of $\varphi = 0.1$ is present in the joint. Furthermore, two sheets can be extracted from the middle of the specimen for sampling tests. In the

lower figure, elongation has been simulated up to l_2 = 567.8 mm, which is almost 100 % of the uniform elongation specified for the material. In this, it can be clearly seen how the homogeneity of the plastic deformation decreases and concentrates towards the center of the specimen. The outer secondary specimens in each case would have a smaller degree of deformation than the specimens from the center. In order to be able to ensure the highest possible material utilization, a plastic pre-deformation of φ = 0.1 is selected for the investigations.

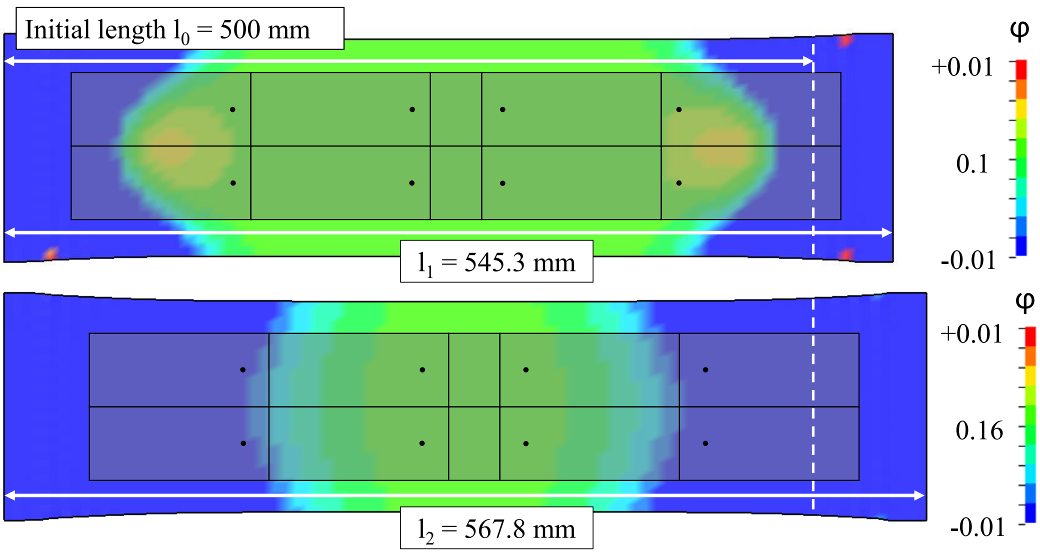


Figure 5: Homogeneity of plastic deformation in the primary specimen at different elongation

The displacement calculated in this way in the simulation was adopted for the experiments and the sheets were preformed accordingly. A Zwick Z1484 universal testing machine with a maximum tensile test load of 200 kN was used to elongate the sheets, see Fig. 6. Special fixtures were used for the primary specimen with a width of 140 mm.

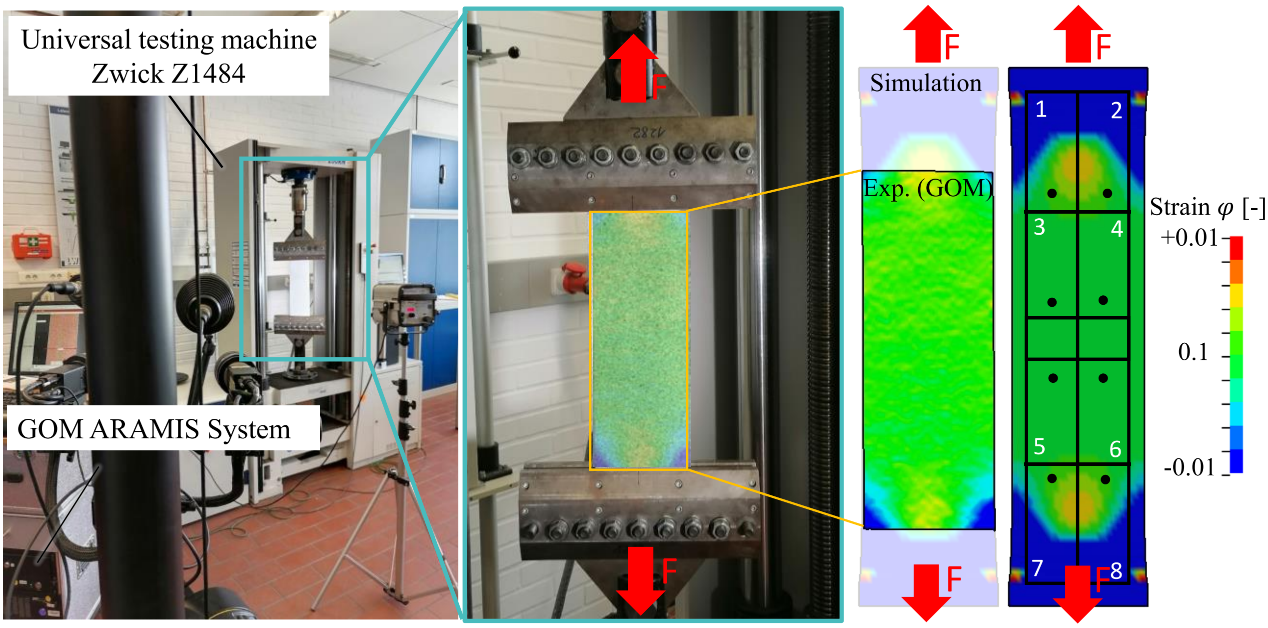


Figure 6: Experimental setup of the elongation process and comparison between experimental and simulated plastic deformation

The fixtures consist of two hardened profiled clamps between which the sheets are clamped and fixed with several bolts. In order to validate the homogeneity of plastic deformation from simulation, a primary specimen was given a stochastic speckle pattern and the elongation of the specimen was recorded using a DIC system (GOM ARAMIS). Fig. 6 shows the comparison between the

deformation evaluated with DIC and the deformation from simulation. The homogeneity of the plastic deformation on the primary specimen for φ = 0.1 is consistent between experiment and simulation. The following primary specimens were elongated without paint pattern in order not to affect the surface conditions for the joining process.
In order to investigate the influence of preformed joining parts on the geometric formation of clinched joints and their load-bearing behavior, four different combinations of preformed parts are joined and evaluated. First, clinched joints without any pre-deformation are evaluated as a reference joint (C0-0). In contrast, clinched joints are examined in which both sheet metal parts are plastically preformed with φ = 0.1 (C1-1). Furthermore, clinched joints are examined in which either the die-side sheet (C0-1) is preformed or only the punch-side sheet (C1-0).

Simulation and metamodel. The FEM simulation used in this study consists of three models. The aim is to predict the influence of the pre-deformation on the geometrical characteristics of the clinched joint and the maximum shear force. The models used for the pre-strain calculation and the joining process were shown in [1], the methods for the shear load calculation is presented [2]. Fig. 7 shows the 2D pre-formation, the 2D clinching process and the 3D shear loading model. The three models are consistently coupled in order to transfer the calculated results (the pre-strained sheet and the formed clinched joint) to the next corresponding model. The pre-straining of the sheet materials and the resulting sheet thinning and hardening is simulated in a 2D model and is therefore biaxial. However, the assumption is made that the degree of deformation introduced and not the pre-strain direction is relevant. Figure 3 shows on the right-hand side the procedure for inserting the data generated from the 2D process model into the 3D shear test model. The strain distribution calculated in the 2D process model and the formed mesh are inserted into a 3D shear test model. Stresses that are not shown in the figure are also transferred so that an elastic pre-stress at the joint is taken into account. The transfer of the strains leads to a consideration of the hardening of the material caused by the joining process.

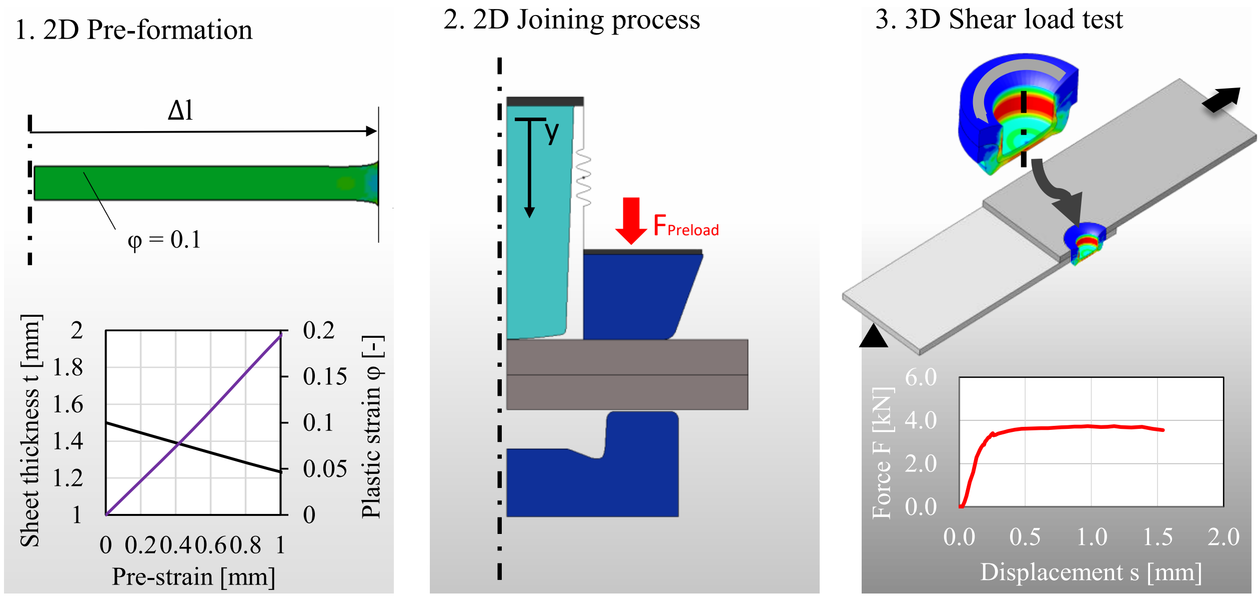


Figure 7 Simulation models for the prediction of the pre-deformation influence on the clinched joint and the maximal shear tensile force.

The results are the geometrical characteristics (bottom thickness, neck thickness and interlock) of a clinched joint, as well as the force-displacement curve in the shear load test, which is evaluated in respect of the maximum transferable shear force (F_{shear}). Based on these parameters, metamodels (Fig. 8) are created using a polynomial quadratic approach. These describe the correlation between the pre-strain and the characteristic values as well as the maximal shear force on the basis of the calculated points. The metamodels are taken from the study in [2].

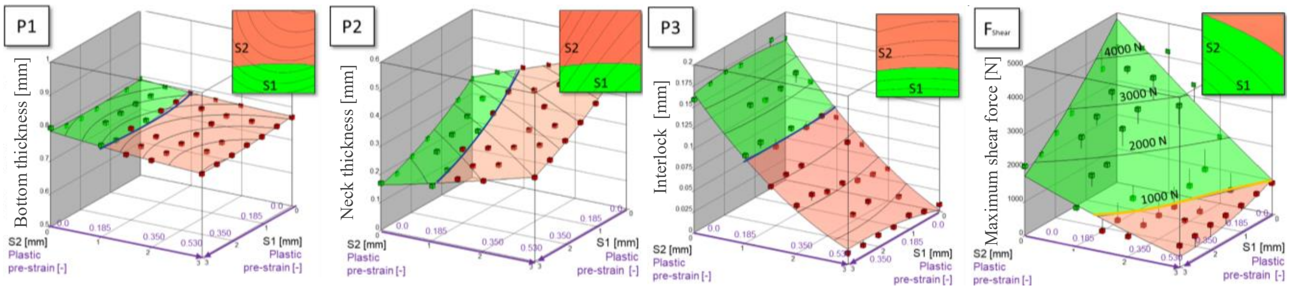


Figure 8: Simulation models for the prediction of the pre-deformation influence on the clinched joint and the maximal shear tensile force [2]

Results and Discussion

Geometrical formation of clinched joints. The results of the experimental investigations as well as from the process simulation with regard to the influence of plastically preformed joining parts on the geometric formation of the clinched joints can be seen in Fig. 9. In the center, a comparison of an exemplary micrograph from the experiments with the simulation results is shown. It can be seen that the process simulation agrees well with the experiments and can model the influence of plastically preformed joining parts on the clinched joint. On the left, the quantitative evaluation from experiment and simulation of the geometrical characteristics interlock, neck thickness and bottom thickness in the various combinations is shown. The deviation from simulation to experiment is indicated as a percentage in each case. The average deviation between the simulated values and the experiment is 6%.

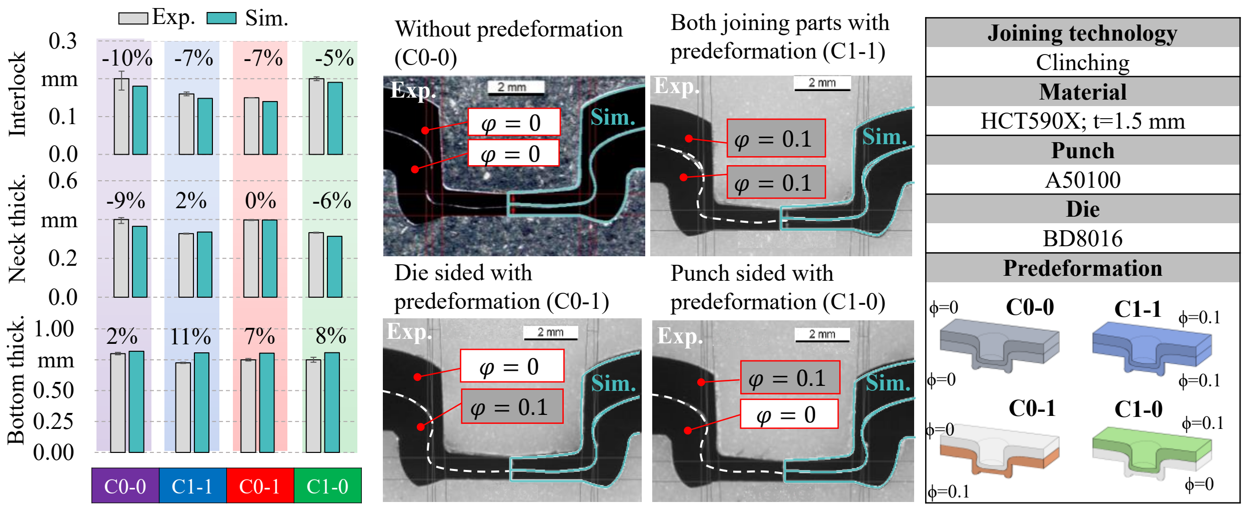
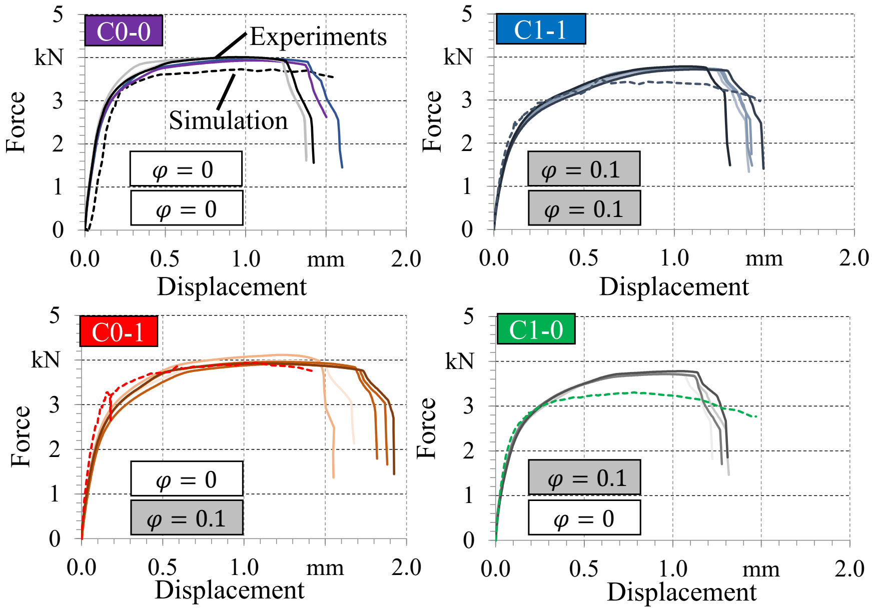


Figure 9: Micrographs of clinched joints with differently preformed joining parts and evaluation of the characteristic properties in comparison with the simulation results

With regard to the geometric formation of the clinched joints, it can be seen that combination C1-1 shows lower values for all geometric characteristics due to the sheet thickness reduction in both joining parts compared to C0-0, which consists of joining parts without pre-deformation. With regard to the combinations C0-1 and C1-0, there are differences in the formation of the geometric characteristics. While the interlock in C0-1 is lower than in C0-0, the interlock in C1-0 is similar to the interlock in C0-0. With respect to the neck thickness, it can be observed that it is at about the same level in C0-1 as in C0-0. In C1-0, however, it is significantly lower than in C0-0. This behavior is in agreement with the investigations in [5].

Load-bearing behavior. In order to investigate the influence of plastic pre-deformation of the joining parts on the load-bearing capacities, the results of the experimental and simulated shear-tensile tests are shown in Fig. 10. This shows the force-displacement curves of the four different joining part combinations. Next to the experimentally determined curves, the result of the simulation is shown as a dotted curve. In general, the curves from experiment and simulation show agreement. The specimen stiffnesses in the rising curves coincide with each other and the progression up to specimen failure also agrees with the experimental curves. This is especially valid for the combinations C0-0 and C0-1, in which the punch-side sheet was undeformed. For the combinations C1-1 and C1-0, the simulation slightly underestimates the force-displacement curve from the experiments after the transition to the plastic range.



Testing method
Shear tensile test (DVS/EFB 3480-1)
Testing facility
Zwick Z100
Test velocity
10 mm/min
Temperature
RT
Displacement measurement
Sensor arm extensometer

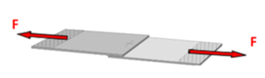


Figure 10: Comparison of the simulated force-displacement curves with differently preformed joining parts with the experiments

Metamodel. To validate the methodological approach, the experimental data obtained in this study are compared with two different metamodels. The metamodels are used to create a correlation between the result variables and the input parameters using a mathematical approach based on the individual FE model results. According to the approach, a function is fitted which can be displayed as a 3D graph for three parameters. Fig. 11 shows the two variable input parameters S1 pre-strain of the top sheet and S2 pre-strain of the base sheet before joining in correlation with the resulting maximum shear force for two different metamodel approaches, the polynomial quadratic (PQ) metamodel calculated in [2] on the left and a feed-forward neural network (FNN) metamodel on the right.

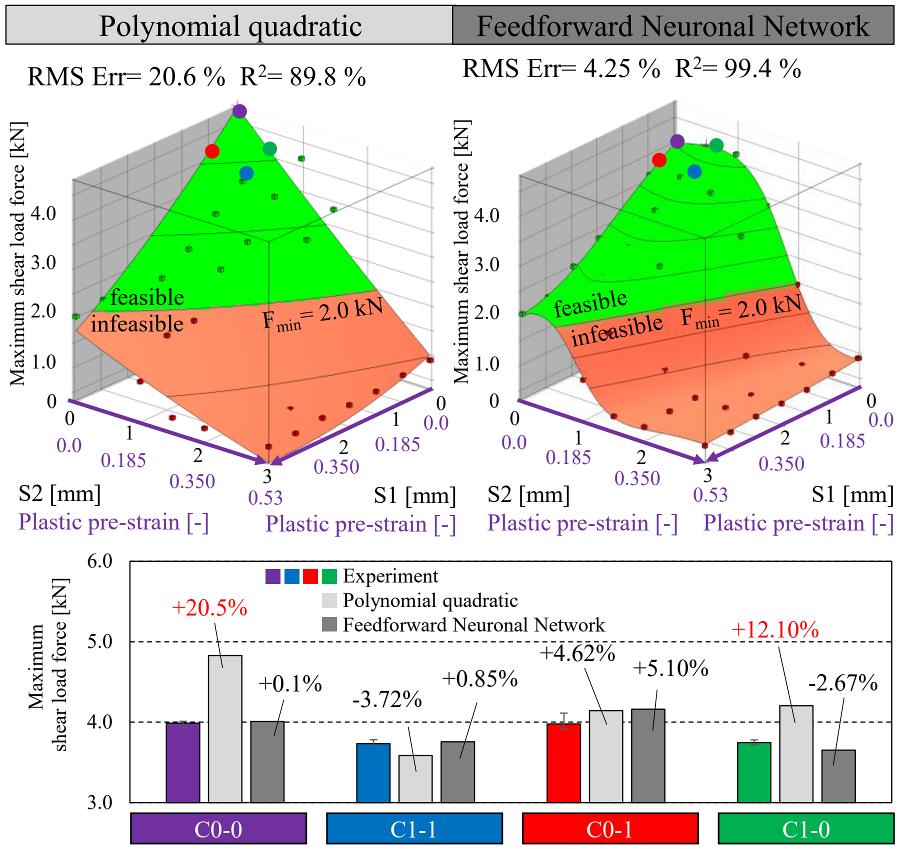


Figure 11: Comparison of the results of the prediction of the maximum shear load force for two metamodel approaches in comparison with the experiment.

The four experiments with the pre-strain of φ= 0 or φ= 0.1 are qualitatively marked as coloured spots on the surface of the metamodels. The green or red boxes, which are same for both metamodels, are the simulated results based on which the metamodels were calculated. The division into possible and impossible, which in this case is made by falling below the maximum shear load force of F_{min}= 2.0 kN due to the pre-strain, is only intended to illustrate by way of example that the selection of the metamodel also has an influence on the limitation curve. Basically, both metamodels have a good mean square error, PQ of R^2= 89.8% compared to FNN R^2= 99.4%. But the RMS error of the PQ is four times as high as that of the FNN. PQ RMS Err= 20.6% compared to RMS Err= 4.25%. The comparison of the prediction accuracy is also shown in figure 11. This deviation results from the inaccurate fitting of the respective metamodel in relation to the calculated data points of the FE models. With these metamodels, maximum shear loads can now be predicted for which no FE model has been carried out. The calculated meta-models have no data points for the strains underestimated in this study and can only predict them.
The maximum shear forces predicted by the meta-models are compared with those determined in the experiment. In addition, the deviations from the experiment are given as percentages. Deviations above 10% are marked in red. Overall, it can be said that the metamodel based on the FNN approach has a higher prediction accuracy than the PQ, which means that the predicted maximum shear load deviates by a maximum of 5%.
In conclusion, it can be said that the procedure presented in [2], which numerically analyses the maximum shear force taking into account the pre-strain, and thus the hardening and sheet thinning, has a high predictive value by comparing the results with the experiment. The investigation of the metamodels showed (Fig. 11) that the selected metamodel used has an influence on the prediction quality. The numerical approach can be considered as valid, with the recommendation for an FNN metamodel.

Summary and Outlook

This study aimed the validation of a previously presented numerical method for describing the influence of preformed joining parts on the geometric formation of clinched joints and their load-bearing capacity. A numerical and an experimental approach was presented in order to produce sheet metal specimens with a defined pre-deformation to investigate clinched joints under this conditions. The numerical prediction of the geometrical characteristics match the experimental data. Regarding the load-bearing capacities, the force-displacement curves from experiment and simulation show agreement as well. It is confirmed that the pre-deformation of a sheet metal material and the resulting hardening and thinning have an influence on the clinched joint with the same joining process parameters. The pre-deformation of the punch-side sheet has an influence on the neck thickness. The neck thickness is reduced in the combinations (C1-1; C1-0) compared to undeformed sheet metal material combination C0-0. The interlock, on the other hand, is influenced by the pre-deformation of the die-side sheet. In the combinations (C1-1; C0-1) the interlock is lower than in the combination without pre-deformation. The shear tensile force curves of the tested combinations show that the maximum shear tensile force decreases for the combinations with preformed punch side sheet metal. The approach shown in previous studies, which resulted in metamodels, could be validated. It was shown that the selection of a metamodel, with the same number of simulated support points, has an influence on the prediction accuracy of the method.

For further investigations, this method will be extended to other loading conditions, such as head tensile tests. In addition, further validation tests will be carried out by applying even higher degrees of deformation to the sheet metal parts by using processes such as rolling and deep drawing.

Another focus of investigation is the comparison between biaxial and unidirectional pre-deformation of the sheet metal materials and how it must be taken into account in the numerical approach.

References

[1] Bielak CR, Böhnke M, Beck R, Bobbert M, Meschut G: Numerical analysis of the robustness of clinching process considering the pre-forming of the parts, Laboratory for Material and Joining Technology ,University of Paderborn, Paderborn, Germany (2020), DOI: 10.1016/j.jajp.2020.100038

[2] Bielak CR, Böhnke M, Bobbert M, Meschut G. Further development of a numerical method for analyzing the load capacity of clinched joints in versatile process chains. In: ESAFORM 2021. doi:10.25518/esaform21.3418

[3] DVS-EFB 3420:2021-04, Clinching – basics

[4] Hahn, O., Klemens, U.: D 707 – Fügen durch Umformen – Nieten und Durchsetzfügen – Innovative Verbindungsverfahren für die Praxis, Studiengesellschaft Stahlanwendung e.V. (1996)

[5] Hahn, O.; Kruzok, J. R.: Umformtechnisches Fügen vorverformter Halbzeuge - Teil 1: Stahl, Berichte aus dem Laboratorium für Werkstoff- und Fügetechnik, Band 37, Shaker Verlag, ISBN: 978-3826543944 (1998)

[6] Hahn, O.; Kurzok, J. R.: Umformtechnisches Fügen vorverformter Halbzeuge - Teil 2: Aluminium, Berichte aus dem Laboratorium für Werkstoff- und Fügetechnik, Band 38, Shaker Verlag, ISBN: 978-3826543951 (1998)

[7] Wiesenmayer S, Heyser P, Nehls T, et al. Berücksichtigung der Herstellungshistorie von Blechbauteilen beim Fügen durch Umformen. Werkstattstechnik Online. 2020;110(10):677-683.

[8] X. He Recent development in finite element analysis of clinched joints Int. J. Adv. Manuf. Technol., 48 (2010), pp. 607-612

[9] Jiang, T.; Liu, Z.-X.; Wang, P.-C.: Effect of aluminum pre-straining on strength of clinched galvanized SAE1004 steel-to-AA6111-T4 aluminum. Journal of Materials Processing Technology, Vol. 215, S.193-204 (2015)

[10] J.P. Varis, J. Lepist¨O A simple testing-based procedureand simulation of the clinching process using finite element analysis for establishing clinching parameters Thin-Walled Struct., 41 (8) (2003), pp. 691-709

[11] Hamel et al., 2000 V. Hamel, J.M. Roelandt, J.N. Gacel Finite element modeling of clinch forming with automatic remeshing Comput. Struct., 77 (2) (2000), pp. 185-200

[12] S. Coppieters, P. Lava, S. Baes, et al. Analytical method to predict the pull-out strength of clinched connections Thin-Walled Struct., 52 (1) (2012), pp. 42-52

[13] HCT590X, Material Data Sheet, Salzgitter Flachstahl, Salzgitter, Germany (2019)

[14] DIN EN ISO 50106: Testing of Metallic Materials – Compression Test at Room Temperature, Beuth, Berlin, Germany (2016)

[15] Böhnke M, Kappe F, Bobbert M, Meschut G. Influence of various procedures for the determination of flow curves on the predictive accuracy of numerical simulations for mechanical joining processes. Materials Testing. 2021;63(6):493-500. doi:10.1515/mt-2020-0082

[16] DVS/EFB 3480-1 (06/2021) Prüfung von Verbindungseigenschaften - Prüfung der Eigenschaften mechanisch und kombiniert mittels Kleben gefertigter Verbindungen