Experimental investigation of the cause and effect relationships between the joint and the component during clinching

Christian Steinfelder[1, a *] and Alexander Brosius[1, b]

[1]Technische Universität Dresden, Chair of Forming and Machining Processes, 01062 Dresden, Germany

[a]christian.steinfelder@tu-dresden.de, [b]alexander.brosius@tu-dresden.de

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Abstract. The combination of the mechanical properties of a clinched joint and of the material surrounding the joint determine the resulting properties of the component and joint. The cause and effect relationships between the joint and the joint environment offers the possibility of a specific modification through an adaptation in the design process. In order to identify these cause and effect relationships and resulting interactions experimentally, numerous of experiments are required. In this publication, a concept for the automated manufacturing of head tensile test and shear tensile test specimens – from cutting to clinching – by using a punch laser machine is presented. Based on a full-factorial experimental design, the parameters change of the properties of the joint environment by beading and change of the punch displacement are addressed. The influence on the properties of the clinched specimen is evaluated based on the variables stiffness, force at the beginning of yielding and maximum force at head tensile loading and shear tensile loading. In addition, the geometric quality parameters of neck thickness, interlock and bottom thickness are evaluated. The relationships can be used to apply uniform loads to joints in joined structures to counteract oversizing.

Introduction

In joined structures, the joints are loaded unevenly. The aim in the design process is to achieve an even loading of the joints in order to avoid oversizing of the joints or an oversized number of joints. The loading of the joints can be influenced by adjusting the joints, the position of the joints or the components. For the targeted use of cause and effect relationships between components and joints in their design phase, it is absolutely necessary to understand them. For example, the joint environment can be influenced by the removal of material, the accumulation of material, or the forming of beads [1]. The loading of the joints can be influenced by such a change of the joint surroundings. In addition, there are influences at the joint level due to the joining process. For example, the punch displacement or the punch diameter can be changed there in order to modify the properties of the clinched joint. In order to identify these cause and effect relationships and resulting interactions experimentally, numerous tests are required. For this purpose, a concept for the automated production of head tensile test and shear tensile test specimens – from laser cutting up to clinching – by using a punch laser machine is presented. For the evaluation of the joint properties, the stiffness, the force at the beginning of yielding and the maximum force at head tensile and shear tensile loading are evaluated. In addition, the geometric quality parameters of the clinched joint are evaluated. The obtained interrelationships can be directly used in the load-oriented adaptation of the joining design of structures in order to adapt the loading in individual joints during the design process.

For lightweight construction purposes, thin sheets of higher strength can be used to transmit tensile and shear forces. However, they have low dimensional stiffness. As a result, they are susceptible to failure under other types of loading and require stiffeners for large-area parts in order to maintain the load-bearing capacity and safety against failure due to instability such as buckling. By forming beads into components, it is possible to change the stiffness locally. The influence of beads depends on both the geometry of the bead and the bead orientation and arrangement of multiple beads. Trzesniowski gives guidance for the design and arrangement of beads based on various examples [2]. Emmrich developed a finite-element-method (FEM) based method for the design of beads for support structures subjected to bending loads in the design process [3]. There are manby studies that are concerned numerically and experimentally with the design of clinching tools and their influence on the clinched joint properties. Ewenz et al. analyzed the influence of different punch geometries on the quasi-static and fatigue behavior of the clinched joints [4]. Mucha analyzed the lock-forming mechanism in the clinched joint in numerical and experimental studies [5]. The interlock can be influenced via the tool geometry and the punch displacement, whereby the punch displacement had almost no influence on the neck thickness in the investigated ranges. Studies that combine the influence of tool parameters, process parameters and the design of the joint environment are not known.

Experimental procedure

A TruMatic 1000 fiber punch laser machine from Trumpf is used for the automated production of head tensile and shear tensile specimens. This can be used to process sheet metal by laser cutting, punching and forming operations. The work on automated production and subsequent clinching of head tensile test and shear tensile test specimens requires adaptation of the existing tool systems for punching and forming operations. This is necessary because these are only designed for the processing of one sheet and not, as is usual for mechanical joining, for at least two sheets arranged one above the other. For this purpose, typical clinching tools were combined with the tools of the machine manufacturer. Fig. 1 b) shows an adapted clinching tool in a tool holder. Like a conventional clinching tool, it consists of a die and a punch. The die has a stripper which presses the sheet out of the die after the joining process, because the die is fixed and cannot be moved down on the system side. The punch has a polyurethane stripper. Fig. 1 c) shows the installed clinching tool with a stripper on the punch side. The punch can be moved in the y and z directions of the machine. The x-movement is realized by moving the sheet. Reverse arrangement of punch and die is also possible and offers advantages for other specimen configurations. However, for the results presented in this publication, only the tools shown in Fig. 1 are used. The processing sequences are determined when the NC program is created using the TruTops Boost software.

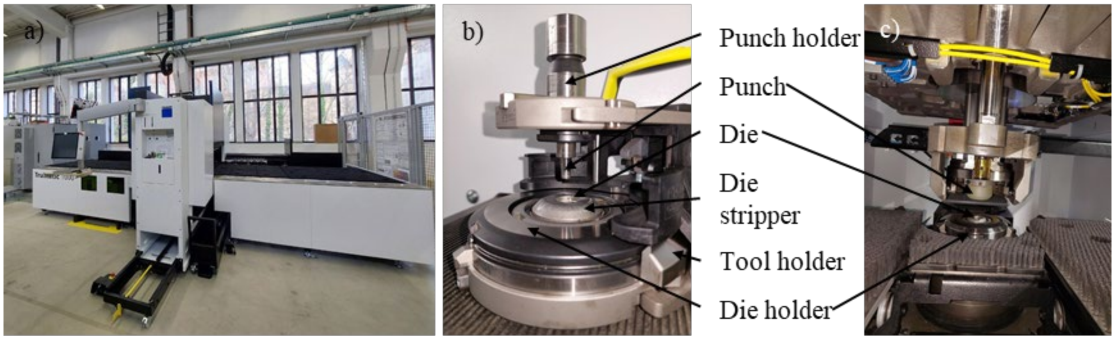

Fig. 1: a) Punch laser machine, b) Adapted clinching tool set (for visibility without punch stripper) fixed in the tool holder, c) Tool with punch stripper installed in the machine

The process is divided into two steps. Firstly, the preparation of the two sheets to be joined and secondly, the clinching itself. The sheets to be joined are first processed separately. Fig. 2 shows the design of the sheets to be joined using the example of shear tensile test specimens. The individual parts of the specimens are positioned in the sheets in such a way that when the sheets are stacked one on top of the other, the individual parts are in alignment with each other and can later be released from the sheet composite as a finished specimen after the clinching process. For this purpose, the individual parts of the specimens are fixed in the sheet with micro joints. Micro joints are a small connection between the blank and the workpiece, with the task of fixing the workpiece in the blank. In order to be able to extract the finished specimens from the sheet metal composite after joining, it is necessary to provide cutouts at the required locations. In addition to cutting operations performed by laser, beads can also be formed at this stage. The beads influence the properties of the specimens in the joint surroundings. The beads change the stiffness of the structure and changes the deformation behavior of the specimens. For the manufacturing of the beads, a standard tool for the production of endless beads with a semicircular profile was used, which was selected based on the sheet thickness. The beading tool has a height of 2 mm with a width of 4 mm. A change in bead geometry and its influence is not part of this investigation. The two sheets are then stacked and joined by clinching. The sheets are aligned by using the machine-side fixed point. Due to the automation, joints with different process parameters or different tools can be produced in a short time without any manual procedure. Finally, the specimens can be removed from the sheet and mechanically tested in tensile test or prepared for micrographs. The dimensions of the shear tensile test specimens and head tensile test specimens are according to EFB/DVS 3480-1 [6]. The dimensions of the shear tensile test specimens are 105 mm x 45 mm with an overlap length of 16 mm. The head tensile test specimens have the dimensions 150 mm x 50 mm.

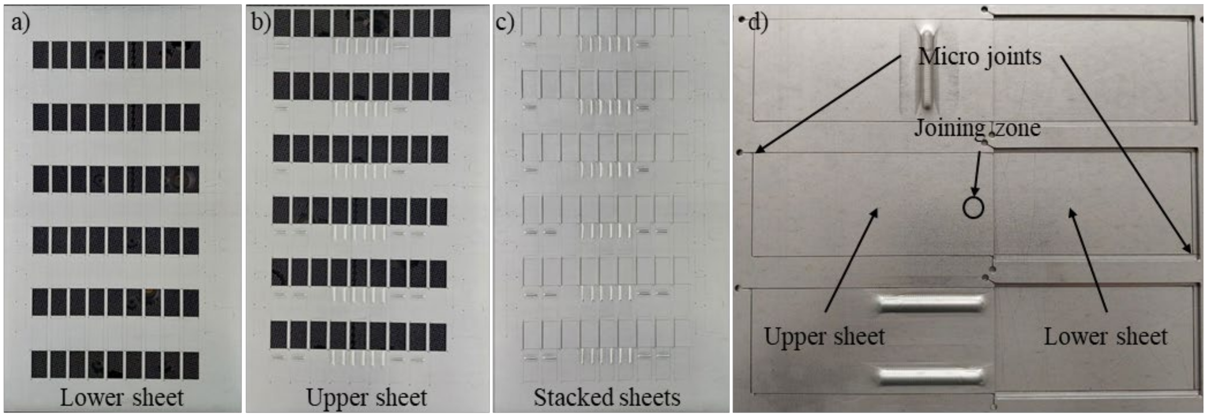

Fig. 2: Sheet metal layer before clinching, a) Lower sheet, b) Upper sheet, c) Stacked sheets, d) Detailed view of stacked sheet metal for clinching of shear tensile test specimen

Fig. 3 shows the specimen types used for investigations. Fig. 3 a) shows the shear tensile test specimens in the variants transverse bead, no bead and longitudinal bead. Fig. 3 b) shows the head tensile test specimens and the respective arrangement of the beads. The beads are arranged in the upper sheet in both variants. In addition, specimens for the preparation of micrographs are manufactured. Two connections were analyzed. 2 x $s_0 = 1.5$ mm HCT590X using a die with a diameter of 8 mm and depth of 1.6 mm (TOX BD8016) combined with a punch of 5 mm diameter (TOX A50100) and 2 x $s_0 = 2.0$ mm EN AW-6014 using a die with a diameter of 8 mm and a depth of 1.2 mm (TOX BE8012). The used punch has a diameter of 5 mm (TOX A50100).

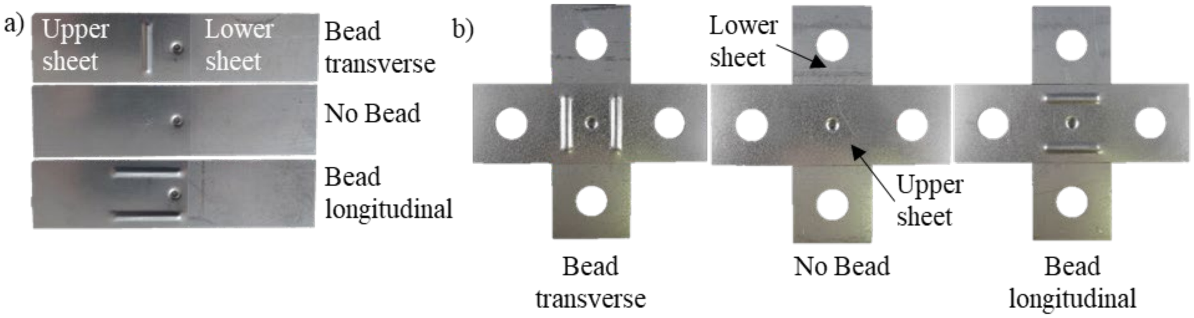

Fig. 3: Specimen for a) Shear tensile test, b) Head tensile test in the variants no bead, bead longitudinal and bead transverse

An experimental analysis is carried out based on a full-factorial design of experiments. The maximum forces under head tensile loading and shear tensile loading, the beginning of yielding, the stiffness and the characteristic parameters of neck thickness, interlock and bottom thickness are evaluated. The test design is based on the parameters given in Table 1 and is identical for both material combinations. For each variant, 7 specimens are manufactured and tested. For each of the two joint types 189 specimens were manufactured and tested. The head tensile test and shear tensile test are performed on a universal testing machine (Inspekt 250, Hegewald & Peschke) and the force and the crosshead displacement are measured.

Table 1: Varied parameters

Parameter level	Beads	Bottom dead center / (punch displacement change)
-1	Transverse	+0.1 mm (less punch displacement)
0	No	0 mm
+1	Longitudinal	-0.1 mm (more punch displacement)

Results

The results for the 2 x s_0 = 1.5 mm HCT590X connection are described below. Changing the punch displacement leads to a change of the bottom thickness and to a change of the interlock. If the bottom thickness is reduced, the formation of the interlock increases. The neck thickness, on the other hand, is not significantly affected by changing the punch displacement, see Fig. 4.

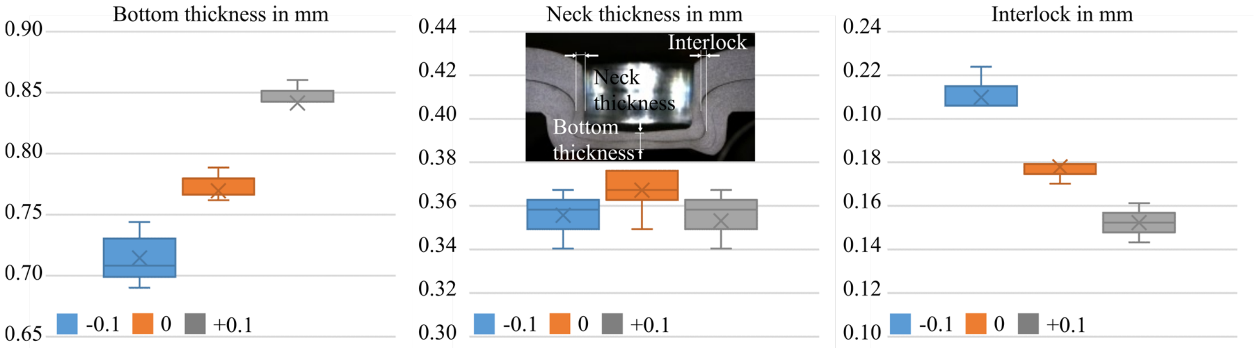

Fig. 4: Geometric quality parameters bottom thickness, neck thickness and interlock of the connection 2 x s_0 = 1.5 mm HCT590X, 7 specimens per series

Fig. 5 shows an example of the mean value curves from shear tensile tests and the scatter range of the maximum forces of the seven repetitions in each case. A change in the joint environment due to beads or a change in the punch displacement does not lead to any significant change in the maximum forces in the shear tensile test when considering the scatter width, see Fig. 5 a), b) and

c) - left. On average, an increase in the maximum force due to beads in the longitudinal direction can be observed, see Fig. 5 a), b) and c) - right. In all cases, the clinched joints failed due to neck cracking.

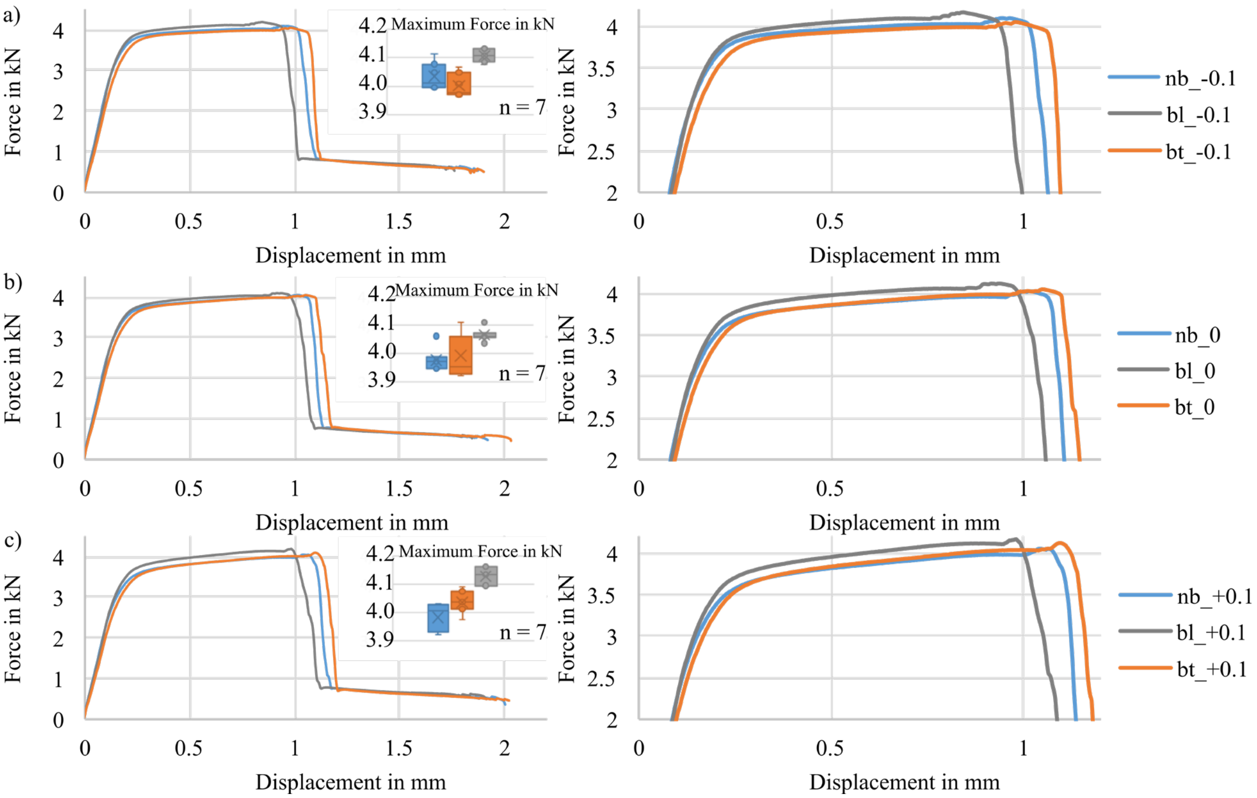

Fig. 5: 2 x s_0 = 1.5 mm HCT590X, left: Mean value curves of shear tensile tests with 7 repetitions and scatter of maximum forces, right: Detailed view: a) -0.1 mm (more punch displacement), b) Reference level, c) +0.1 mm (less punch displacement) in the variants no bead (nb), bead longitudinal (bl) and bead transverse (bt)

The stiffness of the specimen can be influenced by beads and changes the deformation behavior of the specimens. The change in deformation behavior has an influence on the loading of the joint. Thus, beads can be used to influence the loading of the joints. Compared to a specimen without beads, beads in the longitudinal direction increase the force at the beginning of yielding for all punch displacements in the shear tensile test and the head tensile test, see Table 2. By adding beads, the beginning of yielding can be shifted and the energy absorption of the clinched joint in the elastic range can be influenced. At the start of yielding, plastic deformation begins and thus the failure of the joint. The yield point and the stiffness can also be influenced by varying the punch displacement. In the shear tensile test beads in the transverse direction leads to a reduction in stiffness, while stiffness is not affected by beads in the longitudinal direction. In the head tensile test beads in the longitudinal direction leads to an increase in stiffness. Beads in the head tensile test have a greater influence on the properties, especially in the case of plastic deformation.

Table 2: Mean values of the Stiffness and yield force for the shear tensile test and head tensile test for the connection of 2 x s_0 = 1.5 mm HCT590X

Parameter	**Shear tensile test**		**Head tensile test**	
	Stiffness [N/mm]	**Yield force [N]**	**Stiffness [N/mm]**	**Yield force [N]**
nb_-0.1	23380	2586	1420	851
bl_-0.1	22930	2848	1680	1015
bt_-0.1	20620	2601	1750	870
nb_0	22500	2504	1670	659
bl_0	22330	2782	1730	913
bt_0	20300	2478	1430	849
nb_+0.1	21410	2404	1510	765
bl_+0.1	21670	2662	1700	925
bt_+0.1	19280	2447	1460	882

In the following the results for the 2 x s_0 = 2.0 mm EN AW-6014 connection are described. For the parameters bottom thickness, neck thickness and interlock, the same effects were found as for the investigated steel connections, see Fig. 6. But there the influences on the interlock formation were more clearly visible.

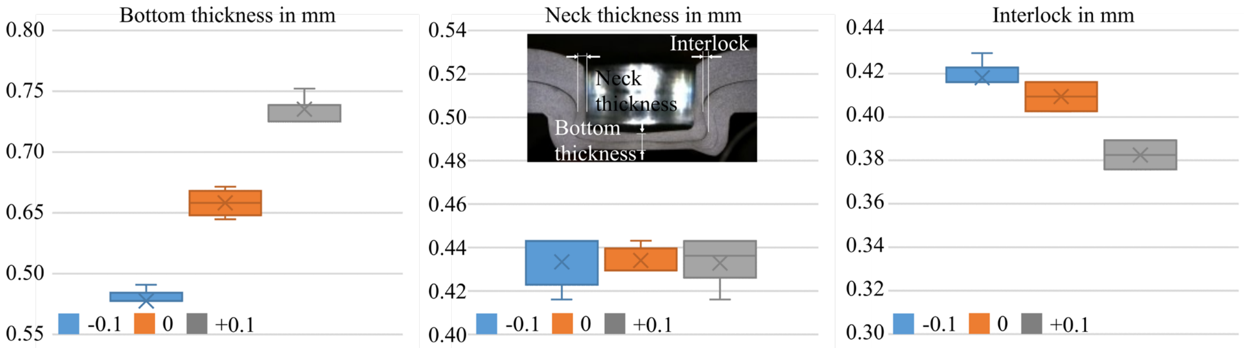

Fig. 6: Geometric quality parameters bottom thickness, neck thickness and interlock of the connection 2 x s_0 = 2.0 mm EN AW-6014, 7 specimens per series

For the connection 2 x s_0 = 2.0 mm EN AW-6014 Fig. 7 shows the mean value curves from shear tensile tests and the scatter range of the maximum forces of the seven repetitions in each case. Based on the measurement data, only a change of maximum forces for parameter less punch displacement and beads in a longitudinal direction can be detected. For the other parameter combinations, no significant changes in the maximum forces can be detected. A change in the joint environment due to beads or a change in the punch displacement does not lead to any significant change in the maximum forces in the shear tensile test when considering the scatter width, see Fig. 5 a), b) and c) - left. On average, an increase in the maximum force due to beads in the longitudinal direction can be observed, see Fig. 5 a), b) and c) - right. In all cases, the clinched joints failed due to neck cracking.

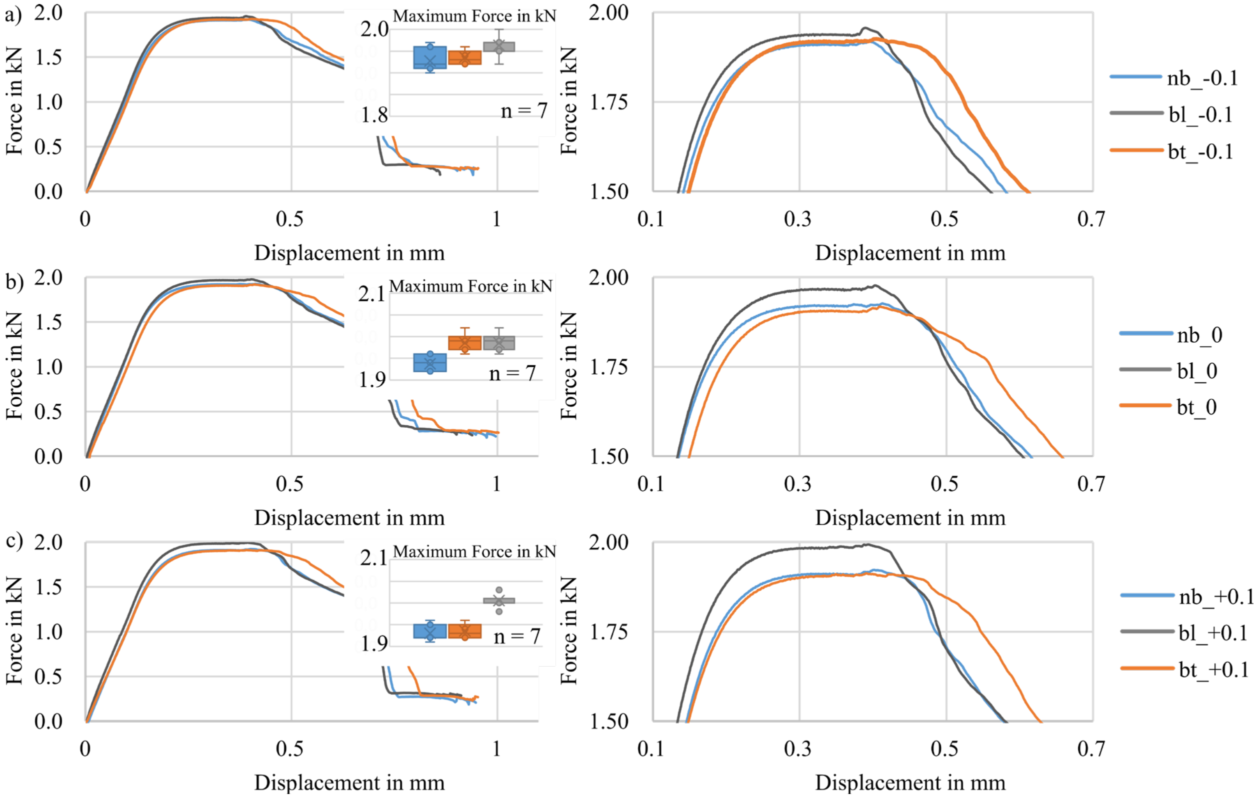

Fig. 7: 2 x s_0 = 2.0 mm EN AW-6014, left: Mean value curves of shear tensile tests with 7 repetitions and scatter of maximum forces, right: Detailed view: a) -0.1 mm (more punch displacement), b) Reference level, c) +0.1 mm (less punch displacement) in the variants no bead (nb), bead longitudinal (bl) and bead transverse (bt)

In the shear tensile test, only a minimal to no influence of the beads could be determined for the connection 2 x s_0 = 2.0 mm EN AW-6014 in total, see Table 3. In the head tensile test, a bead in the transverse direction reduces the stiffness and the beginning of yielding. No significant differences were found between the variants with no bead and with a bead in the longitudinal direction, see Tab. 3.

Table 3: Mean values of the Stiffness and yield force for the shear tensile test and head tensile test for the connection of 2 x s_0 = 2.0 mm EN AW-6014

Parameter	**Shear tensile test**		**Head tensile test**	
	Stiffness [N/mm]	**Yield force [N]**	**Stiffness [N/mm]**	**Yield force [N]**
nb_-0.1	10970	1486	1300	623
bl_-0.1	11360	1530	1340	650
bt_-0.1	10550	1526	1050	501
nb_0	11690	1447	1060	631
bl_0	11450	1468	1340	617
bt_0	11040	1398	1030	577
nb_+0.1	10810	1502	1260	565
bl_+0.1	11290	1476	1310	647
bt_+0.1	10410	1490	1070	526

Due to the large sheet thickness of 2.0 mm, high basic stiffness of the sheet is assumed, so that the beads have only a minor influence on the properties. Since stiffness is a geometrically based parameter and depends on the second moment of area, a greater influence of beads is to be expected with thinner sheets. This was also shown in the first tests and will be investigated in future work.

Summary and outlook

A concept and its implementation for the automated production of head tensile test and shear tensile test specimens using a punch laser machine were presented. By adapting the tooling systems and smart programming of the NC code, individual specimens with varying process parameters or tool geometries can be produced in a short time. This allows numerous test specimens with different process and tool parameters to be manufactured and experimentally investigated at a relatively low time and effort.

Based on the first evaluated data sets, it was possible to show that the resulting properties can be influenced by changing the joint environment and the process-side parameters. Beads can be used to influence the stiffness of the specimens. Changing the stiffness of the specimens modifies the deformation behavior and thus influences the loading of the joint. In particular, the properties in the linear-elastic range could be influenced in the case of the joints investigated. It can be assumed that the influence of the beads is strongly dependent on the sheet thickness and that the effects themselves are not dependent on the material. The ongoing expansion of the test plan is taking place in order to expand the database and thus analyze the cause and effect relationships in greater depth. This knowledge can be used in the design of components with multiple clinched joints in order to set a uniform loading at the joints. As the experimental investigations proceed, interactions between the individual parameters will also be evaluated so that they can be taken into account in the design or used specifically to influence the properties of the joint. This knowledge about the cause and effect relationships is used in further work in the development of a design method for the load-adapted design of joints and components and thus provides a direct contribution to increasing the versatility of the clinching process chain.

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