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Methodical approach for the design and dimensioning of mechanical clinched assemblies

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Abstract. The focus towards multi-material and lightweight assemblies, driven by legal requirements on reducing emissions and energy consumptions, reveals important drawbacks and disadvantages of established joining processes, such as welding. In this context, mechanical joining technologies, such as clinching, are becoming more and more relevant especially in the automotive industry. However, the availability of only few standards and almost none systematic design methods causes a still very time- and cost-intensive assembly development process considering mainly expert knowledge and a considerable amount of experimental studies. Motivated by this, the presented work introduces a novel approach for the methodical design and dimensioning of mechanically clinched assemblies. Therefore, the utilization of regression models, such as machine learning algorithms, combined with manufacturing knowledge ensures a reliable estimation of individual clinched joint characteristics. In addition, the implementation of an engineering workbench enables the following data-driven and knowledge-based generation of high-quality initial assembly designs already in early product development phases. In a subsequent analysis and adjustment, these designs are being improved while guaranteeing joining safety and loading conformity. The presented results indicate that the methodological approach can pave the way to a more systematic design process of mechanical joining assemblies, which can significantly shorten the required number of iteration loops and therefore the product development time.

Introduction

Given their ability to join coated and dissimilar sheet metals, mechanical joining technologies provide a high applicability for generating multi-material connections and thus great potentials for the realization of novel lightweight designs, such as in car body components [1, 2]. In this context, novel developments are available in the field of mechanical joining, such as in [3], whereby this contribution concentrates on clinching as an example. Therefore, the technology offers a fast as well as environmentally friendly procedure to join overlapping sheets, profiles or tubes entirely based on cold forming without additional joining components [4, 5]. However, for the realization of reliable joined assemblies, it is often required to involve both expert knowledge and experimental studies. This results in time-intensive trial-and-error development iterations and therefore high costs until a final design is identified that satisfies all product requirements (see Fig. 1). Thus, it is crucial to not only focus on the selection of feasible and suitable joining technologies, but also on the requirement- as well as the manufacturing-oriented design of the entire joint connection. Especially, the matching of the loading conformity and the achievable individual joint properties are highly important to guarantee a satisfying joining safety of joined components. For the latter, already a few contributions and standards demonstrated the methodical design of clinched joint assemblies based on geometrical characteristics (neck, interlock and bottom thickness) as well as resistances against shear and tensile loading. For instance, in [6] the analytical dimensioning of joint connections by means of stresses is demonstrated. In this regard, the calculation of suitable joint positions enables the load-balanced design of assemblies. Furthermore, to support the analysis of component and joint loadings, the so-called load path analysis can be used for the adjustment of joining designs. Therefore, common methods base on results of a finite element analysis (FEA) calculating the load distribution in a component or an overall assembly. The visualization of load paths in components allows the assessment of the design and structural integrity and can qualitatively show how the loads are redistributed in case of effects of geometric defects [7]. The methods known from the literature depend on the orientation of the component in space and the selected direction of investigation [8]. Usually, a separate load path plot is generated for each coordinate axis of the model, which results in three individual plots for the load path analysis in a 3D simulation. In this regard, the combined evaluation of all plots is necessary, which can be influenced by a lack of information within the individual plots and thus potentially leads to inaccurate results. For this purpose, the method of the effective force developed by Steinfelder and Brosius results in a single plot, which, as a second advantage, is invariant with respect to the orientation in space [9]. The concept was applied to a 2D rotational symmetric analysis of a clinched joint [10]. Nevertheless, a methodical approach that combines the data-driven and knowledge-based initial design of the assembly with the subsequent analysis and adjustment of individual components regarding their energy, stress and loading conformity is not available yet.

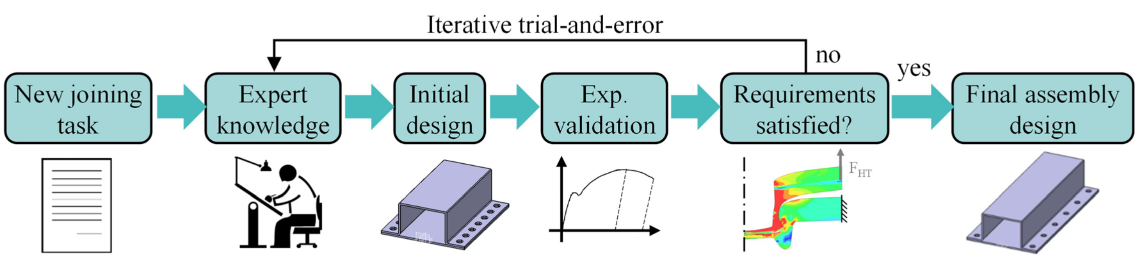

Fig. 1. Overview of the established approach for the design of mechanical joining assemblies

Overview of methodical approach

Motivated by this, the presented contribution introduces a methodical approach (see Fig. 2) that supports the product engineer regarding the comprehensive realization of reliable clinched assemblies by structuring, automating and simplifying the product development process. Especially, the involvement of data-driven and knowledge-based methods targets the efficient generation of high-quality initial product designs. Therefore, the implementation of an engineering workbench, described in [11], offers an efficient and applicable support for product engineers to configure individual joining elements by simultaneously guaranteeing a sufficient joining safety already in the early development phases. In addition to the transfer of expert and manufacturing knowledge into a machine-readable format, this also includes the utilization of predictive regression models for the accurate prediction of joint properties. Moreover, the setup of an interface between the engineering workbench and an available computer-aided design (CAD)

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Software (here: Dassault Systèmes CATIA V5-6) enables both the automated generation of assembly visualizations and the following evaluation of the geometries regarding their manufacturing plausibility. Thus, the generated assembly design provides already a high-quality fundamental for the subsequent analysis of the dimensioning and the altering of the individual joining components. Therefore, the initial CAD models of the particular parts are meshed and a FE-model in LS-Dyna is generated. Moreover, previously calculated clinched joint stiffnesses are implemented in the simulation model and stand for the available elastic joint strength capabilities. Then, the definition of the loading combined with the bearing of the components enables the following evaluation and adjustment of the initial product design regarding a meaningful force distribution. In this context, a method analyzes the existing loads at joints, the load path and the effective force and, based on this, redistributes the force curve in the components by an altering product design. This can be achieved by changing either the position or property of the joints, the component geometry in the proximity of the joints or by changing the included number of joints. After the method has been executed, the final component and joining design can be determined and dimensioned regarding the given joining task requirements.

To get a deeper understanding of the approach, the next sections explain the methodical procedure for the generation of initial assemblies and the following analytical adjustment and dimensioning of these designs in more detail. Therefore, the joining task of a hat-profile and a blank considering a required minimum resistance against shear loading of 23000 N and given process characteristics (material: EN AW-6014-T4; sheet thickness: 2.0 mm) is used.

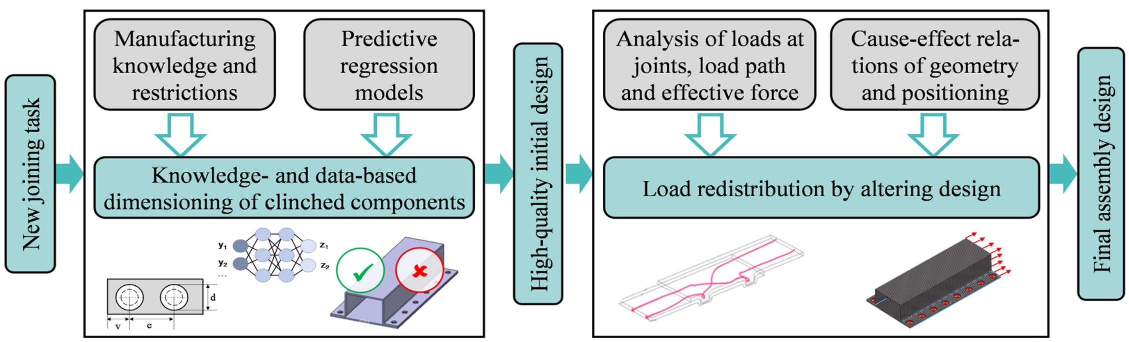

Fig. 2. Novel methodical approach for the design of mechanical joining assemblies

Data-driven and knowledge-based initial design of assemblies

Facing highly cost- and time-intensive development cycles, the following approach, illustrated in Fig. 3, enables the systematical generation of high-quality initial assembly designs already in the early product engineering phases. Therefore, the aim is to ensure both a requirement- and manufacturing-oriented dimensioning of joining connections and components. In this context, it is required to define relevant input information regarding a new joining task at the beginning. This involves for instance process-related characteristics, such as the applied joining tools or material properties, as well as requirements on the joint connection (e.g. shear or tensile load capacity). Based on this, the use of pre-trained predictive regression models enables the following estimation of individual clinched joint properties (e.g. geometrical characteristics). For this purpose and since this is among the most crucial step to guarantee a high reliability of the initial product design, linear and polynomial algorithms as well as artificial neural networks are implemented based on the results in [12]. Furthermore, the development of an engineering workbench [11] ensures both a high applicability of the approach and a consistent and automated data transfer between the product engineer and the involved software (CAD- or FE-environment). Therefore, the system offers estimated joint properties and the opportunity to configure a suitable assembly for the particular joining task. Based on the following design check regarding the compliance with manufacturing constraints and the fulfillment of requirements, an appropriate number of joints and

their positioning can be provided. In this context, the method proceeds according to the first-time-right principle and paves the way to a significant shortening of the product development cycle.
In the case of the chosen joining scenario, the product design involves a minimum of 16 clinched joints evenly distributed on both flanks of the hat-profile. For this purpose, the required minimum resistance against shear loading (23000 N) will initially be multiplied with a safety value of 1.3 in order to cover uncertainties within the joining process. Then, based on the estimation of achievable single joint properties, the minimum number of joints can be calculated. Since currently only less design principles are available in the field of mechanical joining, the selection of the safety value bases on few investigations regarding the process robustness of clinching, such as in [13]. Following, the application of plausibility checks ensures the compliance of the initial product design with implemented manufacturing specifications and limitations. Thus, the presented approach enables the generation of high-quality initial assembly designs already in the early product development phases considering data-driven and knowledge-based methods. As a summery, Fig. 3 shows an overview of the introduced steps.

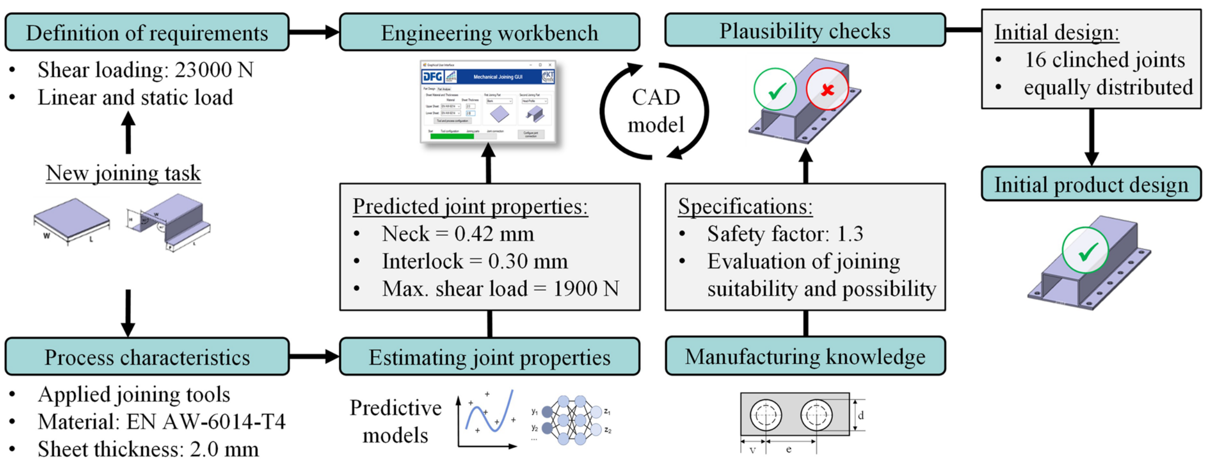

Fig. 3. Overview of the initial knowledge- and data-based design of an assembly

Analysis and load-adjustment of initial assembly design
The initial design of the assembly is then transferred as a CAD file combined with force-displacement information from the numerical experiments to the elastic dimensioning method shown in Fig. 2. The objective of the dimensioning is to ensure that the elastic joint safety is given at each clinched joint and that the sheet metal components are loaded elastically only. In this context, the method starts with the calculation of the maximum permissible force, which can be applied to the design components. For this purpose, the mechanical characteristics in normal and shear direction are determined (see Table 1) from the transferred force-displacement curves of the numerical characterization tests. In this regard, the stiffness is represented by the slope of a linear regression model (R^2 of 0.998, see Fig. 5 a), which is fitted to the provided data. Based on this, the components can be loaded elastically with a shear force up to 16000 N for the given use-case.

Table 1: Maximum force, maximum elastic force, stiffness in head-tension-test and shear-test

	Max. force in N	Max. elastic force in N	Stiffness in N/mm
Head tension test	~1700	~850	~1650
Lap shear test	~1900	~1300	~16000

For the check and dimensioning of the assembly, the components from the CAD file (Fig. 4 a) are meshed with shell elements on the mid surface for the finite element analysis. Here, the joints are mapped with a beam element and connected with a kinematic coupling by rigid spiders to the shells, which is depicted in Fig. 4 b) and 4 d). Therefore, the equivalent stiffness of the beam elements depends on the diameter of the rigid body spiders and thus on the joint's diameter and the edge length of the shell elements. In the presented use-case, the average shell length is 2 mm and the diameter of the rigid spider is 10 mm. The conversion of the experimentally determined stiffness into the stiffness of the equivalent beam is performed by curve fitting. The equivalent normal stiffness is approx. 1E6 N/mm and the equivalent shear stiffness is approx. 3E4 N/mm. The clinched joint is assumed unbendable, so the bending stiffness is set to 1E10 N/mm and the torsional stiffness is set to zero. In addition, Fig. 4 b) depicts the particular bearing conditions.

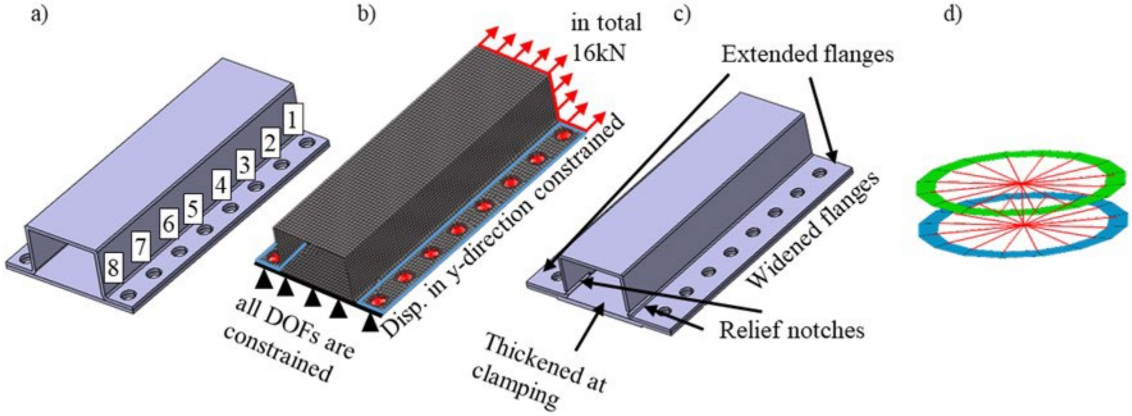

Fig. 4. a) Initial product design b) Load case the given joining task c) Final product design after improvements d) Beam-rigid-spider element

The evaluation of whether a joint is purely elastically loaded is based on a limit curve (Fig. 5 c). Here, this is represented in a simplified form via an ellipse equation in the first quadrant with the semi-axis maximum elastic shear force and maximum elastic normal force. In the fourth quadrant, the curve is parallel to the ordinate based on the equations in Fig. 5 d). The additionally drawn area by two lines with a slope of -1/3 and 1/3 illustrates the joints in which shear force is predominant. The influence of bending on the clinched joints is neglected. Due to symmetry, the subsequent evaluation is only carried out on the front flange with the joints 1 to 8 (see Fig. 4 a). Therefore, the individual loads at the joints are depicted in red (see Fig. 5 c). In that diagram, one can see that joint 8 (CJ8) is outside the limit curve. Moreover, the flanges and the walls of the U-section are tending to bent (see Fig. 5 b). To prevent this effect, the flange width is increased for 10 mm and the clinched joints are pushed 5 mm further out. In addition, the shear force can usually be reduced at the outermost joints if the distance to bearings is increased. For this reason, the profile is extended by 5 mm on the right and left. In order to reduce the shear force at joint 8 (CJ8), the left clamping is concentrated to the center. This enables an increased force flow to the other joints (CJ2 to CJ7). Furthermore, to prevent the aluminum sheet from being plastically deformed, the sheet thickness is increased locally from 2 mm to 3 mm at the left clamping. The changes are depicted in Fig. 4 c) and the obtained new loads at the joints are shown in black in Fig. 5 c). One can see that joint 8 (CJ8) is still outside the limit curve, which mainly bases on the high normal force share. Therefore, relief notches are provided on the side of the hat-profile. As a result, the joints 5 to 7 absorb more axial force based on a load redistribution (see Fig. 5 c green and black dots). However, joint 8 still lies very slightly above the limit curve. This can be changed by adjusting either the geometry again or the mechanical properties of joint 8 and thus the involved limit curve.

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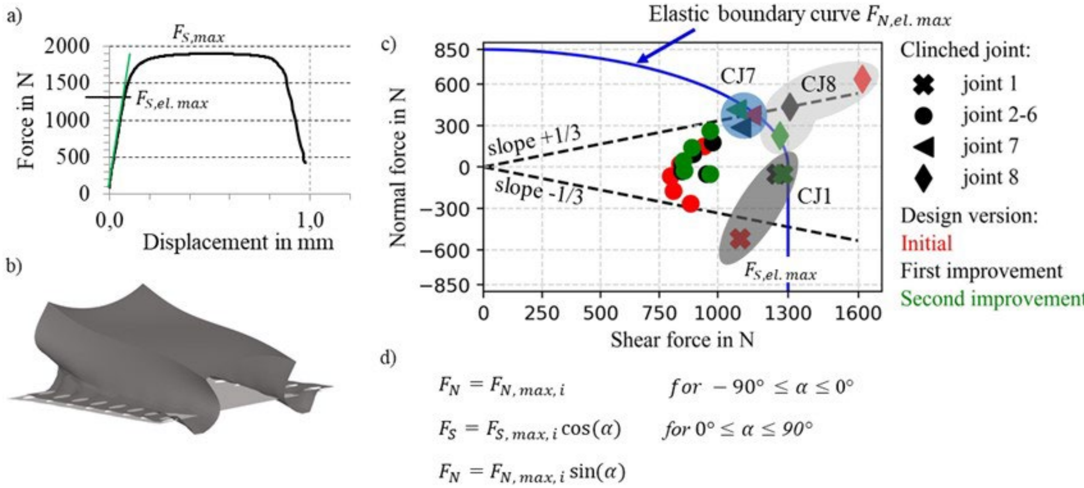

Fig. 5. a) Maximum forces and stiffness b) Deformation of the component with displacement scaled by factor 200 c) Loads at the clinched joints d) Equation of the elastic boundary curve

Besides this, the additional analysis of the normal and shear forces in the joints through the effective force method can identify the load path and the load direction in the assembly. This allows an evaluation of the areas that contribute more or less to the load transfer and, if necessary, how a load application in the component should be adapted. The method can currently also be applied to components with detailed modeling of the joints in 3D. The analysis of joined structures with a large number of joints modeled in detail is not efficient and feasible in terms of computing time. For an analysis of structures with shell element formulations and substitute models of joints, an adaptation of the calculation processes is necessary in further steps. Therefore, in the following, an exemplary investigation based on a 3D shear tension model with two clinched joints is considered. The following simplified example clearly shows why the change of the restraint has significantly relieved joint 8 in the first iteration step. The two clinched joints are arranged directly in series in the direction of loading, as in the flange area of the considered component, and are loaded to shear. The input data for the analysis are the results from a finite element analysis. The setup of the used model is shown in Fig. 6 a). For the calculation of the vector field, the principal stresses λ_i with the associated eigenvector $E_{i,j}$ are evaluated for each integration point per finite element in the model and the effective force $\overrightarrow{\boldsymbol{F}_{\text{eff}}}$, which refers to an infinitesimal area element A_{inf}, is calculated according to Eq. 1. Complementary to the normally used equivalent stress concept, this approach provides not only the information on the location of the highest load, but also the direction of the load in each case. Especially by the use of the direction information the versatility in the process chain can be increased, since modifications to compensate for unexpected changes in the process or at component level can be made in a targeted manner.

$$\overrightarrow{\boldsymbol{F}_{\text{eff}}} = \begin{Bmatrix} \lambda_{\text{I}} \cdot E_{\text{I},1} + \lambda_{\text{II}} \cdot E_{\text{II},1} + \lambda_{\text{III}} \cdot E_{\text{III},1} \\ \lambda_{\text{I}} \cdot E_{\text{I},2} + \lambda_{\text{II}} \cdot E_{\text{II},2} + \lambda_{\text{III}} \cdot E_{\text{III},2} \\ \lambda_{\text{I}} \cdot E_{\text{I},3} + \lambda_{\text{II}} \cdot E_{\text{II},3} + \lambda_{\text{III}} \cdot E_{\text{III},3} \end{Bmatrix} \cdot A_{\text{inf}}. \tag{1}$$

The method of effective force can be used as a support and provides additional information for the design of components and joints. In order to show load paths in a clear way, only nodes are used that have bearings or load inputs as boundary conditions. Two resulting load paths are shown in Fig. 6 b). It can be seen and concluded that loads applied closer to the plane of symmetry (Starting point 1) are mainly transmitted via the first clinched joint. Loads introduced further from the plane of symmetry (Starting point 2), on the other hand, are transmitted via the second clinched joint. When evaluating the effective force as a scalar value, see Fig. 6 c), additional information about the loads in the structure and joints can be visualized. This showed that the neck region of the first clinched joint is more involved in load transfer than the second clinched joint. Thus, the effective force method makes an important contribution to the analysis of loads in joined structures and provides further information about regions of the components involved in the load transfer and internal load directions, which assisted to adapt the joining design to the loadings.

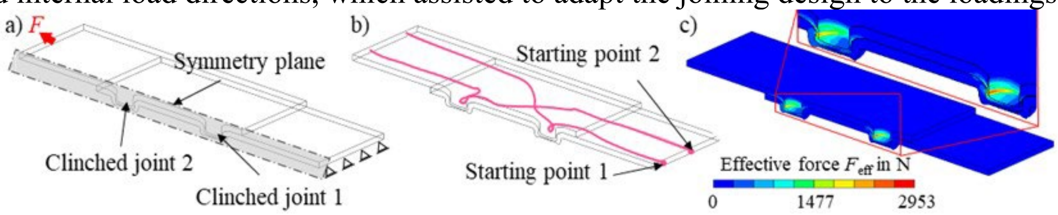

Fig. 6. a) Shear tensile specimen with two clinched joints b) Model visualization of load paths c) Effective force as a scalar value

Discussion

The demonstrated methodical approach provides the opportunity to assist the product engineer in the design and dimensioning of reliable and versatile mechanical clinched assemblies. In this regard, the involvement of knowledge-based and data-driven methods offers the manufacturing- and requirement-oriented generation of initial and high-quality designs already in the early product development phases. However, to guarantee a sufficient applicability of the method, it is crucial to not only focus on clinching but also on further mechanical joining technologies, such as pin joining or riveting. Moreover, currently the realization of complex joining tasks is limited on the available implemented parameterized CAD geometries, materials and sheet thicknesses. Thus, the generation of multi-material and -part combinations requires a deeper focus in future work. Furthermore, the functionality of the analysis and load path method has been shown for linear material and joint behavior. In order to take plasticity into account, it is required to consider a nonlinear behavior in the joint as well as in the material model. For the further analysis of the stress redistribution within a joint, it is recommended to replace the equivalent element by a detailed solid model for individual joints. In addition, the effective force method showed high potentials to visualize the load path in the component and joint graphically and thus to analyze, which regions of the component and which joints are involved in the load transfer. But the analysis of joined structures with a large number of joints currently requires an adaptation of the method with respect to the use of shell element formulations and substitute models for joints. The method is not dependent on a specific mechanical joining process and can also be applied to other processes.

Summary

Given costly and time-intensive development iterations, the presented contribution introduced an approach for the methodical design and dimensioning of mechanically clinched assemblies. Therefore, the integration of knowledge-based, data-driven, and simulation-based methods within an engineering workbench provide high potentials for the initial generation of high-quality designs already in the early product development phases. In this context, this requirement- and manufacturing-oriented configuration of components provides the fundamental for the following analytical adjustment of individual joining elements regarding a well-balanced energy, stress and load distribution. For this purpose, both the position and number of joints or the component's geometry can be systematically changed based on the introduced approach. After the method has been executed, the final component and the final joining design are determined and moreover, the joined component is dimensioned for its use. To demonstrate the entire methodical approach, the joining of a hat-profile and a blank considering a required resistance against shear loading of 23000 N and given process characteristics (material: EN AW-6014-T4; sheet thickness: 2.0 mm) was used as an exemplary joining task. In summary, the presented results can pave the way to a more methodical and simplified design and dimensioning process of mechanical clinched assemblies by providing a comprehensive support for the product engineer. This can also lead to a significant shortening of the required product development cycle and time.

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