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Toward a feature-based approach for fixtureless build-up of sheet metal structures

Florian Schlather, Florian Oefele, Michael F. Zaeh

***Abstract*— Assembly and joining of sheet metal structures involves the use of inflexible, expensive fixtures to properly position and secure the single parts. This paper presents an approach to enable a fixtureless build-up of sheet metal structures. The approach is based on the integration of fixture-related functions into the single workpieces that are to be assembled and joined. Thus, the approach can enhance the flexibility of production systems and save costs. Existing research in this field is outlined and research gaps are identified. The presented approach aims at closing these gaps in a four step methodology. The steps are: preliminary investigations, system modeling and analysis and the deduction of design guidelines. Thereby, the dependencies between features, workpiece and relevant dependent variables are to be identified. These findings can help to enable the approach of feature-based, fixtureless build-up of sheet metal structures.**

***Index Terms*— Feature, fixtureless, flexibility, functional integration, joining, production.**

I. Introduction

In the assembly of sheet metal structures, the single parts have to be positioned, oriented and secured prior to joining. Part-specific fixtures are often used extensively for this task in industry [1]. These fixtures are traditionally designed to exactly meet the geometrical requirements of specific parts. Hence, they are inflexible as even small changes in geometry or dimension require the design of new fixtures [2]. The design and the production of hardware fixtures is very expensive and time-consuming [3]. This is regarded as a major deficit in the automotive industry. The increasing product variety inevitably results in different car body structures and parts and raises the amount of fixture-induced expenditures. The presented approach has the potential to significantly reduce the amount of fixtures for joining operations by integrating fixture-related functions directly into the parts that are to be joined. This approach is presented in detail in section 4. Prior to that, research approaches related to this field are reviewed and discussed in section 2. Relevant terms are defined in section 3. Conclusions on the proposed methodology are drawn at the end of this paper in section 5.

II. Research Approaches

In current research, there are three different approaches for the reduction of fixture use: Robotic fixtureless assembly, flexible fixture design and feature-based fixturing (see Fig. 1). In the following, the approaches are outlined and the advantages of feature-based fixturing are displayed.

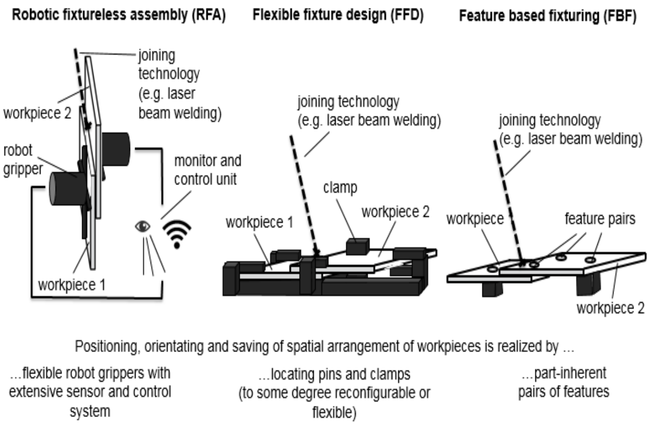

Fig.1. Comparison of different approaches for fixturing of parts

A. *Robotic fixtureless assembly (RFA)*

Recently, fixtureless (or jigless) assembly is often equated with the approach of robotic fixtureless assembly. RFA has the aim of replacing the fixtures with highly flexible grippers, attached to sensor-guided robots. Thus, the reconfiguration for new products only involves changes in software instead of changing the dedicated fixturing hardware. This allows to rapidly change over to run a different product at low hardware expenditures. Hoska [4] was the first to introduce this concept in 1988. Since then, there has been a lot of research activity on this field: Bone and Capson [1] developed a system for vision guided fixtureless assembly of automotive components, comprising simple, three finger grippers attached to handling robots. Part pickup and part alignment prior to joining is controlled by 2D and 3D computer vision, respectively. The positioning accuracy of the system was 2 mm and a cycle time of 3 min could be achieved. Therefore, the system is too imprecise and too slow for industrial use.

The measurement assisted assembly of aircraft engine components was investigated by Jayaweera et al. [5]. A system was developed which uses sensors to determine the components' exact location in the assembly operation. The assembly is executed by standard industrial robots with vacuum-based end effectors for part handling. The core of the system is a set of algorithms which are capable to best fit the measurement data dynamically in order to find optimal (i.e. accurate) assembly of components.

Elser [6] introduced a system to spatially align aluminum space frame structures without fixtures. The single joining partners were marked by a laser system subsequent to the extrusion molding process. These component-inherent markings serve to determine the parts' position and orientation in the assembly process, using a stereo camera measuring system, handling robots, and flexible grippers

M. Sc. Florian Schlather, Institute for Machine Tools and Industrial Management, Technische Universitaet Muenchen, Munich, Germany, Phone +49 151 601 33811

Dr.-Ing. Florian Oefele, BMW Group, Munich, Germany, Phone +49 382 43236

Prof. Dr.-Ing. Michael F. Zaeh, Institute for Machine Tools and Industrial Management, Technische Universitaet Muenchen, Munich, Germany, Phone +49 89 289 15502.

synchronized by a closed-loop control. Other researchers on the field of RFA were Mills and Ing [7], Fleischer et al. [8] and Reisgen et al. [9], amongst others.

Despite the fact that RFA concepts enhance the flexibility of production systems, common deficits of this approach are:

- High initial invest for RFA production cells (handling robots, sensors, grippers, software)
- Comparatively low positioning accuracy of the overall system or high cycle times for computing operations
- High efforts for software changes and teach-in operations for new parts
- The total expenditures are to some extent only shifted from the inflexible fixtures into the complex RFA system.

B. Flexible fixture design (FFD)

The concept of FFD aims on the development of fixtures that are able to cope with different parts. Thus, the total number of fixtures can be reduced as few fixtures can handle many parts. Also, fixture redesign for new parts can be avoided. Bi and Zhang [2] distinguish between two major types of flexible fixture systems: those with a modular, reconfigurable structure (MFFSs) and those with a single, flexible structure (SFFSs). They list various examples of technical implementations for both types.

Arzanpour et al. [3] presented a suction cup based, flexible fixture for the assembly of sheet metal parts for the automotive industry. Flexible fixturing permits grasping of different parts for assembly. Arzanpour et al. derived the concept from bionic structures of an octopus.

Millar and Kihlman [10] investigated the design, manufacture and installation of a reconfigurable fixture to assemble a wing box section in the aircraft industry. The system is based on elements using box joints that allow for flexible reconfiguration of the fixture.

In 2010, Jonsson and Ossbar [11] provided an overview on further approaches for flexible and reconfigurable fixturing systems. They stated that the favorable approach is intimately linked to the manufacturing conditions.

Leonardo et al. [12] presented an approach that combines a reconfigurable fixture basis with highly flexible end effectors which are based on magnetorheological fluids.

Despite FFD enhances the flexibility of production systems, common deficits of this approach are:

- The initial costs of flexible fixtures are high
- The effort for fixture reconfiguration is high
- Flexibility is limited to a set of parts that show certain commonalities in their shape and dimension
- For high volume production, FFD can only reduce fixtures in their diversity but not in their total amount.

C. Feature-based fixturing (FBF)

FBF relies on the concept of integrating fixture-related functions, such as positioning and orienting, into the parts that are to be joined. The approach aims on both, high flexibility as well as low system complexity. FBF was introduced by Koonmen [13] in 1994. Koonmen presented a methodology with the goal of eliminating the use of tooling in the aircraft assembly process. This concept, called ‘Precision Assembly Technique’, is based on the combination of male and female (or positive and negative) part features. These feature pairs are able to constrain and secure certain degrees of freedom between parts prior to joining. The concept is displayed in Fig. 2.

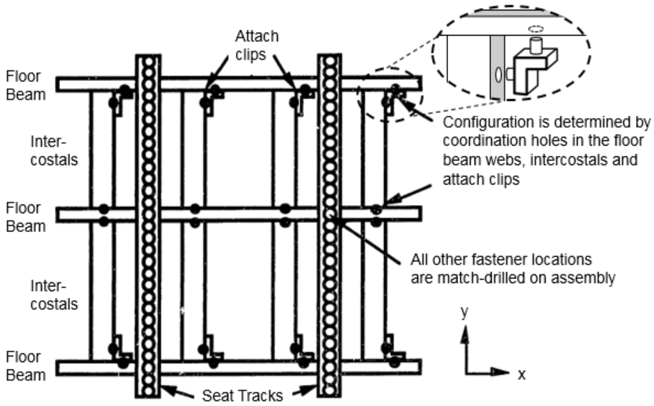

Fig.2. Visualization of a feature-based approach to avoid fixtures in the assembly process [13, p. 41].

Attach clips with pins in combination with coordination holes serve to position, orient, and save the spatial arrangement of intercostals and floor beams. This is usually achieved by the use of external fixtures.

Walcyk et al. [14] presented a method for fixtureless assembly of simple sheet metal parts used for fuselage structures in the aircraft industry in 2000. They used properly toleranced alignment holes that are machined into the parts at the fastener’s locations using a computerized numerical control (CNC) system. Subsequently, the parts are temporarily fastened at these alignment holes for their proper alignment with temporary fasteners. Then, they are permanently joined using rivets and bolts. Walczyk et al. stated, that the developed method is only meant for the assembly of simple, flat sheet metal parts and those that consist of simple bends.

Naing [15] proposed ‘An Integrated Methodology for Jigless Assembly’ (AIM-FOR-JAM) in an approach similar to Koonmen. The author applied feature-based design to aircraft structures. Therein, he presented an ‘Assembly feature library’ to support a target-oriented selection and application of part features in order to substitute jigs and fixtures.

The methodical fundamentals of feature-based approaches originate from research on assembly engineering and the field of feature-based design [16]. Mantripragada and Whitney [17] established the concept of Datum Flow Chains (DFC) in order to describe feature-based assembly processes in 1998. Based on reference parts with a reference datum, DFC serve to determine part features and assembly sequence for product assemblies. Mantripragada and Whitney distinguish between features that establish constraint and dimensional relationships between parts and those features that merely support and fasten a part. The former are defined as mates, the latter as contacts. Based on this work, Whitney et al. [18] developed a theory for the design of kinematically constrained mechanical assemblies. They extended DFC by constraint analysis and a step-by-step procedure on how to design feature-based assemblies.

Despite these research efforts, the approach of feature-based build-up of sheet metal structures has not been successfully applied to car body production yet. The reasons are:

- There is a lack of understanding on how feature-based fixturing of sheet metal parts is suitable to meet requirements such as dimensional accuracy and holding forces during assembling and joining.
- The influence of joining techniques, especially of those

that are relevant to the automotive industry such as resistance spot welding and remote laser beam welding, on feature-based assemblies has not been considered at all.

• Finally, there are no guidelines for product (i.e. car body) developers, on how to design features (e.g. type, size, number, arrangement) with regard to the parts that are to be joined and the joining technique used.

The methodology presented in the following aims on closing these gaps in a four step procedure to enable the approach of feature-based build-up of sheet metal structures in the automotive industry.

III. Definition of Relevant Terms

Prior to detailed description of the methodology, major terms are defined that are used throughout this paper.

Feature and feature pairs

Fazio et al. [19] defined a feature as "any geometric or non-geometric attribute of a discrete part whose presence or dimensions are relevant to the product's or part's function, manufacture, engineering analysis, use, etc., or whose availability as a primitive or operation facilitates the design process." Adams and Whitney [20] concretized this definition for assembly features. Assembly features are objects that are capable of constraining and saving one or more degrees of freedom (DOFs) between the parts they assemble. Naing [15, p. 117] complements that features which are being used for assembly need to be considered in pairs as an object's degrees of freedom depend on the other object or objects providing the constraint. A single pin, for example, cannot constrain DOFs of a workpiece. A pin in combination with a slot hole, however, can constrain certain rotatory and translational DOFs.

Jig, tool and fixture

The term fixture is often mentioned along with jig and tooling, however, the terms can be clearly differentiated. Pollack [21] and Naing [15, p. 18] define a jig as a device to locate and hold a workpiece and to position and guide or control a cutting tool, ensuring the correct location of the machining path relative to the part. A fixture, however, is defined as a device that locates and holds only the workpiece. It is used for machining, inspection, welding and assembling and does not control the position of the tool or the instrument which is being used in the process. Tooling, in contrast, is a generic term for working or manufacturing aids such as cutting tools, dies, gauges and molds. A tooling can include jigs and fixtures ([15, p. 18], [22]).

Assembling and Joining

Throughout this paper, assembling (see Fig. 3) is considered as the process step prior to the joining operation. Assembling includes positioning and orientating of parts relative to a reference coordinate system (→create spatial arrangement, [23]). Saving of this spatial arrangement against external force effects (→ clamping, [23]) is also part of the assembling process. Joining refers to the manufacturing process of permanently connecting two or more parts as defined in DIN 8593 [24]. Joining techniques such as welding, brazing or bonding create this permanent connection. The focus of this and subsequent research will be on the production of assemblies, i.e. the creation of structures from single parts (see Fig. 3, right). Research on the production of single parts with features can for example be found in Parris [25] and Birkert et al. [26].

The joining technique that is used in this approach is remote laser beam welding. Remote laser beam welding provides a high process speed, precise and flexible beam guidance, non-contact interference, low heat input and a high level of automation. This makes it an advantageous application for joining sheet metal parts ([27], [28]).

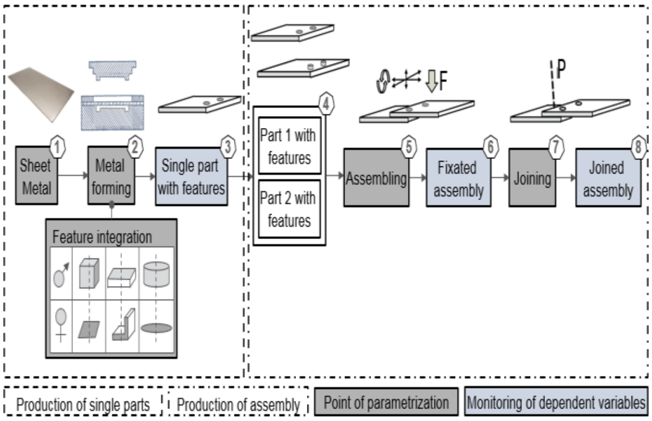

Fig.3. Approach of feature-based fixturing, visualized for the process chain

IV. Methodology to Enable Feature-Based Build-Up of Sheet Metal Structures

The purpose of the research is to understand the dependencies between features, workpiece and relevant dependent variables both, for assembling and joining. Thus, feature-based fixturing should be enabled as the parts and the process can be designed appropriately. According to Trummer and Wiebach [29, p. 17], positioning, orienting, and saving of a spatial arrangement are the main functions of fixtures; dimensional accuracy and holding force are the main dependent variables. For feature-based fixturing, five categories of influencing factors can be distinguished that have an impact on these dependent variables. They are displayed in Table I.

Table I: Influencing factors on dimensional accuracy and holding force for feature-based fixturing

1- The features and feature pairs
• Type of single feature (cylindrical slot, prismatic pin, block …) • Parametrization of single features (length, height, diameter …) • Combination of single features to feature pairs (prismatic pin in prismatic hole, round pin in prismatic slot …) • Number of feature pairs (one, two …) • Arrangement of feature pairs on the parts (position relative to each other and relative to the workpiece) • Others
2- The single sheet metal parts (workpieces)
• Material (steel, aluminum …) • Dimension (length, width, thickness …) • Inherent rigidity (high, medium, low) • Production accuracy of the single parts • Others

3- The joining process
• Force applied on the workpiece during joining • Heat input to the workpiece during joining • Location of the joining zone on the workpiece • Others
4- The assembly process
• Arrangement of single sheet metal parts relative to each other (serial, parallel, mixed) • Force applied on the workpiece during assembling • Others
5- Environmental disturbance variables
• Ambient temperature • Accuracy of measuring systems • Interface of the assembly to the environment during assembling and joining • Others

To cope with the high number of influencing factors, the methodology displayed in Fig. 4 is being proposed.

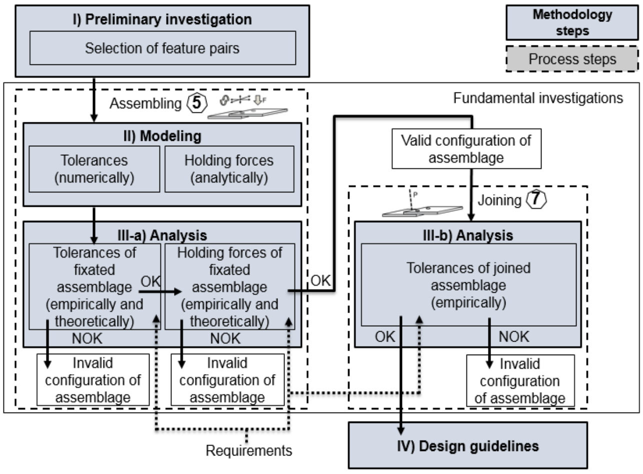

Fig.4. Overview of the research approach

The next sections explain the purpose and scope of the single steps.

1) Preliminary investigations

As introduced in section 2, feature pairs that are able to constrain and secure DOFs between the parts they join are the basis of FBF. The identification of possible feature pairs is based on existing research data such as [15], [30] and [31]. They propose numerous feature pairs for assembly operations. In a second step, feature pairs are selected that appear to be suitable for further investigations specifically for the build-up of sheet metal structures. This involves a systematic assessment of criteria such as feature manufacturability, cost, and DOFs that can be constrained.

2) Modeling

As displayed in Fig. 4, the process steps of assembling and joining are analyzed separately. As assembling happens prior to joining, the full range of parameters for assembling are analyzed first. Therefore, models are developed to represent the behavior of the dependent variables in dependency of the influencing factors. Feature pairs that are regarded as suitable in the preliminary investigations are manufactured in a statistically relevant number, using a close-to-production molding press process. Then, their dimensions are measured with a laser scanner. Based on these real geometries, feature tolerances and expectable holding forces are modeled. The modeling of tolerances is performed in CATIA 3DCS. The holding forces are calculated analytically and calibrated with empirical reference experiments (see Fig. 5). The modeled features are then applied to reference workpieces that build the basis for subsequent analysis. Design of reference workpieces and the analysis procedure are explained in the following section.

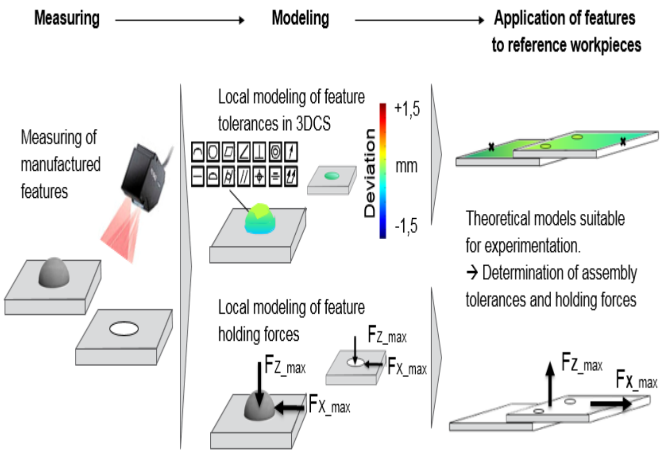

Fig.5. Modeling of features and application to feature-based assemblies

3) Analysis of the assembly operation

Assembling (see Fig. 3) of feature-based structures is analyzed, using the developed models for tolerances and holding forces. For this, the influencing factors of features (1) and workpieces (2) identified in Table 1 are systematically varied and the behavior of dependent variables is measured. Potential influences by the assembly process (4) or other environmental disturbance variables (5) are kept constant. The CATIA 3DCS tolerance model is used for the analysis of tolerances. By coupling a MATLAB script with the 3DCS model, dimensional accuracy is determined for all combinations and variations of feature pairs and workpieces used. At the starting point, two flat sheet metal parts are used as reference workpieces for the parameter studies (see Fig. 6). For those system configurations that fulfill defined geometric requirements (e.g. requirements from the joining process and product specifications) in the simulation, holding forces are calculated by applying the analytical models. System configurations that also meet holding force requirements are then manufactured in order to analyze both, tolerances and holding forces empirically. The manufactured parts are then used as specimens for the subsequent joining operation.

4) Analysis of the joining operation

The manufactured and assembled workpieces are then joined by remote laser beam welding and measured with regard to final geometric accuracy (see Fig. 4). In the joining process, the process parameters (3), which are listed in Table 1, are systematically varied in order to identify suitable ranges of values for joining fixated feature-based assemblies. The determination of suitable system configurations (i.e. those assemblies that fulfil requirements for assembling and joining) may require several iterations as requirements for geometrical accuracy and holding forces are, amongst others, affected by the joining operation.

5) Systematic extension of the investigations

The analysis of feature-based structures is necessary for a wide spectrum of workpieces to qualify the approach of FBF for industrial applications. Hence, the fundamental investigations presented in Fig. 4 are systematically extended as displayed in Fig. 6. Subsequent to the investigations on two flat sheet metal parts, the number of parts in the assembly is increased (step 1). Reference workpieces of higher complexity (e.g. with simple bends) are analyzed and the number of parts in the assembly is increased successively in step 2. In step 3, the workpiece complexity is raised again (e.g. parts with complex curvature are investigated) and part count is increased as well. At each of the experimental points displayed in Fig. 6, the steps modeling and analysis are executed as described previously. For validation of the procedure and the results, the procedure is applied to workpieces from industrial production that are similar to the reference workpieces at selected experimental points (see Fig. 6).

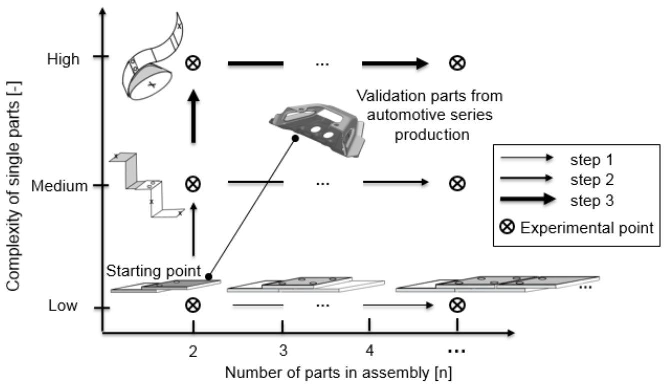

Fig.6. Approach of systematic development of the part spectrum

6) Deduction of design guidelines

To qualify the approach of FBF, dependencies between features, workpieces, and relevant dependent variables both for assembling and joining are being analyzed as described in sections I-III. To make the approach applicable for an industrial context, both, product and process planners need to be able to design the product and process appropriately. Hence, the investigations serve to derive design guidelines that allow for the design of FBF-suitable workpieces as well as for the laying-up of FBF-suitable joining processes: Depending on the workpieces that are to be joined (dimension, complexity, total number …), suitable feature pairs are suggested (type, dimension, total number …) and process parameters for laser beam welding are given that allow for appropriate joining.

V. Conclusions and Future Work

In this paper, an approach is presented to realize a fixtureless build-up of sheet metal structures. It is based on the integration of fixture-related functions into the single workpieces that are to be assembled and joined. The approach is called feature-based fixturing (FBF). A four step methodology is proposed that starts with preliminary investigations to identify feature pairs that appear to be suitable for this approach. Then, feature pairs and workpieces are modeled to determine their influence on relevant dependent variables. The core of the methodology is formed by detailed analyses on interactions between features, workpieces, and dependent variables for assembling and joining operations. The results of the analysis are being used to enable the approach of FBF and to derive design guidelines that allow for the design of FBF-suitable workpieces and FBF-suitable joining processes. All investigations proposed in this paper are subject to ongoing research of the authors.

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M. Sc. Florian Schlather
PhD Student, Institute for Machine Tools and Industrial Management

Dr.-Ing. Florian Oefele
Senior Manager Innovation Production Ressort, BMW Group

Prof. Dr.-Ing. Michael F. Zaeh
Head of the Institute, Institute for Machine Tools and Industrial Management