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Tolerance analysis of compliant, feature-based sheet metal structures for fixtureless assembly

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ABSTRACT

Products made of compliant sheet metals are widely used in automotive, aerospace, appliance and electronics industries. One of the most important challenges for the assembly process with compliant parts is dimensional quality, which affects product functionality and cost. Joining fixtures serve to position and secure the parts in the assembly process and thus significantly contribute to product quality. However, these fixtures are costly and inflexible. Feature-based fixturing is an approach to reduce fixtures in the assembly process. The approach relies on part-inherent fastening features that ensure the fixture functions. This paper presents an approach to calculate assembly variations for feature-based fixturing in the automotive body shop. The mathematical fundamentals are described and the approach was implemented using a numerical model. The model was validated and applied to car body structures. The validation shows a high quality of the model and the suitability to predict assembly variations. Finally, an assembly that is built with conventional fixtures is compared to an assembly that is set up with feature-based fixturing. This comparison shows that the approach of feature-based fixturing has a high potential to meet the requirements and thus being applied in the future.

1. Introduction

The process of automotive body assembly involves joining of sheet metal components to form a body-in-white. Welding is the primary joining technology in the automotive industry. Resistance-spot welding, inert gas welding and laser beam welding are among the main used welding technologies [1]. Fixtures play an important role in the joining process. A fixture positions a part relative to the other parts and clamps the parts to place. After being properly positioned and fastened, the sheet metal parts are welded together [2]. Part-specific fixtures are often used extensively for this task in industry [3]. These fixtures are inflexible and even small changes in geometry or dimension require the design of new fixtures [4]. The design and the production of hardware fixtures is expensive and time-consuming [5]. This is regarded as a major deficit in the automotive industry. The approach presented in Schlather et al. [6] has the potential to significantly reduce the amount of fixtures for joining operations by integrating fixture functions directly into the parts that are to be joined. This is achieved by using part-inherent fastening features. This paper focuses on the development of a model to calculate achievable product accuracy after the assembling and joining of feature-based sheet metal structures. The aspects described in this paper are: review of research approaches, modeling approach for tolerance analysis of feature-based assemblies, model build-up, validation and comparative studies.

2. Assembling of sheet metal structures

In the assembly of sheet metal structures, four process steps are distinguished: *positioning (a)*, *clamping (b)*, *joining (c)* and *clamp release and springback (d)* [7–9]. In this process, fixtures are used to position and clamp the single parts as displayed in Fig. 1. Locators establish the datum reference frame and provide deterministic positioning. Clamps grant total restraint by holding the parts in position during the manufacturing process by application of an external force. In conventional fixturing systems, three supporting elements are used to restrict two rotatory and one translational degree of freedom (dof) in the first plane. A pin-hole (2 dof) and a pin-slot hole (1 dof) combination restrict the remaining degrees of freedom (see Fig. 1). For compliant structures such as sheet metal, more than three supporting elements are required to adequately support the parts [10]. When the parts are properly positioned and secured in the fixture, the parts can be joined. The clamping force is then released and the assembly can be removed from

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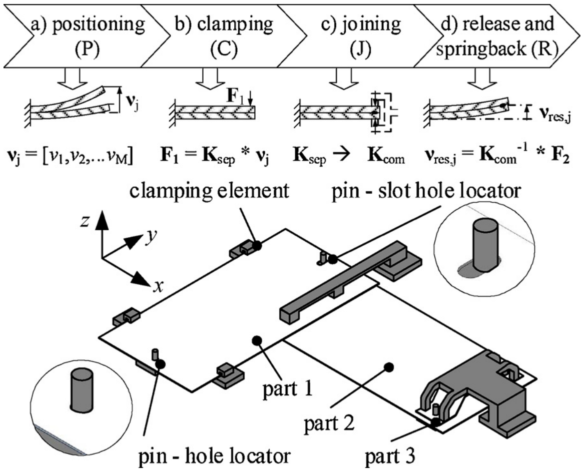

Fig. 1. Sheet metal assembly process in conventional fixturing systems (top, [9]) and exemplary fixture setup (bottom).

the fixture.

The main purpose of this process is to generate an assembly that meets the requirements with regard to joint strength and dimensional accuracy. This paper focuses on the dimensional accuracy that can be achieved. However, part-inherent fastening features are used instead of conventional fixturing systems (see section 2.2).

2.1. Tolerance analysis of conventionally fixed assemblies

Variations in parts and tooling are a major problem in the sheet metal assembly process [7]. Those variations from the nominal dimensions adversely affect the assembly quality, functionality and cost. Hence, variation simulation analysis is used in the design stage to predict such uncertainties. There are various approaches and models that aim to predict product accuracy in the assembling of sheet metal structures. In the beginning, models were developed for rigid bodies only [11–14]. The authors identified three sources of variation in such assemblies: part variation, fixture variation and joining tool variation. Shi and Jionghua [12] as well as Mantripragada and Whitney [13] proposed a variation propagation model. The model is based on vector representations of points. The position of a point A on a part P with a part coordinate system ($X_PY_PZ_P$) can be represented by a vector $\mathbf{A} = (x_{AP}\ y_{AP}\ z_{AP})^T$. The point's position relative to a reference coordinate system ($X_RY_RZ_R$) can be described by a homogeneous 4 × 4 matrix transform. This matrix transform $_\mathbf{R}\mathbf{T_P}$ is composed of a 3 × 3 rotation matrix and a translation vector:

$$_\mathbf{R}\mathbf{T_P} = \begin{pmatrix} \text{rotation} & \text{translation} \\ \text{matrix} & \text{vector} \\ 0\ \ 0\ \ 0 & 1 \end{pmatrix} \tag{1}$$

The coordinates ($x_{AR}\ y_{AR}\ z_{AR}$) of a point A relative to the reference coordinate system ($X_RY_RZ_R$), see Fig. 2, left, can be calculated according to

$$\begin{pmatrix} x_{AR} \\ y_{AR} \\ z_{AR} \end{pmatrix} = {}_\mathbf{R}\mathbf{T_P} \begin{pmatrix} x_{AP} \\ y_{AP} \\ z_{AP} \end{pmatrix} \tag{2}$$

with

$$_RT_P = ({}_RT_1) * ({}_1T_2) * ({}_2T_3) * ({}_3T_P) \tag{3}$$

Part deviations from the nominal dimensions (see Fig. 2, right) are represented by homogeneous error matrix transforms $\mathbf{j}\mathbf{T'_i}$. The actual tolerance zone is defined by a three-dimensional kinematic parameter boundary. It has an associated density which is derived by performing a Monte Carlo Simulation on the parameters. The derivation of tolerance zones for different geometric bodies is explained in detail in [11]. For rigid bodies, the vector chains are only determined by geometrical relations. The deviation of points relative to the nominal dimensions can be calculated by simple vector algebra, stacking up all relevant deviations in the vector chain [11]. These rigid body approaches are not sufficient for valid tolerance analysis due to the compliant nature of sheet metal parts and often lead to large-scale inaccuracies [7]. Hence, the models were extended to compliant parts, including linear Finite Element Analysis (FEA) in the calculations.

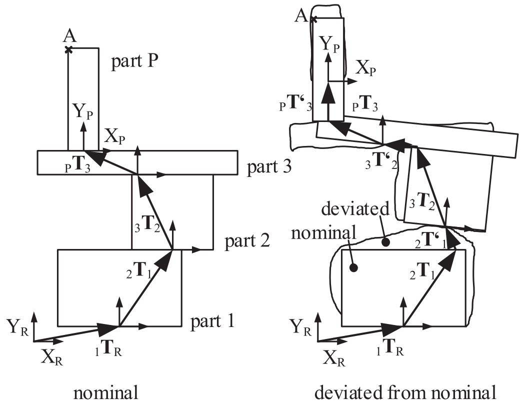

Fig. 2. Homogeneous matrix transform for tolerance representation (based on [11]).

Liu et al. [15] introduced an approach to model variation for deformable sheet metal assemblies. The authors presented a model to analyze the effect of component deviations and assembly springback on assembly variation based on linear mechanics and statistics. This is explained by means of a simple two-beam model as displayed in Fig. 1 (a). The beams have an initial deviation $\boldsymbol{\nu}\ j = (\nu_1, \nu_2,..., \nu_M)$. A force $\mathbf{F_1}$ is necessary to push the beams to nominal, applied by clamps in a fixture (b). This force can be calculated according to

$$\mathbf{F_1} = \mathbf{K_{sep}} * \boldsymbol{\nu}\ _\mathbf{j} \tag{4}$$

$\mathbf{K_{sep}}$ represents the stiffness matrices of the single beams. After joining (c), the clamps are released and the assembly springs back (d). Springback is equal to a force

$$\mathbf{F_2} = \mathrm{K_{com}} * \boldsymbol{\nu}\ _\mathbf{res} = \mathbf{\text{-}F_1} \tag{5}$$

that now affects the final assembly. $\mathbf{K_{com}}$ represents the combined stiffness matrix of beam 1 and 2 due to the joining operation. Thus, the final deviation $\boldsymbol{\nu}\ _\mathbf{res}$ can be calculated. This approach can be extended to 3D problems applying matrix and vector algebra. The assumption of linear mechanics is valid as part deviations are in the range of production tolerances. Thus, they are small relative to the part dimensions [8].

Other authors applied the beam model to more complex sheet metal assemblies from the automotive body shop [14,16,17].

In 2002, Praun [8] developed an extended model for tolerance analysis of compliant sheet metal assemblies. He considered deviations that emerge from fixture element deviation and joining tool deviation and combined linear FEA with a Monte Carlo Simulation. Praun [8] defines elements that are used to position, clamp and join, such as pins, holes, clamps and weld guns, as mating elements. Four vectors serve to describe the tolerance chain that results from operation steps a–d in Fig. 1:

the deviation

$$\boldsymbol{\delta_j} = [\,\delta_x \ \ \delta_y \ \ \delta_z \ \ \delta_\alpha \ \ \delta_\beta \ \ \delta_\gamma\,]^T \tag{6}$$

the relative movement

$$\boldsymbol{\vartheta_j} = [\,\vartheta_x \ \ \vartheta_y \ \ \vartheta_z \ \ \vartheta_\alpha \ \ \vartheta_\beta \ \ \vartheta_\gamma\,]^T \tag{7}$$

the force