Increasing the efficiency of designing hemming processes by using an element-based metamodel approach

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Abstract. In the automotive industry, the manufacturing of automotive outer panels requires hemming processes in which two sheet metal parts are joined together by bending the flange of the outer part over the inner part. Because of decreasing development times and the steadily growing number of vehicle derivatives, an efficient digital product and process validation is necessary. Commonly used simulations, which are based on the finite element method, demand significant modelling effort, which results in disadvantages especially in the early product development phase. To increase the efficiency of designing hemming processes this paper presents a hemming-specific metamodel approach. The approach includes a part analysis in which the outline of the automotive outer panels is initially split into individual segments. By doing a parametrization of each of the segments and assigning basic geometric shapes, the outline of the part is approximated. Based on this, the hemming parameters such as flange length, roll-in, wrinkling and plastic strains are calculated for each of the geometric basic shapes by performing a metamodel-based segmental product validation. The metamodel is based on an element similar formulation that includes a reference dataset of various geometric basic shapes. A random automotive outer panel can now be analysed and optimized based on the hemming-specific database. By implementing this approach into a planning system, an efficient optimization of designing hemming processes will be enabled. Furthermore, valuable time and cost benefits can be realized in a vehicle’s development process.

1. Introduction
In the automotive industry digital methods are commonly used to validate manufacturing processes of automotive outer panels. To evaluate the feasibility of press shop related sheet metal forming processes, especially forming simulations that are based on the finite element method are important [1]. These kind of simulations can also be used for the simulation of body shop hemming processes. This makes it possible to check the feasibility of a hemming-specific product design and also to define adequate optimization measures for the associated overall manufacturing process. Because of the automotive manufacturer’s steadily growing product portfolio, which results in an increased number of various vehicle types, an efficient simulation procedure has to be realized. For this reason, it is necessary to further develop finite element forming simulations but it is also necessary to develop special purpose systems for specific manufacturing use cases.

In this context, the development of a specific metamodel-based planning system is desired, which enables a fast analysis and optimization of hemming processes especially in early product development.
phases. To be able to check the feasibility based on CAD data of random automotive outer panels, a specific defined part analysis in combination with a suitable metamodel formulation has been developed. In addition to an overall feasibility check, the planning system also assists in defining a suitable hemming strategy that is based on the evaluation of several hemming results of various product and process variants. For this purpose, this paper presents a metamodel formulation which can be used in combination with a hemming-specific part analysis technique to quickly analyse and optimize complex shaped automotive outer panels.

2. Development of a hemming-specific metamodel approach
During the past years the potential of finite element hemming simulations has been improved steadily. Besides basic research with simple shaped specimens for studying the factors of influence in hemming processes as [2], [3] and [4], the simulation of complex shaped automotive outer panels has always been part of automotive related research projects [5]. In this case, relevant simulation processes have been further optimized over the last years in order to realize an improved design of hemming processes [6]. However, it still demands significant expenditure of time to set up hemming simulation models of complex shaped automotive outer panels.

In order to reduce simulation effort, metamodels can be used to describe the correlation between hemming-specific parameters by using mathematical models. Metamodels based on regression analysis that can be used to quickly determine characteristic hemming parameters of specific parts have already been presented in [7] and [8]. However, these models can only be used for limited use cases when it comes to predict the feasibility of complex shaped automotive outer panels. This paper will present a new metamodel approach, which is specialized on the requirements of hemming complex shaped automotive outer panels by using a specific part analysis technique for segmental product validation.

2.1. Part analysis technique for segmental product validation
The part analysis technique is based on a simplification of a complex shaped part by decomposing the outline into individual segments. By replacing the part outline with simple geometric basic shapes (Geo) the original contour is approximated [9]. Each of the segments can be evaluated subsequently by using a hemming-specific metamodel approach. Figure 1 shows an overview of the related process steps.

![Figure 1. Process steps of the metamodel-based part analysis according to [9]](image-url)
Geometric parameters defining the basic shape of segment and shape of the corresponding hemming flange are used as metamodel inputs. The parameters \( R_k \) and \( R_b \) describe the segment’s radius of curvature and camber. In addition the parameters flange length before hemming \( (FL) \) and flange opening angle \( (OA) \) are entered. During the metamodel-based evaluation the result parameters are provided for each of the segments. By assembling the segments an overall evaluation of the complete part is possible. To enable an effective evaluation process, a hemming-specific and element-based metamodel approach will now be presented.

2.2. Formulation of an element-based metamodel
In hemming processes various product and process variants have to be considered. Therefore, the metamodel requires a formulation which allows an easy adjustment of these variants. By using an element-based approach as it was presented in [10] and [11], where a metamodel was used to predict the formability in sheet metal forming processes with nonlinear strain paths, it is possible to define a flexible and hemming-specific model setup. The basic model approach is based on a definition of nodes and elements in analogy to the method of finite elements. A range of system input parameters can be defined in such way that the model’s solution space is covered by nodes as model supporting points. The resulting setup of the hemming-specific model considers several geometric basic shapes as well as various hemming flange designs. Figure 2 exemplifies the defined model setup.

![Figure 2](image_url)

**Figure 2.** Hemming-specific model setup including the levels “geometric basic shapes“, “hemming flange“ and “reference data“

The basic model is divided into three model levels: geometric basic shapes, hemming flange and reference data. Within the geometric basic shape level each of the nodes is representing a product variant of a specific geometric basic shape which is characterized by the parameters radius of curvature \( R_k \), radius of camber \( R_b \) and packet thickness \( PM \) (combination of the outer and inner part thickness). The hemming flange level includes the design variants of the corresponding hemming flange design. Here,
the parameters FL and OA are used. Each defined geometric basic shape and its corresponding hemming flange design includes a dataset of various hemming results which has been generated by previously done hemming simulations. This so called reference dataset is stored in a database which is connected to the reference data model level and which forms the basis for evaluating various product and process related hemming results.

As a first step to evaluate the hemming feasibility of a random automotive outer panel, its part outline is approximated by parameterized geometric basic shapes. The parameters, which describe the present part segment and mark the evaluation points in the corresponding model levels, are subsequently used as input variables for the metamodel. If these evaluation points are located within the element boundaries, as a second step a result evaluation will be performed on the basis of the surrounding element nodes. For this purpose, the required hemming result variables are provided by the reference dataset as nodal function values. Through an interpolation computation the relevant hemming results are being calculated on the basis of the existing reference data. This interpolation approach is based on the method of the isoparametric concept which enables a universal interpolation computation. In this context, figure 3 shows the basic functionality of the interpolation computation using the example of the hemming flange model level.

\[ \begin{align*}
\omega_1 &= \frac{1}{4} \cdot (1 - \xi) \cdot (1 - \eta) \\
\omega_2 &= \frac{1}{4} \cdot (1 + \xi) \cdot (1 - \eta) \\
\omega_3 &= \frac{1}{4} \cdot (1 + \xi) \cdot (1 + \eta) \\
\omega_4 &= \frac{1}{4} \cdot (1 - \xi) \cdot (1 + \eta)
\end{align*} \]

**Figure 3.** Schematic of the interpolation computation based on the isoparametric concept
It is assumed for the illustrated example in figure 3 that the parameterized geometric basic shape, which is assigned to the segmented part outline, is exactly matching with a nodal point of the geometric basic shape model level. This causes only an interpolation computation of the basic shape related hemming flange design in the hemming flange model level, where the parameters FL and OA are representing a product state before hemming. Based on this, firstly an evaluation point is generated within the global element system of the second metamodel level. Secondly, a coordinate transformation into the local system of the standard 4-node Lagrange element is performed in order to use the shape functions of the Lagrange element as universal interpolation functions. For each of the element nodes the existing reference dataset of hemming results is now being provided by the database as nodal function values. In order to evaluate the hemming feasibility of automotive outer panels the most relevant result variables include the resulting flange length after hemming, the value of the roll-in, the wrinkling tendency and the resulting plastic strains. To finally determine the hemming results for the present evaluation point a linear interpolation computation is performed based on the provided reference data of the surrounding element nodes. Therefore, various flange lengths and opening angle combinations can be evaluated regarding their impacts on the hemming process.

By combining several model levels it is possible to cover various product and process variants with one universal metamodel. The accuracy of the evaluated hemming results is primarily associated with the validity of the existing reference data. For this reason, special validation measures are required when the reference dataset is being generated through numerical simulations. Every node in the model is representing a simulation variant. The definition of these model supporting points and the resulting element size of the model is essential for the required simulation effort and the accuracy of the interpolation results. By defining finer meshed regions locally a good compromise between simulation effort and model accuracy can be achieved. Namely, the element-based metamodel approach provides good flexibility in model setup as well as in model extension. For example, the reference data are provided as a set of nodal function values that can be extended easily by adding new hemming result variables to the database. These characteristics make the presented metamodel approach particularly suitable for the implementation into a computerized system. A planning system can be configured with the basic metamodel functionality in combination with an automated part analysis and a graphical result evaluation interface to increase the efficiency of designing hemming processes including feasibility checks.

3. Planning system implementation and result validation
The element-based metamodel approach has been realized and tested in a special C# programmed planning system. Besides basic features for part analysis and metamodel computation the system includes a graphical user interface which enables hemming feasibility checks based on 3d CAD product data. Various model input parameters, such as product status before hemming and planned process strategy, can be entered and varied quickly by using a hemming-specific input form. This makes it possible to efficiently prepare, analyse and evaluate various hemming variants and to subsequently derive suitable optimization strategies. Because of the possibility of computing numerous product and process variants, the metamodel approach has significant advantages regarding required expenditure of time compared to conventional finite element hemming simulations.

The validity and accuracy of the defined element-based metamodel formulation has been tested by performing corresponding finite element simulations and experimental tests with several automotive outer panels. All finite element simulations were done with AutoForm Engineering GmbH’s commercial sheet metal forming software AutoForm® plus R6. Within the result validation mainly geometrical hemming parameters such as flange length after hemming and roll-in were analysed. Additionally, the ability of detecting wrinkles and splits was tested. An abstract of the validation procedures is illustrated in figure 4 using the example of a hood.
**Product and Process Properties**

- **Material:** Aluminium AA6014-T4
- **Thickness Outer Part:** 1.0 mm
- **Thickness Inner Part:** 1.0 mm
- **Hemming Process:** Roller Hemming in 4 Steps
- **Type:** Flat Hem
- **Add-on for Roll-in:** 0.6 mm

**Comparison of Hemming Results**

**Flange Length**

| Section | Planning System | FE-Simulation | Experiment |
|---------|-----------------|---------------|------------|
| Section 1 | [Bar Graph] | [Bar Graph] | [Bar Graph] |
| Section 2 | [Bar Graph] | [Bar Graph] | [Bar Graph] |

**Roll-in**

| Section | Planning System | FE-Simulation | Experiment |
|---------|-----------------|---------------|------------|
| Section 1 | [Bar Graph] | [Bar Graph] | [Bar Graph] |
| Section 2 | [Bar Graph] | [Bar Graph] | [Bar Graph] |

**System Information**

- **Workstation:** Workstation with 4 CPUs @ 3.4 GHz and 32 GB RAM
- **FE-Simulation in AutoForm®plus R6**
- **Hemming-specific Planning System:**

**Figure 4.** Comparison of planning system, finite element simulations and experimental tests regarding hemming results and expenditure of time
Two distinctive part sections of the hood, which represent a straight and a convex shaped part outline and which are characterized by significant opening angles and initial flange lengths, were chosen for the hemming result evaluation. As it can be seen in figure 4, the resulting flange length and roll-in values provided by the planning system are well matching with those of the finite element simulations and the experimental tests. The planning system’s implemented element-based metamodel formulation has sufficient accuracy in predicting the illustrated geometrical hemming result parameters.

In addition to the result evaluation, the required computation times of finite element simulation and planning system were compared. Besides significant shorter times in solving, the expenditure of time in pre-processing is notably reduced. For analysing numerous parameter variants, as it is necessary for designing optimal flange cut outs to reduce the risk of wrinkling in convex shaped part sections, several finite element simulation loops and model adjustments are required. In contrast, the planning system allows a direct computation of several product and process variants. Compared to common metamodel approaches that are mostly based on response surface models, the presented element-based formulation also provides a generalized metamodel concept for checking the hemming feasibility of complex shaped automotive outer panels.

4. Summary and outlook
In this paper a metamodel approach specially designed for evaluating an automotive outer panel’s hemming feasibility was presented. The approach is based on a specific part analysis technique in which a complex shaped automotive outer panel is segmented into simple parameterized geometric basic shapes. Each segment is evaluated subsequently by using a hemming-specific metamodel. An element-based metamodel formulation with three model levels was defined in order to cover a wide spectrum of various geometric shapes and hemming flange designs. A reference dataset provides hemming results for the defined supporting points of the model which are represented by element nodes. Based on the metamodel input parameters the relevant hemming results are calculated through an interpolation computation between the surrounding element nodes of the present evaluation point. By doing a coordinate transformation into the standard Lagrange element the corresponding shape functions can be used as universal interpolation functions. This approach enables efficient evaluation of various product and process hemming variants based on existing reference data.

The presented approach is particularly suitable for the implementation into a computerized system. In this context, a hemming-specific planning system including an automated part analysis function and a graphical user interface for checking the feasibility of hemming processes based on 3d CAD data has been realized. The validity and accuracy of the presented approach was analysed through corresponding finite element simulations and experimental hemming tests.

References
[1] Birkert A, Haage S, Straub M 2013 Umformtechnische Herstellung komplexer Karosserieteile - Auslegung von Ziehanlagen (Springer-Verlag, Berlin, Heidelberg, 2013, ISBN 978-3-642-34669-9)
[2] Lin G, Li J, Hu S J, Cai W 2007 A computational response surface study of three-dimensional aluminum hemming using solid-to-shell mapping (Journal of Manufacturing Science and Engineering Vol. 129) pp 360-368
[3] Maoût N L, Thuillier S, Manach P Y, Debois D, Wadoux J C 2006 Numerical simulation of flat-surface roll hemming: Influence of geometry and material models (Proceedings of the International Deep Drawing Research Group Conference)
[4] Thuillier S, Maoût N L, Manach P Y, Debois D 2008 Numerical simulation of the roll hemming process (Journal of Materials Processing Technology 198) pp 226-233
[5] Sigvant M, Mattiasson K 2005 FE-Simulation of hemming in the automotive industry (Proceedings of the 6th International Conference and Workshop on Numerical Simulation of 3D Sheet Metal Forming Process) pp 675-680
[6] Eisele U 2012 *Ein Beitrag zur verbesserten Auslegung von Rollfalzprozessen* (Dissertation, Universität Stuttgart, 2012)

[7] Zhang G, Hao H, Wu X, Hu S J 2000 *An experimental investigation of curved surface-straight edge hemming* (Journal of Manufacturing Processes Vol. 2/No. 4) pp 241-246

[8] Eisele U, Roll K, Liewald M 2010 *Development of an empirical model to determine results from FEA roller hemming processes* (9. LS-DYNA Forum, Bamberg, 2010)

[9] Kaiser C, Zubeil M, Roll K and Volk W 2015 *New diagnostic techniques for an automated hemming validation of hang-on parts* (Key Engineering Materials Vol. 639) pp 509-516

[10] Volk W, Hoffmann H, Suh J, Kim J 2012 *Failure prediction for nonlinear strain paths in sheet metal forming* (CIRP Annals - Manufacturing Technology 61) pp 259-262

[11] Volk W, Weiss H, Jocham D, Suh J 2013 *Phenomenological and numerical description of localized necking using generalized forming limit concept* (Proceedings of the International Deep Drawing Research Group Conference) pp 1-7