Simulation Prediction and Forming Quality Control of Hemming Structure with Dissimilar Materials Oriented to Process Chain

Jianjun Li\textsuperscript{1,a}, Wenfeng Zhu\textsuperscript{1,b,*} and Yuanhui Li\textsuperscript{1,c}

\textsuperscript{1}School of Mechanical Engineering, Tongji University, Shanghai, China

*E-mail: zhuwenfeng@tongji.edu.cn

Abstract. Multi-material mixed-use has become an important way to realize autobody lightweight. However, due to the difference of material properties, the structure is prone to material mismatch when using thin and dissimilar materials. In this paper, a deformation compensation method oriented to the process chain is proposed to eliminate the quality defects. Based on the simulation and prediction of the process chain, the final deformation is advanced to the spreading preparation stage to realize the geometric pre-compensation of the structure. Firstly, in the spreading and hemming stage, the prediction of hemming with adhesive was realized by establishing SPH (Smoothed particle method)-FEM (Finite element method) coupling model. Then, a coupled thermal-chemical-structural model is established to predict the curing deformation. Finally, the deformed dimension is fed back to the spreading stage to achieve the deformation compensation. The results show that the multi-field coupling model can achieve accurate prediction, and the structural deformation is reduced to more than 95%. This provides a basis for material matching and optimization of the whole process chain.

1. Introduction

As the development of advanced manufacturing technology and structural optimization technology has entered a bottleneck period, multi-material mixed-use has become an important development direction of autobody lightweight \([1, 2]\). On the premise of not reducing the performance, the multi-material structure can reduce the body weight and the material cost, which has a strong competitive advantage in the market. Under this background, autobody closure panels with dissimilar materials, such as hoods, doors and decklids, have become the focus of the industry.

Due to the high requirements of appearance geometric accuracy, such as illumination grade A, smooth and continuous contour, no indentation scratch, and NVH performance indexes, the assembly including inner and outer panels must adopt a special composite forming process, which involves adhesive spreading, hemming and temperature baking \([3, 4]\). When using homogeneous materials, the relevant technology has been relatively mature. By optimizing the geometry and process parameters, the assembly deviation of the structure can be controlled to a reasonable range. However, when using different materials, due to the significant differences in the material properties of the inner and outer panels, with the curing of the adhesive, the hemming structure may produce large warpage under the baking temperature load. Therefore, it is an important problem to restrain deformation and improve manufacturing accuracy of low density panels with dissimilar material.

At present, the research on forming precision is mainly focused on the independent single process. Thuillier et al. \([5]\) and Maoût et al. \([6]\) studied the effects of constitutive model, anisotropy and Bauschinger effect on roll in/out and hemming forces. Gürgen \([7]\) took the bending angle, roller diameter, panel thickness and roller hemming force as process parameters, and took roll in, deformation
and wrinkle as the target quality, and then established their relationship through regression analysis. Considering the viscosity-pressure effect when the adhesive was rapid extruded, Li et al. [8] took into account the influence of the adhesive layer parameters on the forming quality. As for the baking process, Xin et al. [9] studied the curing process of autobody panels with homogeneous materials, and showed that different heating positions and methods may affect the roll in/out values. Priesnitz et al. [10] found that heating rate, maximum temperature and other factors can affect the curing accuracy by experiments. Zhu et al. [11] studied the curing process of steel/aluminum-adhesive structure, and found that the properties and geometric parameters of adhesive can affect the deformation. However, as the forming quality involves many processes, the single process is easy to cause the accumulated errors before and after the forming process, especially for the forming of dissimilar material structure. Generally speaking, there is no systematic research and modeling method for the connection of the inner and outer panels with dissimilar materials.

In this paper, a process chain oriented modeling and quality optimization method is proposed. Firstly, the simulation model of hemming and curing is established successively to realize the quality prediction under multi-physics coupling field. Then, the deformation is fed back to the spreading stage in advance to realize geometric pre-compensation. Finally, the deformation is reduced and the forming accuracy is improved.

2. Forming Model Oriented to Process Chain

In the whole forming process, adhesive spreading, roller hemming and baking are needed from sheet to component, as shown in Fig. 1. There are many factors affecting the forming quality, such as flanging length, flanging angle, friction coefficient, etc. Therefore, it is easy to produce a variety of quality defects, such as roll in/out, shortage and overflow of adhesive, etc. When homogeneous materials are used, the defects can be reduced by optimizing the process parameters. However, when using lightweight and dissimilar materials, it is easy to have a variety of quality problems, and the quality defects can’t be eliminated by optimizing the process. In order to obtain qualified products, it needs to be modified by repeated experiments, which wastes a lot of time and cost.

![Figure 1. Roller hemming process chain.](image1)

![Figure 2. Geometric pre-compensation method oriented to process chain.](image2)
In order to eliminate the defects and reduce the experimental cost, this paper presents a method of geometric pre-compensation oriented to process chain, as shown in Fig. 2. Firstly, the adhesive spreading, hemming simulation and curing deformation prediction are completed in sequence, and then the deformation after curing is fed back to the preparation and spreading stage in advance, and finally the deformation pre-compensation of the structure is realized. The finite element method can simulate different forming processes, predict fracture, wrinkling, springback and adhesive layer thickness distribution, which is beneficial to cost saving.

3. Simulation of Roller Hemming with Adhesive
In the process of spreading and hemming, not only the thickness of the adhesive layer affects the forming process parameters, but also it has complex mechanical effect on the metal sheet. At room temperature, adhesive is a high viscosity fluid, and the transient viscosity-pressure effect occurs in the fluid during the squeezing, which is related to the geometry dimension, extrusion speed and the dynamic viscosity [12]. However, it is difficult to quantify the adhesive flowing in narrow gap by conventional methods. When the traditional Euler method is used, it may leads to the low efficiency of calculation, and the convergence of the calculation results.

In order to accurately quantify the influence of the adhesive and realize the accurate prediction of forming quality, SPH method [13] is introduced to simulate the adhesive. It is a mesh free method that assigns physical quantities, such as mass, density and velocity, to interacting particles. SPH is suitable for solving free surface flow problems, and has been widely used in hydrodynamics fields.

![Flow chart of numerical modeling of hemming with adhesive.](image)

SPH and the traditional Lagrangian method FEM complement each other, which is good at solving solid mechanics. The coupled SPH and FEM model can simulate the interaction process between the adhesive and metal sheets. The modeling flow diagram is shown in Fig. 3. Considering the rheological properties of adhesive layer and the constitutive model of the panels, the numerical model under different constraint conditions is established. By the coupling calculation algorithm, the mechanical equation and fluid equation of the structure are solved respectively. In commercial software, the defects such as adhesive flow and sheet forming mechanism are predicted. It provides an important reference for optimizing the process and rheological properties of the adhesive layer.
Taking the curved edge structure as an example, the material of inner panel is DC04 steel, and the outer panel is AA6016-T4 aluminum alloy. The adhesive is simplified to be a viscous Newtonian fluid. The roller hemming by SPH-FEM simulation and experiment is conducted (Fig.4). The experimental results are consistent with the simulation results of roll in/out value and surface wave. It shows that the SPH-FEM model can effectively predict the roller hemming quality.

4. Curing Simulation of Structure with Dissimilar Materials

In the baking environment, the curing of the adhesive will inevitably lead to structural mismatch deformation due to the difference of material properties. Under cyclic loading, the adhesive changes from viscous fluid, high elastic state to glass state. The cross-linking of molecular chains in the adhesive leads to chemical shrinkage, which can’t only cause local deformation of the sheet, but also induce the overall deformation of the structure. Due to the complex changes of mechanical properties, there is no unified constitutive model, so it is difficult to achieve accurate prediction.

Combined with the previous work [14], this paper proposes a multi-stage model, as shown in Fig. 5. When the temperature is lower than the gel point temperature, the adhesive can flow and its influence be neglected. The mechanical reaction mainly occurs in high elastic state and glass state. Because of the obvious change of Poisson’s ratio, the error of elastic modulus is large. Therefore, the constitutive relation of stress-strain can be expressed by bulk modulus $G(t)$ and shear modulus $K(t)$:

$$\sigma_{ij} = \delta_{ij} (K(t) - \frac{2}{3}G(t)) \cdot d\varepsilon_{ii} + 2G(t) \cdot d\varepsilon_{ij}$$

(1)
The constitutive relation of stress and strain can be constructed by stages. In the heating stage, the shear modulus can be used as a function of the curing degree. In the cooling stage, the adhesive layer is completely cured. The viscoelastic model is used to establish the relationship between different temperature points through the time-temperature equivalent model. The bulk modulus and coefficient of thermal expansion can be simplified to be temperature dependent. Generally, the linear model can be used when the curing shrinkage is in the high elastic state I.

When heated by the air, the heat is transferred to the adhesive layer through the inner and outer plates, and the adhesive layer has a curing reaction and releases heat. Based on the multi-stage constitutive model, a multi-physics field coupled model is established, as shown in Fig. 6. Considering the constitutive model and boundary constraints of the panels, the numerical model under complex geometric conditions can be predicted. The multi-physics modeling and simulation process can be achieved based on commercial software COMSOL. Similar to roller hemming process simulation, the curved edge structure is took as an example. The material of inner panel is DC04 steel, and the outer panel is AA6016-T4 aluminum alloy. The curing process of the hemming structure is shown in the Fig. 7. The experimental results measured by DIC system, are consistent with the simulation results of deformation. It shows that the simulation model can effectively predict the deformation process of the hemming structure with adhesive.

Figure 6. Thermal-chemical-structural coupling calculation process.

Figure 7. Curing process of the hemming structure. (a)Simulation; (b) Experiment.
5. Deformation Compensation of Hemming Structure

Due to the different thermal expansion coefficient, stiffness and structural asymmetry, the cured structure with dissimilar materials may inevitably cause serious mismatch deformation. In general, the optimization of geometric process parameters can’t completely eliminate this deformation. Therefore, it is necessary to put forward new methods to eliminate it. The common compensation methods of surface geometric modification are mainly used in the fields of autobody welding deformation and panel springback. On this basis, the reverse compensation of the structural profile is proposed to make the final contour reach the ideal state, as shown in Fig. 8.

![Figure 8. Reverse geometric compensation principle.](image)

In fact, a single geometric compensation can’t eliminate the deformation, which needs to be corrected several times, as shown in Fig. 9. Based on the ideal contour, the curing deformation process is simulated, and then the compensation factor is determined to form a new structure. When the error is declined within the suitable range, the calculation is stopped. The compensated profile provides reference for the parameter correction of spreading and hemming process.

According to the flow chart (Fig. 2 and Fig. 9), the deformation of curved edge structure is compensated. Simulation and experimental results show that the final curing deformation of the modified model is greatly reduced. Compared with the original component, the sample deformation based on process chain compensation is reduced to more than 95%. This method can effectively solve the problem of deformation mismatch of structure with dissimilar materials.

![Figure 9. Deformation compensation flow chart.](image)

6. Summary

A process chain oriented deformation compensation method is proposed to eliminate quality defects. Firstly, in the spreading and hemming stage, the prediction of adhesive curling was realized by establishing the coupling SPH-FEM model. Then, the thermal-chemical-structural coupling model of
curing deformation was established to predict the forming quality. Finally, the final deformation was advanced to the spreading preparation stage to realize the geometric pre-compensation of the structure. The results show the compensation method for process chain is helpful to eliminate the structural deformation fundamentally. In the future, this method will be applied to the manufacture of aluminum-steel hybrid autobody closure panels oriented to process chain. An equal scale model will be made to further verify the feasibility of this method by experiments.

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