Method to increase denting stiffness of car body skin panels

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Abstract. Induction of extrinsic stresses states may lead to significant increases of the denting stiffness of skin panels. For this purpose, the component needs to be produced in a dedicatedly maligned shape. Forcing the part into its target geometry in the joining operation evokes said stress states and preserves them in the sheet. The approach discussed herein shall contribute to the reduction of sheet thickness and subsequent weight of skin panels without impairing the haptic quality of the car body.

1. Introduction
Lightweight design of the car body is an effective lever to reduce vehicles’ weight for diminution of fuel consumption and exhaust emissions or enhancement of the battery range of electric cars. One common procedure therefor is sheet thickness reduction of stamped parts while applying materials of higher strength in order to achieve comparable component performance under operating and crash loads [1].

Whilst this method is widely applicable to structural components, its utilization on skin panels is limited by the resultant decline of their denting stiffness [2]. This effect is of particular criticality for weakly curved parts such as roof, door or frontlid panels [3, 4]. This paper presents an innovative approach to increase denting stiffness of such parts based on the induction of extrinsic stress states. It thus allows for weight reduction of the body shell without compromising the haptic quality perception of the vehicle.

In a joint research project¹ of Heilbronn University and FMF-WWF Werkzeug- und Prototypenbau GmbH this approach has been validated on the actual sunroof segment of a sports car. In the field of numerical simulations, advanced procedures were developed in the course of this work which enable the geometry-based evocation of favourable stress states, the realistic modelling of the physical boundary conditions of sheet metal components, and the computation of denting processes.

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2. Dent resistance, denting strength and denting stiffness

The dent resistance of a skin panel is defined as its ability to resist denting, provoked by loads and energies acting locally and predominantly perpendicular to its surface. Dent resistance is constituted by denting strength and denting stiffness, which stand in complex interdependency [5, 6, 7].

Denting strength describes the resistance against plastic denting due to e.g. hail impact or minor collisions. Denting strength can be improved by the use of materials with higher initial yield strength, the utilization of thermal hardening effects such as in bake-hardening steels and AA6xxx aluminium alloys, or by increasing strain and work hardening in the stamping process [1, 8].

Conversely, denting stiffness – often also referred to as panel stiffness – represents the component’s ability to withstand elastic, i.e. fully reversible denting. It is thus a mainly haptic quality criterion inherent particularly to skin panels and perceived e.g. under palm pressure, when polishing the roof or when slamming shut the liftgate. Higher denting stiffness is commonly associated with better product quality [9, 10]. Furthermore, literature suggests correlations between components’ denting stiffness and flutter tendency at higher travelling speed [11].

While comprehensive research exists on denting strength, denting stiffness has so far been studied to a much lesser extent and only gained attention during recent years in the course of intensified efforts to reduce the sheet thickness of skin panels. There are numerous factors specific to the respective component that affect its denting stiffness, such as panel size and shape, or assembly and clamping conditions [7, 8]. Determining factors of generic nature onto denting stiffness are however panel curvature, Young’s modulus of the sheet material, and sheet thickness [12]. Panel curvature is generally preassigned by vehicle design. Young’s modulus is given as a material property – usually steel or aluminium. Only sheet thickness may be adjusted in the conflict of weight and denting stiffness aims.

The correlation between sheet thickness and denting stiffness is of exponential nature. Under different boundary conditions, literature indicates magnitudes ranging from approximately power 2 to power 3, effecting a substantial loss in denting stiffness already at minor reductions of sheet thickness [3, 4, 13]. Conventional compensation methods comprise e.g. the application of stiffening structures, which yet lead to additional manufacturing steps and lessen the weight savings [14, 15].

Under lab conditions, denting stiffness is determined by slowly pressing an indenter against the surface of the test specimen. The inclination of the quasi-static load-displacement curve recorded in the test represents the denting stiffness. The tests described in the present paper have been conducted in analogy to the procedures described in SAE J2575 [10].

3. General approach and preliminary studies

Considering the case of an uniaxially curved specimen it is evident that, apart from membrane compression, an indentation evokes compressive stress in the outer fibre and tensile stress in the inner fibre of the sheet. The rationale underlying the approach to increase denting stiffness is, simply put, to pre-stress the inner and outer fibre in the same orientation, similar to preloaded springs. Once the indenter comes to effect, it would first have to overcome the pre-stress before the dent may evolve. Consequently, the specimen needs to be manufactured in a deliberately malaligned “false” initial geometry, and then forced into its target shape by gradually pulling its straight edges apart from each other, thus inducing said desired stress states before initiating the denting process.

By use of analytical methods, a procedure was developed to identify suitable initial geometries for uniaxially curved specimens and to calculate load-displacement responses. It is based on the principle of minimal elastic energy according to equation (1),

\[
\int_0^l \left[ \frac{EI}{2} \left( \kappa - \kappa_0 \right)^2 - N(x'(s)^2 + z'(s)^2 - 1) \right] ds = \min
\]

where \( x'(s)^2 + z'(s)^2 - 1 \) serves as the constraint of constant sheet length \( s \), and section force \( N \) is the Langrange multiplier. \( E \) represents the Young’s modulus, \( I \) the moment of inertia. \( \kappa = (z'x'' - x'z'') \)
and $\kappa_0$ are the curvature of the initial geometry and the target geometry. The application of Ritz’s direct method hence leads to the approximation of $x(s)$, $y(s)$ and $N(s)$ by polynomials fulfilling boundary conditions for $x$, $z$, $x'$ and $z'$ and variation of the energy functional with respect to the coefficients. The computerized execution of this calculation scheme with varying parameters showed significant increases of denting stiffness with decreasing curvature of the initial geometry. This two-dimensional case was then modelled and computed in ANSYS 17, leading to results well consistent with the semi-analytical approach.

In the subsequent step, a variety of uniaxially curved samples were produced according to initial geometries computed beforehand. An aluminium alloy AA6016 was used for the sheet material to avoid significant fluctuations of the Young’s modulus due to deformation [16] and aging [17] as known e.g. from steel sheet materials [18, 19]. In order to maintain the initial sheet thickness, a heat-assisted forming method [20] was applied in the forming of the samples. The samples were clamped on a rigid fixture to be forced into target geometry for experimental dent testing. The tests furnished experimental evidence of the anticipated augmentation of denting stiffness with decreasing initial curvature, i.e. with increasing pre-stress of the samples.

4. Application onto a car body assembly
The findings were then transferred on the sunroof segment of the Porsche 911, an assembly consisting of a weakly curved skin panel and a highly rigid inner frame. In serial production, both parts are stamped from steel sheet and joint by hemming and adhesive bonding. The outline of the assembly is non-rectangular with spatially curved rims, and the skin panel is doubly curved with radius transitions. This assembly hence meets the requirements of a complex BIW component. In accordance with above explanations, aluminium AA6016 in sheet thickness of 1.0 mm was chosen as skin panel material. Tensile tests of the actual sheet material batch from physical validation served to generate a material model for numerical simulations with isotropic hardening behavior and a combined Swift and Hockett-Sherby model for yield curve extrapolation.

The panel geometry was modelled in ANSYS 17 using Shell 181 elements sized 2 to 20 mm and five integration points in sheet thickness direction. A methodology was devised that allows for the development of a suitable “false” skin panel geometry. Accordingly, the original geometry first undergoes deformation into a substantially overcrowned shape. The resultant stresses are then discarded. Next, the panel is deformed back into its original shape whereby elastic stress states arise that are to positively affect denting stiffness. Circumferential fixation, representing the assembly situation with the frame, preserves the shape and stresses for subsequent denting simulations. ANSYS Parametric Design Language (APDL) code was used extensively in order to adequately represent boundary and clamping conditions. The distance analysis in figure 1 depicts the deviations between the ideal target geometry and the pre-stressed “false” geometry. It can be stated that the original geometry recurs with good accuracy.

Figure 1: Distance analysis of pre-stressed “false” geometry to initial geometry

Figure 2 (a) and (b) indicate the mean stresses in planar stress state in the top and the bottom layer, respectively. While absolute stress values are low, it can however be perceived that the top layer is predominantly under compression, the bottom layer predominantly under tension. Simulations of
denting process within the elastic regime were carried out in six denting loci of the pre-stressed and the stress-free component, using an indenter with a 100 mm spherical radius. Figure 3 shows the so-called secant stiffness [13] values obtained at an intrusion of 1.7 mm, calculated as the ratio of normal force to displacement.

**Figure 2 (a), (b):** Planar stress distribution of pre-stressed “false” geometry in MPa, top (left) and bottom layer (right)

It can be perceived that in the center of the component, an increase in denting stiffness of almost 19% is prevalent for the pre-stressed configuration. Here, the initial stiffness in the load range between 10 N and 25 N increases even by almost 60%. However, a direct correlation between the local stress gradients across the sheet thickness and the achievable increase in denting stiffness cannot be determined for the extension of the dent area is of a more regional nature. This is visualized in figure 4 (a) and (b) by the deformation plots of the stress-free and the pre-stressed configuration in denting locus 2. It is quite evident that the dent in the pre-stressed panel is more constraint. It can be stated further that for the dent loci closer to component contour, the stiffness increases vanish almost completely due to the rigid circumferential fixation.

**Figure 3 (a), (b):** Denting stiffness of stress-free and pre-stressed assembly in six denting loci at 1.7 mm intrusion

5. **Experimental validation**

Experimental validation took place on two types of assemblies, one with a quasi stress-free panel and one with a panel under designated pre-stress. For the production of the skin panel in its original geometry by stamping, laser trimming and flanging, equipment from a previous prototyping project came to use which required only moderate adjustments. However, the dies and fixtures for the production of the panel in its “false” shape were specifically designed and manufactured. Forming simulations with AutoForm R7 for process set-up and die face design included sensitivity and robustness analysis. The Compensator module was used to provide for dimensional accuracy after springback. Forming analyses supported the adjustment of strain distribution in the course of the
commissioning of the draw dies. Hence, both variants of the skin panel exhibit comparable
distributions of effective sheet thickness.

![Figure 4](image)

Figure 4 (a), (b): Dent geometry at 1.7 mm intrusion in stress-free (left) and pre-stressed configuration (right)

For component assembly, a sufficient number of steel inner frames were obtained from serial production. The assembly process took place in a purpose-built fixture capable to accommodate both panel variants. As for the “false” shape panel, the fixture serves to force it into its target geometry and lock in the resultant stress states by adhesive joining with the frame. In contrast, no stresses emerge when positioning and joining the original panel geometry in the assembly fixture. It should be noted though that the hemming process as performed in serial production was omitted here in order to evade any distorting stress-strain states in the panel. Optical 3D measurement assured the prerequisite of due dimensional accuracy of the assemblies.

![Figure 5](image)

Figure 5: Load-displacement curves from simulation and experiment at denting locus 2

These specimens were subjected to elastic denting on the institute’s test rig. Comparative tests were conducted in nine denting loci according to figure 3 (b). Sufficient accordance between simulation and experiment was achieved, exemplarily illustrated for denting locus 2 in figure 5. However, the derived stiffness values differ due to inevitable curvature deviations rooted in the panel production and assembly process.

6. Discussion and outlook

Superposition of induced stresses may be a pragmatic method to increase denting stiffness and hence facilitate sheet thickness reduction in skin panels for the purpose of car body lightweighting. The validity of the approach has been demonstrated on simple test geometries as well as a real car body assembly. The generic simulation methodology developed was further applied to a highly demanding frontlid outer panel in investigations not to be discussed here in detail. As a result though, a fivefold increase of initial stiffness was achieved, however at the price of an early and pronounced oil-canning effect and limited geometrical accuracy.
One may argue that the stress states induced to optimize denting stiffness will be annihilated during the paint drying process. In fact, according to Regensburger et al. [21], creep and relaxation of AA6016 in the e-coat drying process at 200°C occurs already at residual stresses below 22 MPa, as prevalent in the sunroof panel under consideration. These findings however indicate that creep strains are in the magnitude below 10^{-4} and might therefore be neglectable. This assumption is founded by own investigations of panel curvature under stress before and after paint-bake.

In order to precisely match simulation and experimental results it has been found, ultimately, that an elaborate, industrial-scale commissioning process of dies, fixtures and processes would be necessary that could not be carried out to full extent in the scope of the project. Further research focusses on (homogeneously) distributed surface loads and respective denting energies in the context of air pressure and subsequent fluttering behavior during while driving.

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