Application Limits of a Method to Predict Distortion Caused by Mechanical Joining Technologies in Car Body Construction

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Abstract. This paper deals with the determination of application limits of an already presented method \cite{1} to predict distortion of joined car body assemblies caused by mechanical joining technologies. The investigated method is particularly developed concerning the demands coming from the application in the automotive body production. Parameter studies in simulation and experiment are presented which show the influence of pre-straining and clamping on the joints properties and dimensional accuracy of the assembly. The gained cognitions allow conclusions about the quality of prediction of dimensional accuracy using the proposed simplified model in different joining situations. Finally, the investigated method is applied to a car body assembly.

Keywords: Finite Element Method, mechanical joining, simplified model, distortion, application limits, process chain

INTRODUCTION

In the automotive industry reducing cars weight is the most promising solution to meet customers and governmental demands - concerning fuel consumption and emissions. Reducing weight goes along with an increased use of lightweight materials like high strength steels, aluminium and magnesium. In car body assemblies, single parts made of the same type of material as well as of different types of material need to be joined. One of the main technical challenges concerning lightweight concepts is the development of appropriate joining technologies, as former established technologies like resistance spot welding (RSW) do reach their limits. Looking at aluminum and mixed material car bodies there is a high use of mechanical joining technologies like selfpiercing riveting (SPR) and clinching. Investigations of \cite{2, 3, 4, 7} show that mechanical joining techniques significantly cause distortion in joined assemblies and influence the dimensional accuracy and quality, customers expect (shape, gap, flush). In the past different methods to predict distortions of car body assemblies using FEM (finite element method) were presented. Industrial applicable methods have a high potential to reduce costs in the planning phase of car body tools/ devices and shorten the time between first assembly from series tools/ devices and series launch. These goals can only be achieved if applied methods are reliable and the application limits are determined. In this paper application limits of a method to predict distortion caused by mechanical joining techniques are determined.

STATE OF THE ART

Different papers have been published the last years dealing with assembly distortion caused by mechanical joining technologies \cite{2, 3, 4, 6, 7}. These investigations show the relevance of assembly distortion for car body quality. Simulative methods and practices to predict multi-station sheet panel assembly dimension were shown in \cite{14, 15}. It needs to be mentioned that this method does not take distortion caused by the applied joining technology (welding, mechanical joining) into account. Cai et al. \cite{4} presented the only known approach to predict local and
global distortion of car body assemblies joined by SPR with tubular rivet. Using this method to predict distortion of a car body structure (door assembly) it was shown that the results are sufficient in global but insufficient in local regions of the assembly.

In [1] a method, using simplified models in FEM software to predict distortion caused by SPR, was presented. This method is particularly developed to meet the demands coming from the car body production process and making process chain simulation possible. Demands coming from the planning and production process of car body assemblies are:

- Consideration of effects coming from prior processes (pre-straining, reduction of blank thickness and springback/ pre-deformation of the parts to be joined)
- Consideration of effective surfaces of tools for clamping and joining processes
- Creation of distortion caused by different joining technologies using simplified models (without explicit simulation of the joining process)

The principle of the method, considering these demands, is illustrated in Figure 1.

The illustrated simplified model was applied to pre-deformed and non-pre-deformed riveted specimen (steel top blank, aluminum bottom blank) with a gradual increase in complexity. It was shown that the dimensional accuracy of simple as well as complex structures can be reliably predicted in local (gap) and global regions of the assemblies. In [2] the simulation of the process chain from the single parts to the hemmed assembly, including sub-assembly processes, are performed. It is shown that the shape of the sub-assembly after joining is crucial for the final geometry of this hemmed assembly. Looking at the sub-assembly process (SPR with solid rivet) it is shown that effects coming from the stamping process after springback (stress, strain, thickness reduction) have a significant influence on the simulated joining distortion in local and global areas. The consideration of pre-straining is also suggested and proven in case of welded car body structures in [10].

After own research there are no publications in science and industry relating to the influence of pre-straining on distortion caused by mechanical joining. Scientific works like [8, 9] only investigated the influences due to the joining process, geometry of joint and especially the static, dynamic and high-dynamic structural behavior [16, 17, 18]. Furthermore in the publication of [8] appropriate methods to produce test-specimens were discussed like e.g. rolling, stretching and the Deep-Drawing Marciniak test. Especially the Marciniak test was recommended but not used due to the unavailability of adequate sizes of the test-setups. Relevant positive aspects of using the Marciniak test are [13]:

- production of uniformly and plane pre-strained test-specimens
- different levels of pre-deformation can be reached

Target-orientated studies to the influence of clamping devices on a mechanical joint or mechanical joined car body assembly also have not been the focus of investigations in recent years. In contrast to that, in the field of welding various experimental and numerical studies [11, 12] have shown the influence of clamping on residual stresses and distortion. Especially in case of clamping in the heat affected zone [12]. In addition to that Cai [5] showed an numerical and deterministic method for fixture optimization of welded assemblies taking into consideration variations of welding guns, e.g. misalignment.

**APPLICABILITY OF METHODS TO PREDICT DISTORTION OF CAR BODY ASSEMBLIES**

In addition to previously performed studies on the proposed simplified model, application limits need to be defined. On the one hand there are topics concerning the simplified model itself and the process of gaining input information and on the other hand there are further demands coming from the process of producing car body components.
- **Small local deviation:** Depending on the joining technique, the used joining parameters, the parts to be joined geometry as well as the material, locally only very small distortions occur. Nevertheless these small local distortions can cause relevant global distortions. To consider small distortions in simulations these distortions need to be measureable and it needs be shown that these deviations are predictable using the proposed simplified model.

- **Stiffness of joints:** Depending on the joining technology and the joining task, joints set next to each other can interact and influence each other [1]. Known methods using simplified models neglect this influence. It needs to be found out, if there is a change in simulative results and if these come closer to measured values of experimental joined specimen.

Figure 2 shows a car body clamping device with positioned and clamped parts to be joined. Due to prior stamping processes usually the parts to be joined are pre-strained. It is a goal of this investigation to identify the interactions between joints and clamps/ pre-straining looking at changes in spot quality and distortion. For the applicability of the simplified model it is crucial to keep it as simple as possible and know the limits of the method. It is to be investigated if it’s possible to use the same simplified model in different car body relevant joining situations or if it needs to be adjusted for different joining situations.

- **Influence of clamps on distortion and joint quality:**
  In welding it’s known that clamps have an influence on residual stresses and the samples distortion. The proposed simplified model is based on measurements or simulations of a specific joint with its properties and characteristic distortion of reference samples. The influence of clamps on the distortion and the quality of mechanical spot joints is investigated in experiment and simulation in this paper.

- **Influence of pre-straining on distortion and joint quality:** Reductions in sheet thickness and pre-straining in general influence the quality of the joint (behaviour under load, joint geometry). Changes in the joint quality can also have an influence on the distortion of specimen and assemblies in general.

![FIGURE 2](image)

FIGURE 2. Car body assembly in clamping device. Left side - pre-strained parts (thickness). Right side - clamps and joints

In the following the state of the art to these topics is described and discussed.

**EXPERIMENTAL AND SIMULATIV STUDIES ON DISTORTION CAUSED BY DIFFERENT JOINING TECHNOLOGIES**

The aluminium (AA6181-T4, upper blank 1.5mm, lower blank 1.0mm ) sub-assembly pictured in Figure 2 is an idealized assembly which includes most of the characteristics of a typical car body assembly. It allows investigating different design variants for each process step along the process chain of car body production. In detail this assembly is described in [2]. For this assembly the joining sampling process was run through for the three joining techniques Clinching, riveting with solid rivet and riveting with semi tubular rivet. Because of the limited approachability caused by the clamping device the joining direction is given for all the technologies. The used joining parameters and the micro sections of the reference samples are shown in table 1.

<table>
<thead>
<tr>
<th>Joining Process</th>
<th>SPR solid rivet</th>
<th>SPR semi tubular rivet</th>
<th>Clinching</th>
</tr>
</thead>
<tbody>
<tr>
<td>Machine</td>
<td>KerbKonus</td>
<td>Eckold</td>
<td>Eckold</td>
</tr>
<tr>
<td>Rivet diameter / length</td>
<td>4mm / 2.7mm</td>
<td>3.3mm / 4.0mm H2</td>
<td>-</td>
</tr>
<tr>
<td>blankholder diameter</td>
<td>12mm</td>
<td>18mm</td>
<td>18mm</td>
</tr>
<tr>
<td>blankholder force/ spring stiffness</td>
<td>- / 277N/mm</td>
<td>2000N/ -</td>
<td>1500N/ -</td>
</tr>
<tr>
<td>die</td>
<td>6.5 mm (ring diameter)</td>
<td>-</td>
<td>TOX</td>
</tr>
</tbody>
</table>
The joining techniques were applied to circular blanks with a diameter of 45mm. Circular blanks were chosen because of the identical geometrical stiffness in the different directions. The specimens (7 specimens per experiment) were measured using the optical laser triangulation technique, before and after joining. Different joining technologies cause different kinds of distortion. To compare the deviations the illustrated definition (Figure 3) is used in this paper.

**FIGURE 3.** Definition of deviation caused by mechanical joining (example riveting with solid rivet)
- **out-of-plane distortion:** distortion of joined blanks in vertical direction
- **gap:** maximum distance between upper and lower blank
- **in-plane-distortion:** difference of maximum measured horizontal distance before and after joining

The measured distortions for the three joining techniques are shown in Figure 4. It can be seen that the results differ in kind, direction and value of distortion. SPR with semi tubular rivet causes for this joining parameters and joining task the lowest out-of-plane distortion but the highest in-plane distortion. Clinched specimens have a deviation of both sheets in the direction of the punch and a negative in-plane distortion. That there is no gap in a single spot specimen looking at clinching and SPR with semi tubular rivet doesn’t mean that there is no gap in multi-spot specimen.

**FIGURE 4.** Comparison of distortions caused by different joining techniques

SPR with solid rivet causes by far the highest out-of-plane distortion. As the values of distortion differ significantly there is a gap of approximately 0.27mm. Compared to the distortion values of a mixed material specimen (steel, aluminum) with SPR with solid rivet in [1] these measured values are very low. To get an idea about the prediction quality of the simplified model it is applied to a two-spot-specimen (rectangle 100x45mm). The preciseness of the measured values of the one-spot-specimen makes it possible to exactly calibrate the simplified model before applying it to specimens of different complexity.

**FIGURE 5.** Comparison of measured and simulated distortions (gap) of a two spot specimen (SPR with solid rivet)

The measured and simulated results of section A-A and B-B show very good compliance. Due to an improved measurement technique these results even improved compared to the results presented in [1]. It can be assumed, that the joints stiffness plays the most significant role if a joint causes a high in-plane distortion. As SPR with solid rivet causes the highest in-plane distortion this joining technique and the corresponding
simplified model is chosen. These connections characteristics are defined by tension (1KN/mm) and shear stiffness (21KN/mm). The stiffness of the connection was determined in experiment using KS2-specimen [18]. Looking at Figure 5 it can be seen that the simulative determined gap gets reduced. For this case better results are achieved using stiff connector elements. For the further investigations stiff connector elements are used. Investigations on the modelling technique, different joining situations and different joining techniques are in progress.

INFLUENCE OF PRESTRAINING AND CLAMPING ON DISTORTION AND JOINT QUALITY

Investigations concerning the influences of pre-straining and clamping on the distortion and joint quality were performed on all the three presented joining techniques. Selected results for SPR with solid rivet and clinching are presented and discussed. To compare results the following quality criteria are used:

- **Distortion**: out-of-plane distortion is compared calculating the total of the absolute values of the deviations of upper and lower blank
- **Joint quality**: filling of shank groove (SPR with solid rivet), undercut (Clinching), reduction of base thickness (SPR with solid rivet, Clinching)

Concerning the joint quality, generated micro sections of pre-strained and clamped specimen are compared to the micro section of the reference sample.

Joining of pre-strained specimen

Figure 2 shows that car body single parts are usually pre-strained due to stamping processes. In the state of the art it is shown that pre-straining of blanks has a significant influence on the joints quality. It should be emphasized that sampling processes of new joining connections are executed on simply rolled, not on pre-strained specimen. In this paper the influences of pre-straining on the joints quality (as defined above, mechanical behavior) and the caused distortion in one-spot and two-spot specimen are investigated. To get plane pre-strained specimen an up scaled Marciniak-test (punch diameter 200mm, here biaxial load) is used. One (diameter 45mm) and two spot joining specimen are cut out (lasercutting) of the plane area. The process chain of assembly simulation using pre-strained specimen is illustrated in Figure 6.

**FIGURE 6.** Experimental setup/process chain of assembly simulation using pre-strained specimen

As car body single parts are not uniformly pre-strained, used blanks (1.5mm, 1.0 mm) are pre-strained to 3, 5, 8.5% strain. To determine the exact values AutoGrid® was used. The maximum level (8%) causes a reduction in sheet thickness of about 16% on the thick as well as the thin sheet. For this investigation sheets with the same level of pre-straining are combined (thick blank punch side, thin blank die side) and joined using riveting with solid rivet (same tools for all levels – according to real production processes). In the simulation the entire process chain is run through. Deep drawn parts are trimmed and joined using the simplified model approach. For the simulations with the pre-strained blanks the same simplified model is applied to the non-pre-strained specimen. This matches to the industrial demand to keep the simplified model approach as simple as possible. Figure 7 shows the results for the different pre-straining-levels. It can be seen that pre-straining significantly influences the distortion as well as the joint quality. Caused by the reduction of the sheet thickness (corresponding to the results described in the state of the art) there is a decrease of the joint quality compared to the reference sample.
FIGURE 7. Influence of pre-straining on distortion and joint quality/ comparison of measured and experimental results

Looking at the base thickness and the filling of the shank groove the joint quality of the maximum pre-straining level can be considered as insufficient [16]. For production processes this would go along with a change of the process parameters of the reference sample. While the joint quality gets reduced the total measured distortion increases. It can be noticed that there is a higher change in distortion of the bottom sheet (side of the die ring).

Qualitatively the results of the simulation correspond to the measured values. Quantitatively there are deviations of up to -33% from the simulative to the measured results. It needs to be said that the distortion gets simulative underestimated using the simplified model. To reduce this error pre-strained specimen should be used in experiment and simulation to calibrate the simplified model.

Joining of clamped specimen

Car body single parts are positioned and clamped prior to joining processes. Figure 2 shows a typical car body clamping device. It can be seen that there are joints with and without clamps located next to it. To investigate different clamping situations and determine the interactions of clamps and joints a clamping device for single spot and multi-spot specimen was build. In this paper results of a circular specimen clamped with four clamps are presented. The specimens get clinched and joined with SPR with solid rivets. Looking at Figure 8 differences in the experimental setup of clinched and riveted specimen can be seen. While clamping and joining takes place in the same plane for clinching, the parts to be joined need to pushed over the die ring, being held in position by the clamps, for SPR with solid rivet to get the groove shanks filled.

FIGURE 8. Experimental setup for clamping one-spot specimen/ differences concerning joining and clamping plane of SPR and Clinching

As Figure 9 shows the significant change of boundary conditions of the SPR process leads to a reduction of the joints quality. It can be noticed that this has a strong influence on the total distortion of the specimen. As the sheets get pushed over the die ring the measured distortion of the bottom sheet increases while the distortion of the top sheet decreases. Simulative results using the characteristic information of the reference sample are in opposite hardly influenced by the clamps.

In the case of clamped, clinched specimen only slight differences can be detected comparing the clamped simulated/ measured results to the results of the simulated/ measured reference specimen. There is neither a significant change in the caused distortion nor in the joints quality. To correctly predict the distortion caused by SPR with the shown experimental setup the joining situation needs to be considered while calibrating the simplified model. It is shown that clamping processes taking place in the same plane like the joining process can be correctly simulated.
Application of the simplified model to a car body assembly

To underline the practical relevance of the presented results the method is applied to a car body assembly. The experimental setup is illustrated in Figure 2. The parts in the simulation are simulative deep drawn parts that are riveted (with solid rivet, reference specimen) in the car body device. The simplified model (reference sample) is implemented after clamping (clamping device and joining tongs). When the last spot is set the opening of the clamps causes another change of the assemblies’ geometry. The process and the results for global and local distortion are illustrated. The above described effects of clamping and pre-straining help to interpret the gained results. It needs to be mentioned that the clamping situation strongly differs from the above described clamping situation. Due to that, the effect on the change in distortion and joint quality will be reduced and the simulative prediction quality will be improved in this case.

CONCLUSION

In this paper demands to determine application limits, of a proposed method to predict distortion caused by different mechanical joining techniques, are described. Coming from the state of the art the functionality and the results’ quality is described. Based on the existing results further demands concerning the applicability in the automotive industry are named:

- Predicting small distortions
- Influence of clamps on distortion and joint quality
- Considering the joints´ stiffness
- Influence of pre-straining

It is shown that different joining technologies (Clinching, SPR) cause different kinds of distortion (in-plane, out-of-plane, gap) applying these to the same joining task (aluminum, 1.5mm/ 1mm). Compared to the deviations of a mixed material specimen in [1] these deviations are small. Using optical measurement equipment the simplified model is calibrated for the SPR with solid rivet and applied to a two spot specimen. The simulative and the measured results show very good compliance. The influence concerning joints stiffness in the simulation is also illustrated on this joining task. For this connection the simulative results of the gap get underestimated. Further investigations concerning the joints stiffness are in progress. Concerning the applicability of the influence of clamps and pre-straining of the blanks is investigated. The simplified model, calibrated to the reference sample of SPR and
Clinching, is applied to both pre-strained and clamped specimen. Pre-strained, plane specimens are gained using a scaled up Marciniak-test. The process chain is run through in simulation and experiment. Experimental results show, that the distortion increases with increasing pre-straining while the joint quality decreases. These results are highly relevant as blanks with different pre-straining levels are joined with the same tools in car body production.

Comparing measured and simulative results it can be said that the simulation (using the initial state of the simplified model – calibrated with a non-pre-strained specimen) underestimates the gap’s height. To the clamped sheet two different joining techniques are applied to show the difference of joining and clamping plane. The distortion and joint quality of clinched specimen, a process with the same level of clamping and joining plane, is hardly effected by the clamps (strongly clamped specimen – 4 clamps). In contrast to that, the joint quality and the distortion of the riveted specimen (different levels of joining and clamping plane) are strongly affected by the clamps. The total distortion and the joint quality decreases. Obviously this effect can not be shown in a simulation using the initial simplified model (calibrated with a non clamped specimen).

Depending on the demanded quality of simulation results used simplified models can be recalibrated using pre-strained and clamped reference specimen, but this increases the effort. To clarify the functionality and the use of the proposed method the simplified model gets applied to a car body assembly. Local and global distortion of the assembly is shown. The prior described effects can be used to interpret the gained results. A comparison of measured and simulated results using the described assembly is published in the near future. Part of current work packages is to determine the effect of the elasticity of the robot/ joining tongs and the boundary conditions of the specimen on the final position of the tools and the distortion of the specimen/ assembly. The effects described in this paper should on the one hand be considered in the planning phase when tools and clamping devices for new assemblies are chosen. On the other hand these effects are relevant looking at the phase between first part from tool/ device and series launch when the assemblies’ quality is optimized.

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