Hemming of layered composites dedicated to stiffness increase

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Abstract

Aluminum/polymer/aluminum composites do show advantages compared to monolithic materials when strength, stiffness and damping characteristics are set to a global optimum. Although their mechanical properties have been improved during recent years, application of such hybrid materials in automotive industry is not well-established due to unsufficient knowledge about its forming characteristics (e.g. in table-top hemming). This paper deals with challenges of delamination of stiffness increasing composites in industrial table-top hemming processes. Stiffness increasing composites are consisting of two aluminum sheets and a viscoelastic damping layer: The inner sheet includes stamped beads and increases the stiffness while the outer sheet is set up as cover sheet. The main concern is delamination behavior in flanging, pre-hemming and final hemming used in real components consisting of those layered materials. In this investigation hemming parameters were varied, e.g. flanging radius, bending direction and level of pre-strain. Additionally, surface quality of the hemming rope is evaluated dedicated to delamination after each process step. Computer tomography investigations were used to identify different zones of delamination within the hemmed flange area.

1. Introduction

Original Equipment Manufacturers are seeking to develop new vehicle lightweight strategies that will allow them to cost-effectively meet fuel economy targets, and increasingly shifting their focus to application of mixed-material solutions at mass produced scales. Future automotive industry aims are determined by a set of society`s upcoming challenges, e.g. demand for energy efficiency, climate protection, security in driving and comfort. However, applying lightweight materials to mass produced vehicles comes with a set of challenges, because OEMs need to select the optimal combination of materials being used for car body components including aluminium, high-strength steel, composites and magnesium. Such material is sourced in volumes and specifications required for high volume production and the optimal joining and casting techniques for mixed material manufacturing at scale. [LIG14]

A current common trend in lightweight strategy is to achieve the above mentioned goals of reduction of emissions and energy consumption by using lightweight materials having specific advantages. However, composites provide the possibility of individual combination of different mechanical properties into one hybrid sheet metal due to the fact of their layered structure. The poor formability of advanced lightweight materials has seriously hampered their wider application in deep drawing process to produce high end car body components.

Lightweight materials, such as ultra-high-strength steel, titanium alloy and aluminum alloys etc. are used extensively in aerospace and automobile industries which lead to increasing demands on advanced forming technologies. Conventional forming methods are not useful to fabricate lightweight structures. In the 21st century, in metal forming, many researchers and R&D facilities during recent years have proposed many advanced innovative forming methods dealing with this problem. These particular forming methods do reveal both advantages and disadvantages in their suitability for different types of sheet metal forming processes [LAN14].

Beside monolithic materials such as aluminum, further light-weight materials such as layered composites are used to reduce vehicle weight and energy consumption. It is essential to analyze their forming potential in terms of current applications (e.g. table-top hemming) in the automotive industry. Few selections of layered composites are able to transmit shear stresses in the adhesive layer, which is the main reason for a non-comprehensive use of adhesives in the automotive industry. Shear forces are mainly the reason for failure of the adhesive in layered composites. [BUH14, BOL14, NUT08, MIL07] Material characterizations based on tensile, shear and bending tests were carried out by [MIL07], [BUH14], [BOL14] and other authors. [BOL14] investigated the V-die bending, bending and hemming of plane edged areas on universal testing machines. Experiments with pre-stretched cover plates with low minor strain did not improve ductility in an way. The exterior/outer sheet metal fails below bending radius of 1 mm. Uniaxial tensile tests of numerous composite fabrics has been extensively analyzed in [BOL14].

[BAL90] classifies composite materials into four categories, which are shown in Figure 1. [HUF96] subdivides the layered composites into three more categories (Figure 1).

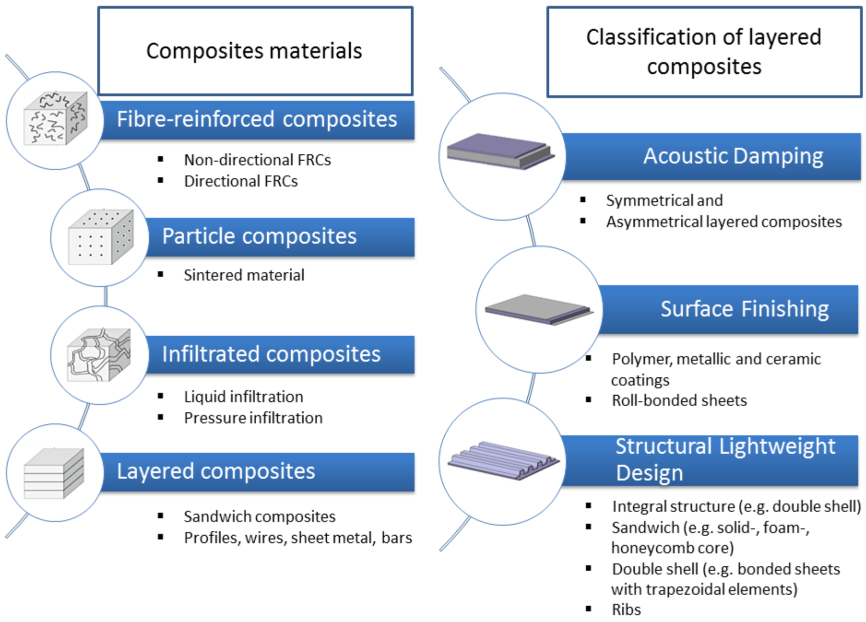


Figure 1: Classification of composite materials [BAL90] and classification of layered composites [HUF96]

As a result of increased customer expectations on the quality of new vehicle generations during recent years, visual appearance of the car body exterior came into focus of engineering. The trend towards smaller bending radii around exterior parts of passenger car bodies such as hoods, bonnets or doors in accordance with increasing use of lightweight materials requires a deeper understanding of mechanics of bending and hemming processes [RUP12, HÖN13].

The two major joining processes being used in today's industry to hem inner and outer automotive parts are roller or table-top hemming processes. This paper describes the influence of a standard table-top hemming process on layered composites. The basic sequence of table-top hemming is characterized by four single steps: Flanging, boxing, pre-hemming, final hemming. During final-hemming (step four) a vertical moving tool (final-hemmer) does complete the hemming operation. At the end of the hemming operation inner and outer sheets are fixed to each other [HÖN14].

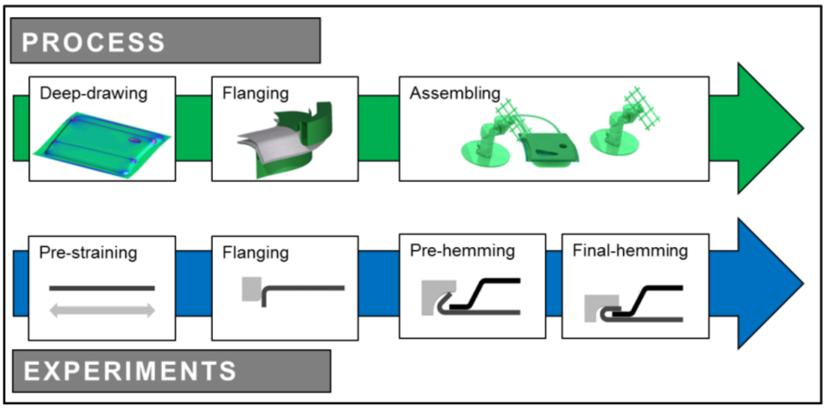


Figure 2: Hemming process [HÖN14]

This paper deals with symmetrical layered composites - which offer an advanced acoustic damping character – and their application in table-top hemming processes in the automotive industry.

2. Materials and Methods

Materials

Two sheet metal components being used in this work (inner and outer panel of bonnet / see Fig. 8) consist of the aluminum alloy EN-AW5754 H22 (AIMg3) having a thickness of 0.6 mm. The intermediate layer consists of a two-component adhesive (manufactured by COLLANO® RS8500) and was applied manually (thickness of 0.15 mm). The adhesive entirely was cured after 24 hours. In order to adjust the adhesive joint, a constant surface pressure of $7.5 \cdot 10^3$ N / m² was applied on the sandwich structure in normal direction.

Chemical composition

The chemical composition of the aluminum alloy used in this investigation is analyzed by standard spectral analysis to check the alloying elements. Table 1 shows the different alloying elements.

	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al	Rest
Spectral analysis [%]	0,26	0,36	0,05	0,27	2,96	0,04	0,03	0,03	95,97	0,03

Table 1: Chemical composition of the aluminum alloy EN-AW5754 H22

Tensile test

Tensile tests and shear tests were performed on standard devices (Zwick testing device, 200kN) under standardized conditions. Table 2 shows a summary of the average mechanical properties of the aluminum alloy AA5754. The specimens are analyzed at different drawing directions (SD) related to rolling direction (RD) to investigate influence of the anisotropic behavior of the alloy. In this case, especially the r-value depends on the load direction.

Material	SD	$R_{P0,2}$ (MPa)	R_m (MPa)	n (-)	r (-)	A (%)	E (GPa)
AA5754	0°	178,94	257,84	0,18	0,75	11,91	69,39
AA5754	45°	166,79	245,87	0,17	1,41	16,14	67,83
AA5754	90°	167,90	249,61	0,17	0,80	15,60	67,26

Table 2: Average mechanical properties of the aluminum alloy AA5754 gained by tensile test

Stiffness increased sheet

Beads are groove-shaped indentations which increase the rigidity in sheet metal components. As a matter of fact, beads do not fit in industrial table-top hemming devices, so the sheets are pre-stretched uniaxial by using a clamping frame developed at the Institute for Metal Forming (Figure 3) to simulate material hardening during bead forming [WER12]. The clamping jaws are fixed hydraulically and driven separately.

The pre-stretching of the inner sheet was designed similar to the load path of the bead (φ_1 = 0.05, φ_2 = 0.01, φ_3 = -0.06, φ_v = 0.06). Uniaxial strain is much easier and more repeatable to apply than plane strain (just two clamping jaws are needed), so a simplified uniaxial strain (φ = 0.05) was applied on the sheets in this case. The following equation calculates the equivalent plastic strain according to v. MISES:

$$\varphi_v = \sqrt{\frac{2}{3} \cdot (\varphi_r{}^2 + \varphi_t{}^2 + \varphi_n{}^2)} \qquad (1)$$

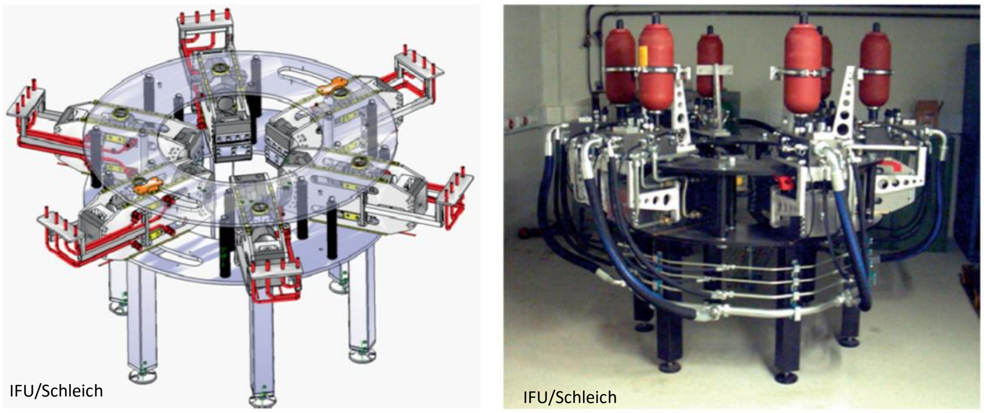


Figure 3: Schematic diagram of the clamping frame for any bilateral and uniaxial pre-strains in cross or hexagonal-shaped samples of aluminum sheets [SCH10]

Layered composite manufacturing

The adhesive layer thickness was adjusted manually by means of a hand coating bar. Figure 4 shows the coating bar with a winding of 0.15 mm. For a repetitious accuracy the coating bar has to be pushed flat on the sheet to adjust a constant layer thickness. For the adhesive interlacing of the two component adhesive, a plate tool of constant surface pressure was used until complete curing of the adhesive is finished.

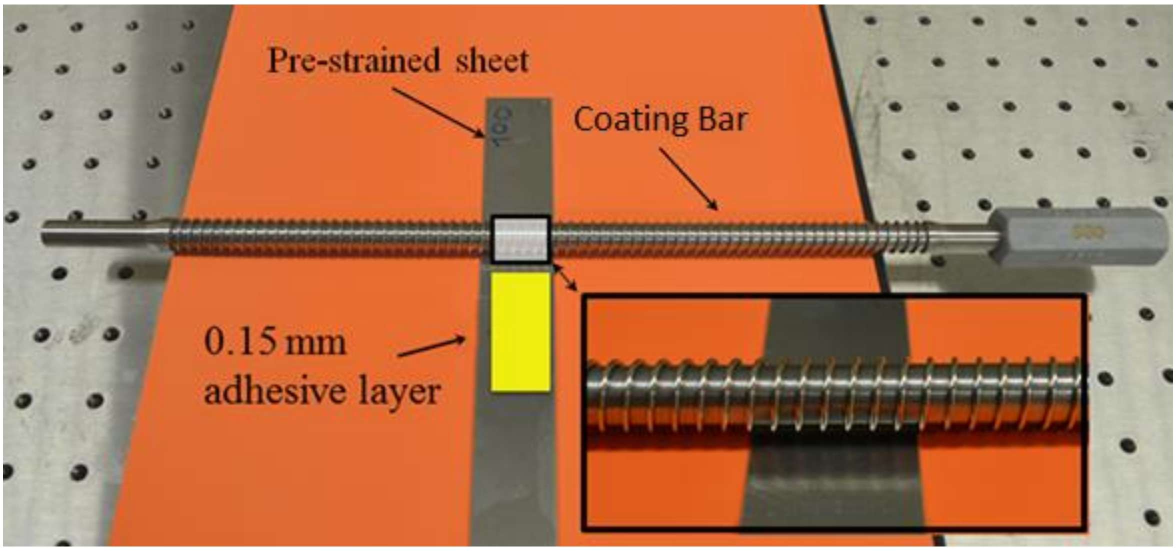


Figure 4: Hand coating bar for setting up the adhesive layer thickness of 0.15 mm

Shearing tests

The standards DIN EN 53281, DIN EN 15336 and DIN EN 1465 do characterize testing conditions of metal adhesive joints in terms of their shearing strength due to external forces. Figure 5 shows a draft of the shearing test specimens according to DIN EN 53281. Different testing conditions are leading to an incomparability of different shearing tests [RAS90]. The shearing strength of the adhesive is also dependent on the length of overlapping of the specimens. Figure 6 shows the measured shearing strength of the adhesive (COLLANO® RS8500) varied with different overlapping lengths.

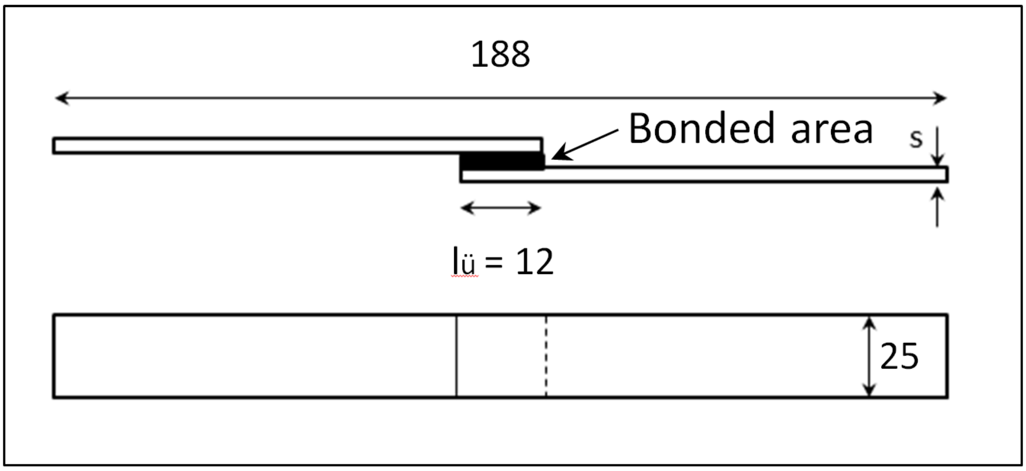
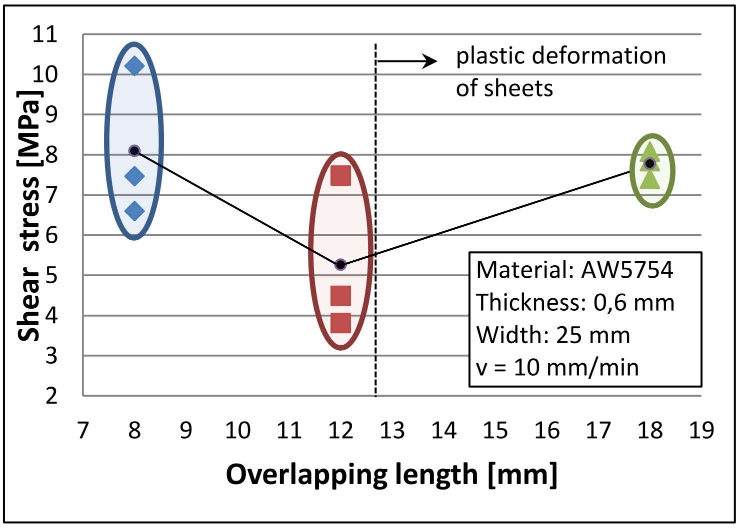


Figure 5: Testing condition for adhesively bonded metal joints [DIN 53281]

The adhesive joint is dependent on a number of factors, which are explicitly described in [DIL04]. The overlapping length has a significant influence on the shear stress. A larger overlapping length does not automatically lead to a higher shearing strength of the joint. Thus, the results can also be observed in other investigations [HAB09]. The overlapping length should be adjusted to insure that no plastic deformation occurs in the material. The overlapping length of the adhesives $l_Ü$ can be calculated according to [BUH14]

$$l_ü = \frac{R_{eH} \cdot s}{\tau_{max}} = 12{,}45\ mm \qquad (2)$$

Having a yield stress of 166 MPa and shearing strength of the specifications of the manufacturer (8 MPa). [COL14]



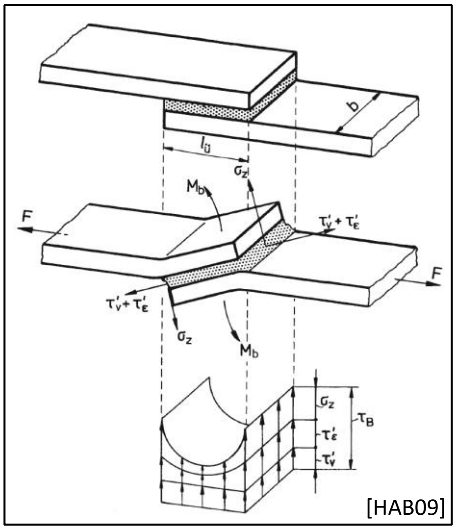


Figure 6: Left: Fictitious increase of shear stress due to plastic deformation Right: Stress, force and moment in shearing test [HAB09]

The total stress state is dependent on three different stress conditions according to [HAB09]: (1) shear stress (τ_e') resulting from the shift of the adhesive joining , (2) shear and tensile stress (τ_v') parallel to the bonding surface caused by the adhesive joining, and (3) tensile stress caused by the bending moment (M_B, σ_Z). Considering only the stress values (1) and (2), a lower strain of the adhesive joint is caused if the overlapping length is increasing. Similar results can be observed in [HAB09]. In contrast, if the overlapping length exceeds the critical plastic deformation length according to (2), the shear stress of the adhesive layer increases again due to plastic deformation of the sheets. Summing up it is essential to distinguish between shear stress of sheets without plastic deformation (or ideal rigid plates) and shear stress of sheets containing plastic deformation. Plastic deformation (see Fig.6 right) leads to a fictitious increase of shear stress and has to be considered for an appropriate designing.

Hemming device

The testing device for table-top hemming is schematically shown in Figure 7. The lower tool is used to locate the specimen and to set up bending radius of the hemming rope. The upper tool also performs a vertical movement, and is used for adjusting the residual closing angle. Table-top hemming is used in the automotive industry and can be separated significantly by the different force discharges points in the hemming tool of standard universal characterization tests (e.g. V-die tool).

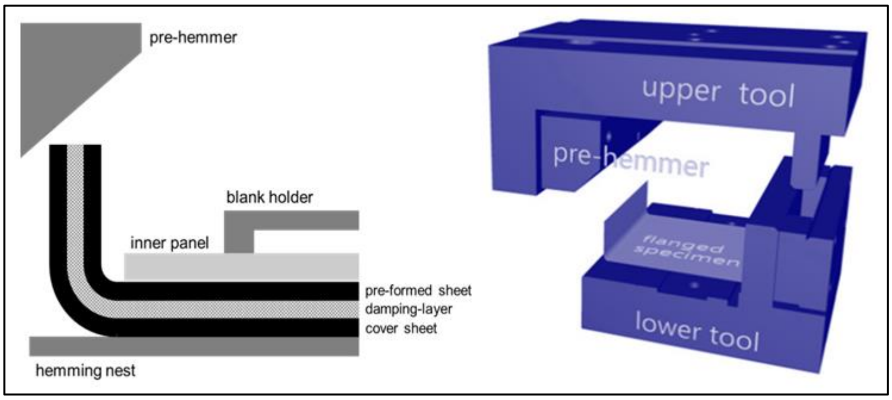


Figure 7: Table-top hemming test of layered composites (left); hemming device (right)

3. Aim of the investigation

The aim of investigation conducted was to examine the applicability of a one-sided stiffness increasing layered composite for hemming processes in the automotive industry (Figure 8). The main concern is the delamination-behavior in the different hemming sub-processes. The quality of the layered composite is evaluated after each sub-process (flanging, pre-hemming, final hemming) by visual inspection. The following parameters were varied in the test series:

- Influence of flanging radii of one-sided stiffness increasing layered sheets (corresponding to the load path the pre-stretched bead)
- Influence of bending direction of unilateral one-sided stiffness increasing sheets
- Influence of the bending direction of the cover sheet
- Influence of pre-strain level of the cover sheet (un-stretched 0% and pre-stretched 5%)

Additionally, the surface quality of the hemming rope can be evaluated after each of the different sub-processes (flanging, pre-hemming and final hemming). Hemming ropes are visual edges on the outer skin of automotive vehicles and are eligible for the highest surface quality. Cracks and micro cracks cannot be accepted in this case. One-sided stiffness increasing layered composites are ideal for applications in the automotive industry since the stiffened side has a non-visible character (structural part) and the outer side (visible part) is additionally protected by the adhesive layer (damping).

The fundamental hemming capability for the specific aluminium alloy is the aim of this research investigation.

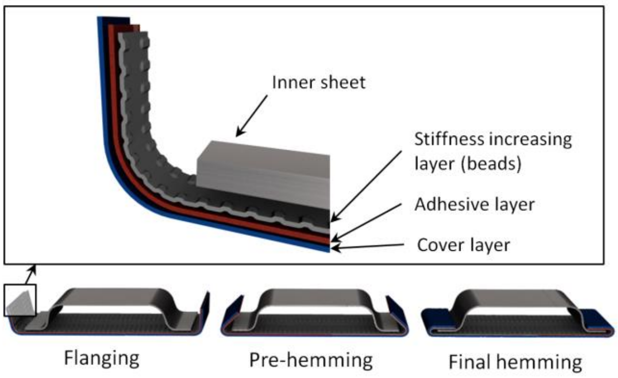


Figure 8: Hemming of layered composites: Stiffness increasing layer on the inner side, cover layer on the outer side

The following design of experiment plan (Table 3) shows the different variations of layered composites. First, the inner sheet is pre-stretched (5%) and the outer side in unstretched. The second variation is the rolling direction to analyze the anisotropic behavior, the bending load direction and the hemming radius.

Table 3: Hemming results of the layered composite (PS – prestreched; PSD – prestreched direction; BLD – bending load direction; RD – rolling direction)

Cover sheet (outer side)				**One-sided stiffned sheet (inner side)**			**Radius [mm]**
	PS	**PSD**	**BLD**	**PS**	**PSD**	**BLD**	
1	0%	-	in RD (0°)	5%	in RD (0°)	in RD (0°)	1
2	0%	-	in RD (0°)	5%	in RD (0°)	in RD (0°)	1,8
3	0%	-	in RD (0°)	5%	in RD (0°)	in RD (0°)	2
4	0%	-	in RD (0°)	0%	-	90° to RD	2
5	5%	in RD	in RD (0°)	5%	in RD (0°)	90° to RD	2
6	0%	-	in RD (0°)	5%	in RD (0°)	90° to RD	2
7	0%	-	in RD (0°)	0%	-	in RD (0°)	2
8	0%	-	90° to RD	5%	in RD (0°)	90° to RD	2

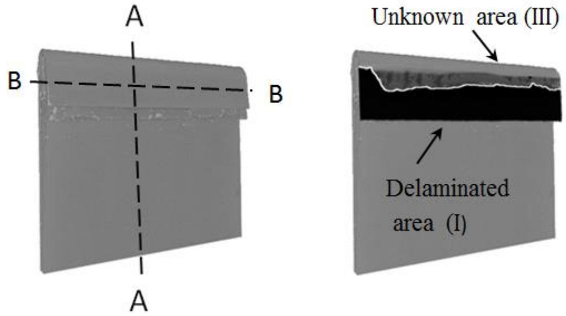
4. Results

The results in this chapter are divided into three major sections. First, the hemmed specimens are analyzed in the computer tomography device on delamination progress. Second, a qualitative test method to measure the opening angle is presented. Third, the surface quality of the hemmed specimens is analyzed and evaluated.

Measurement of the delamination process by visual testing and computed tomography (CT)

X-ray technology as a non-destructive testing method for components is used in the automotive industry. During the analysis, the CT scanner creates a large number of projection images from various angles and uses them to calculate a 3D visualization of the object. Observers can cut a virtual cross-section through it from inside. As a result, it is possible to recognize faults within a component that are invisible from outside. An x-ray computed tomography (CT) scanner consists of an x-ray tube assembly and an opposing image recording system. The object to be examined rotates between the tube and the detector. This results in x-ray images from which three-dimensional pictures are created. Those pictures can then be analyzed and evaluated. [AUD14]

In this section delamination is detected with two methods. In the first step, the individual specimens are visually inspected for each sub-process on delamination of the edge areas. The results are shown in Table 4. Finally, the hemmed specimens are analyzed on a CT. After final hemming the adhesive layer fails in every upper part of the hemming rope (Figure 9). The hemming rope can be structured in three major areas: First, a simple to identify area which is fully delaminated (I.). Second, an area which is geometrically delaminated, but the adhesive layer and the sheets are still having contact, known as kissing bond. (II.). Third, there is an unknown area, which exhibits no geometrically delamination. It is not sure if the adhesive layer and the sheets are still forming an adhesive bonding.



Area of hemming rope	Description
I.	Delaminated, no contact between adhesive layer and sheet
II.	Delaminated, but contact between adhesive layer and sheet
III.	Unknown area

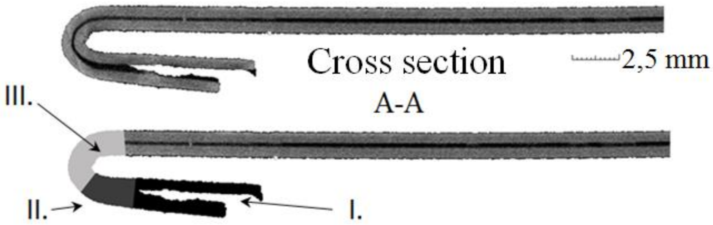


Figure 9: Computed tomography of a stiffness increased layered composite revealing delamination in hemmed flange area

The computer tomography show the different areas of delamination of stiffness increased composite material. First, there are areas (I) which are delaminated allover meaning that there is no contact between the adhesive layer and the sheet. Second, some areas are delaminated, but they still having contact between adhesive and sheet. Third, there are areas which are unknown.

Opening angle of the cover sheet

In order to quantify the failure mode of the opening angle after final hemming, a simple evaluation method was used. A small opening angle (small) means that it is not possible to slide the inspection reference sheet (0.25 mm) 2 mm below the cover sheet. However, for a large opening angle (large) it is possible to push the inspection sheet by more than 2 mm between the top and stiffness increasing sheet without any force. Figure 10 outlines the qualitative testing method. The testing method is simple by pushing the reference sheet between the cover and stiffness increasing sheet to check if the layers are still joined or not. Even in CT analysis in cannot be seen if the layers are still joined or not in all areas (see Figure 9).

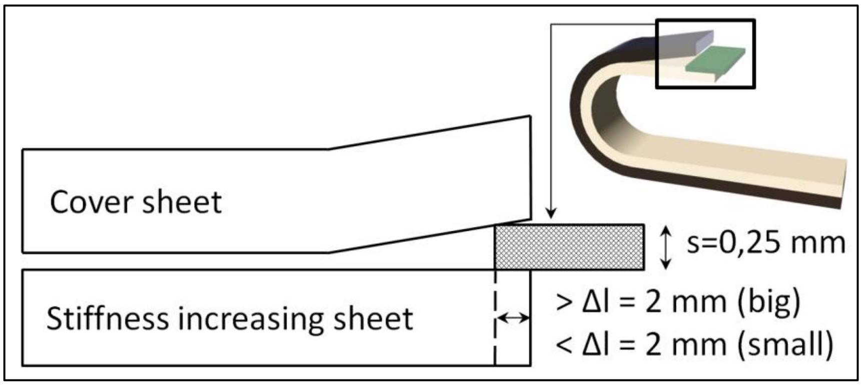


Figure 10: Testing sheet (0.25 mm) for delamination

The following Table 4 shows the results of the examination of delamination after each sub-process and the quality assessment of the opening angle of the hemmed samples. The variable parameters of the cover and stiffness increasing sheet are limited to pre-stretching, bending load direction and pre-stretching direction.

Table 4: Hemming results of the layered composite (PS – prestreched; PSD – prestreched direction; BLD – bending load direction; RD – direction of grain; ✔ - no delamination occurred; O – delamination occured)

	Cover sheet (outer side)			One-sided stiffned sheet (inner side)			Radius [mm]	Visual testing			
								Delamination			Opening angle
	PS	PSD	BLD	PS	PSD	BLD		Flanging	Prehemming	Final hemming	Final hemming
1	0%	-	in RD (0°)	5%	in RD (0°)	in RD (0°)	1	✔	✔	◯	small
2	0%	-	in RD (0°)	5%	in RD (0°)	in RD (0°)	1,8	✔	✔	◯	small
3	0%	-	in RD (0°)	5%	in RD (0°)	in RD (0°)	2	✔	✔	◯	small
4	0%	-	in RD (0°)	0%	-	90° to RD	2	✔	◯	◯	big
5	5%	in RD	in RD (0°)	5%	in RD (0°)	90° to RD	2	✔	◯	◯	big
6	0%	-	in RD (0°)	5%	in RD (0°)	90° to RD	2	✔	✔	◯	small
7	0%	-	in RD (0°)	0%	-	in RD (0°)	2	✔	◯	◯	big
8	0%	-	90° to RD	5%	in RD (0°)	90° to RD	2	✔	✔	◯	small

Table 4 shows the numerous parameter variations and their results in terms of delamination and the opening angle of the springback of the composites. Specimens 1 to 3 indicate that the bending radius does not influence the delamination and the opening angle. Specimens 6 and 8 also show a small opening angle after the hemming process. Nevertheless, there are some specimens (4, 5, 7) which have an objectively measurable larger opening angle.

The value of stretching of the two metal sheets has a significant influence on the opening angle. If they have the same absolute value of pre-stretching (eg, 0%), the opening angle is greater than if the absolute value of stretching is similar to cover and stiffness increasing sheet.

It should first be noted that all samples are delaminated at a hemming angle of 180°. The critical shear strength was exceeded. All samples examined, however, did not show any delamination after flanging (90 °). The critical shear strength of the adhesive has not been reached. After hemming different phenomena can be observed, which occur as a function of pre-stretching and bending load direction. Some samples delaminate earlier compared to other samples.

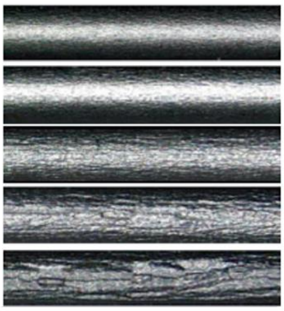
Surface quality of the hemmed sheets

[BOL14] detected cracks of the outer sheet of the layered composite at a flanging radius of 1 mm on a universal testing device. These cracks cannot be observed in the table-top hemming process. The surfaces contain no visible cracks or damage and thus the material is suitable for unrestricted use in the automotive industry when surface quality is in focus.

The visual appearance of the painted car body is determined primarily by the quality of the paint surfaces of the hang-on parts. Thus quality defects like fading and splotching, which might appear during painting, have to be avoided. The quality of the painted surface also depends on the initial non-coated surface of the formed sheet which emerges from initial roughness of the material and the forming operations. Table 5 shows different quality grades of hemming ropes of an aluminum alloy.

Table 5: Quality grades of hemming ropes of aluminum alloys based on [SCH10]

Level	Appearance	Example
	No surface detects	
	Moderate surface detects	
	Considerable surface detects	
	Micro cracks on surface	
	Considerable micro cracks	



Influence of flanging radii of one-sided stiffness increasing layered sheets

Figure 11 shows the surface quality of the hemmed composites after each process step (flanging, pre-hemming, final hemming). Compared to the scaled quality grades (Table 5) the quality of the hemmed aluminum alloy AA5754 can be classified as a surface with no detects.

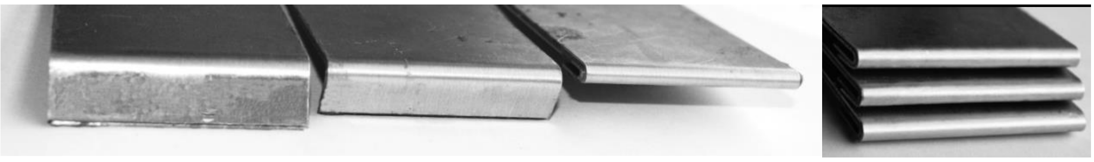


Figure 11: Quality of the bending radii after hemming of the aluminum alloy AA5754

Influence of bending direction of unilateral one-sided stiffness increasing sheets and cover sheet

The experimental results show no influence of the bending direction of unilateral one-sided stiffness increasing sheets regarding the opening angle and delamination. Same observations can be seen for cover sheets.

Influence of pre-strain level of the cover sheet

The experimental results show an influence of the pre-strain level of the cover sheet. Specimen 1, 2, 3, 6 and 8 (Table 3) are pre-stretched (5 %) in the inner sheet and non-stretched in the outer sheet. In contrast, specimens 4, 5 and 7 are non-stretched on both sides of the composite. Specimen 1, 2, 3, 6 and 8 are not cracked after pre-hemming and show a smaller opening angle after final hemming than the other combinations. Combinations 4, 5 and 7 fail completely after pre-hemming and also have a larger opening angle after the final hemming process.

5. Discussion

The results do not show any influence regarding surface quality, the opening angle and delamination on the above mentioned parameters except the pre-strain level of the cover sheets. The final discussion is intended to explain the relationship between pre-strain, delamination and different springback of the individual sheets. It is noticeable that some combinations of cover and stiffness increasing sheets have a larger opening angle than other combinations. [BUH14] analytically describes the displacement as the sum of geometric displacement and the displacement of the springback. The various failure cases can be attributed to different springback configurations. Figure 12 shows schematically different springback of the different layers and its impact on the failure to the adhesive layer.

Specimen combination 1, 2, 3, 6 and 8 (Figure 12 b) were pre-stretched in the inner sheet and thus experienced a hardening in the material. The outer cover sheet was not pre-stretched in these combinations. Thus, the inner pre-streched sheet relieved the outer sheet through the larger springback leading to a small opening angle and a non-delaminated intermediate layer after pre-hemming. Combinations 4, 5 and 7 (Figure 12b) were not pre-stretched on both sides and have therefore the same springback configuration. It is assumed that this same configuration leads to a non-load releasing of the adhesive layer and delamination after pre-hemming.

In addition, the theory is supplemented by the different flanging gaps. Pre-stretched material is thinner than unstretched material. The following equation shows difference between the original thickness (two unstretched sheets 1.35 mm) in comparison to the pre-stretched sheets:

$$0.6\,mm + 0{,}95 \cdot 0.6\,mm + 0.15\,mm = 1.32\,mm \quad (2)$$

The slightly difference of thickness of 3 % leads additionally to more stress, more delamination and a larger opening angle.

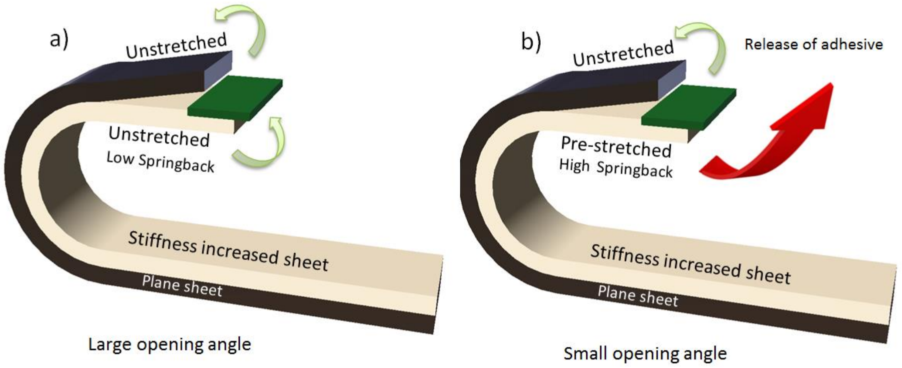


Figure 12: Delamination test and effect of pre-stretching and different springback on hemming of layered composites

To summarize the results, one –sided stiffness increasing layered composites can be used for industrial table-top hemming processes under the tested conditions. Further research can be carried out by the reduction of the delamination progress of the composites. It is assumed that the application of additionally local adhesive at the edge areas reduces the delamination progress.

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