Hem flange bonding: a challenging joining process in automotive body construction

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Abstract. Hem flange bonding is widely used in the automotive body shop, especially in the manufacturing of hang-on parts such as doors, hoods and tailgates. By combining the hemming and adhesive bonding processes, components can be joined by material fit and form fit. In this way, new properties are integrated into the assembly, such as higher load-bearing capacity and improved resistance to corrosion. However, both processes also influence each other in the joining process and in the further production process chain, which makes the hem flange bonding process really challenging.

The paper gives an overview of the state of the art. For this purpose, based on the structure of the bonded hem flange, the requirements and criteria for quality evaluation are described. The common hemming technologies and adhesive application methods as well as the industrial process chain, in which the hemming operation takes place, are presented. Essential correlations between component / process parameters and the quality in the hem flange bonded joint are discussed.

Fraunhofer IWU has been researching various aspects of hemming and hem flange bonding for many years and supports the industry in the analysis of assemblies and processes. Our aim is to systematically increase the quality and appearance of hem flange bonded assemblies and the robustness of hem flange bonding processes. Two current examples from research practice will provide a brief insight:

Hemming adhesive dimensioning: Adhesive application plays a decisive, quality-defining role in the hemming process. At every point of the circumferential hem seam of an assembly, the adhesive quantity and adhesive position have to match the existing geometry precisely. The paper shows how the adhesive dimensioning can be carried out. Current test results on the effect of glass beads in the adhesive layer to ensure a defined adhesive layer thickness are also discussed.

Hem testing: A testing device was developed at Fraunhofer IWU to carry out quasi-static strength tests on hem flange bonded joints. For the first time, the influence of various hem and process parameters on the joint strength can be determined. The functional principle of the test and first results are presented.

Keywords: Hem flange bonding, Hemming, Degree of filling, Degree of bonding, Glass beads, Hem flange pull-out test.

1 State of the art

1.1 Hemming and hem flange bonding

Hemming is an established technology for joining sheet metal parts without an externally visible joint. The most common application is the joining of a skin panel and an inner part of a car body assembly (eg. doors, hoods, tailgates). In a multi-stage process, a previously produced flange at the outer edge of the outer skin is bent around the inner part.

Hem flange bonding combines the form fit joining process of hemming with the material fit joining process of adhesive bonding. Before the hemming process the adhesive is applied to the outer skin and flows between the joining partners into the resulting hem during the hemming process (Fig. 1). The adhesive bonding results in increased work absorption for improved crash safety [1], bending and torsional stiffness ([2], [3]), corrosion protection, more uniform force transmission [4] and vibration damping. These properties are necessary to meet the constantly increasing safety, comfort and quality requirements.

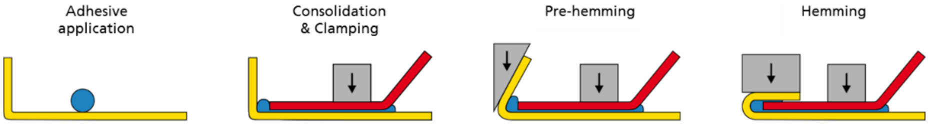

Fig. 1. Hem flange bonding process sequence.

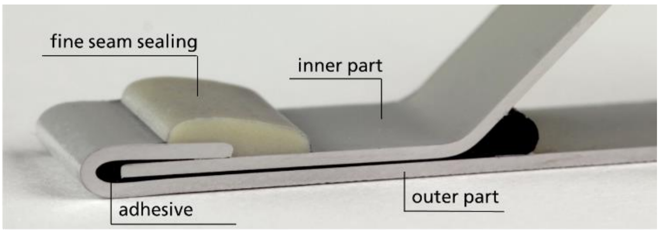

Fig. 2. Structure of a bonded hem.

1.2 Requirements and quality evaluation of a hem flange bonded joint

The requirements for a hem flange bonded joint are as follows: Tightness, mechanical strength, aesthetics. In order to measure the fulfilment of the requirements and to evaluate the quality of a hem flange bonded joint, they can be divided into bonding features and hemming features. They are usually determined by destructive testing. On the one hand by means of microsections and on the other hand by opening the hem adhesive surfaces. Minimum dimensions and tolerances shall be specified in the design for all features to be tested.

To assess the bonding features of a hem flange bonded joint, it is divided into four areas a, b, c, d (Fig. 3). The requirements for filling these four areas with adhesive are as follows:

- Area a and c: complete filling
- Area d: visible leakage of adhesive
- Area b: filling according to design specification ("degree of filling").

In addition to the degree of filling, the degree of bonding must also be evaluated. This is a measure for the registration of defects in the area a and describes the percentage of bonded surface area to surfaces without adhesive bonding [6].

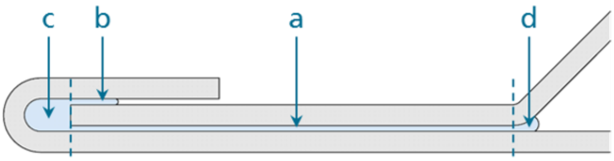

Fig. 3. Definition of the hem flange bonding areas [5].

The hemming features describe the hem geometry and are measured in the cross section. The most important features are shown in Fig. 4.

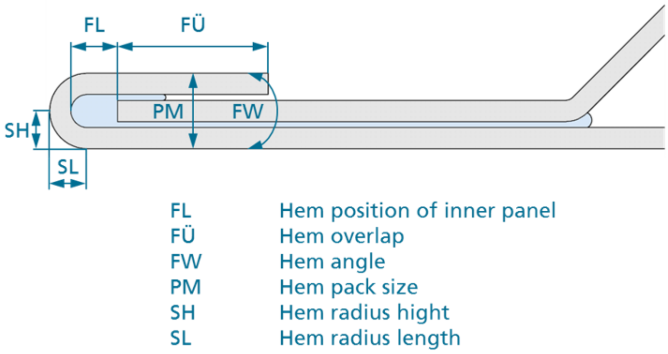

Fig. 4. Hemming features [5].

1.3 Hemming technologies

Tabletop hemming. Classic hemming is tool-bound, i.e. the components lie in a hemming bed and the hem is closed over the entire seam length by hemming tools with linear workpiece contact. The components of the hemming plant are specifically designed for the component to be hemmed. The hemming process of the flange, which is already set to 90°, takes place in two stages (135° pre-hemming, 180° hemming). Each component requires a special two-stage hemming tool with mostly complex tool geometries. Therefore, and due to the short process time, the process is particularly suitable for high quantities.

Table 1. Advantages and disadvantages of tabletop hemming (according to [7] - [9]).

Advantages	Disadvantages
• Short cycle times, high productivity • High hemming quality • Simple hemming process • Low tool wear	• Complex tool geometries • High investment costs • Low flexibility

Roller hemming. For roller hemming, the workpieces also lie in a hemming bed. The flange is formed incrementally by driving a robot-guided roll in several steps along the component contour [16]. The process is usually three-stage (30°; 60°; 90°). The tool costs for roller hemming lines are lower than for tabletop hemming, since only the hemming bed is required as a geometry-bound element. Robots and roller hemming tools are highly flexible. The process time depends on the length of the component contour and the number of hemming stages. Especially for large components it is therefore considerably higher than for tabletop hemming. This is one of the reasons why roller hemming lines are designed for smaller quantities [17].

Table 2. Advantages and disadvantages of roller hemming (according to [9] - [15]).

Advantages	Disadvantages
• High component flexibility and customizability • Low tool and investment costs • High parameter flexibility	• Long cycle time due to many hemming steps • High set-up effort, complex process with many parameters to control • Hemming quality depends on stiffness of the robot

Pliers hemming. The technology of pliers hemming offers a low investment and space-saving alternative to the above-mentioned technologies for smallest quantities. Hydraulically operated hemming pliers, which are hand-guided and close the flange step by step along the longitudinal direction of the hem seam from 90° in one stage, are well-known. There are also servo-electrically driven and robot-supported pliers, which open and close the hemming tool at up to 25 Hz via a swivel mechanism and can thus achieve a high feed speed [18].

Table 3. Advantages and disadvantages of pliers hemming [18].

Advantages	Disadvantages
• High flexibility/individuality • High hemming speed • Low device weight • Closing from 90° flange opening angle in one stage	• Complex hemming bed (guide groove required) • Partial pliers marks on the component surface • Effects on bonding features and assembly tolerances unknown

1.4 Hemming adhesives and application methods

Hemming adhesives must meet the following requirements: good gap bridging ability, good adhesion on contaminated sheet metal surfaces, tolerance to further subsequent production steps (e.g. resistance to washing out) and good automation capability. These requirements are mainly met by one- and two-component epoxy resin adhesives and rubber-based adhesives. [19]

The common application methods for hemming adhesives are bead application and the Swirl method (Air-Swirl or Electric Swirl). As further possible methods, double-bead application and jet stream spraying are also being investigated. [5]

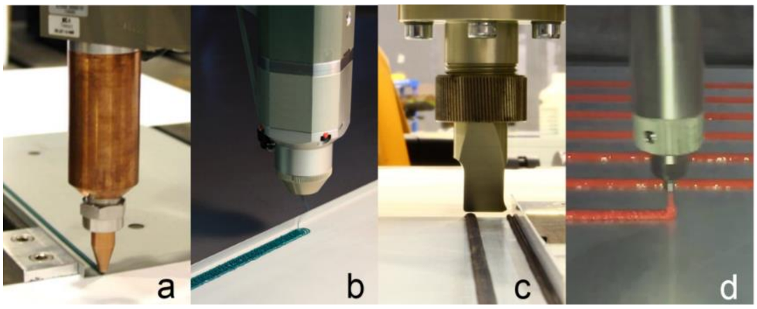

Fig. 5. Adhesive application: a) bead, b) Electric Swirl, c) double-bead, d) jet stream spraying [5].

1.5 The hem flange bonding process chain

The outer skin and the inner part are brought together in the hemming station. The inner part is usually joined with other parts before hemming (e.g. reinforcing parts). The outer skin comes directly from the press shop, the flange required for hemming was already formed there.

The first step in the hemming station is to apply the hemming adhesive to the outer part. The application quality is usually higher if the outer part lies in the hemming bed and the adhesive dispenser is guided along the path by the robot. However, it is also common to work with a fixed dosing unit and robot-guided component under the nozzle. In the subsequent consolidation process, the inner part is placed on the outer part, followed by robot transport of the consolidated assembly to the hemming plant. The inner and outer parts are then fixed on the hemming bed by the blank holder. The hemming can be done by roller hemming or tabletop hemming.

After hemming, the adhesive can be pre-cured if high handling strength is required. This is achieved either inductively in a gelling bed or in an oven. There can be a few minutes or several days or weeks between the hemming process and the installation of the assembly on the body-in-white. In some cases, the uncured hem assembly is transported to other plants during this period.

After mounting on the body-in-white, the hem assembly passes through the cataphoretic painting process. This includes several pretreatment stages, the cataphoretic dip bath and downstream washing processes. The body then passes through the paint oven, where it is heated to a maximum temperature of 190°C for approx. 30 minutes and the hemming adhesive cures. After the KTL process the seam sealing is applied. A PVC plastisol is used as the seam sealing material, which is usually applied automatically by flat or jet stream spraying. Afterwards, the material is heated in a PVC oven to cure all PVC seams. Finally, the further painting processes such as filler and final coat are carried out.

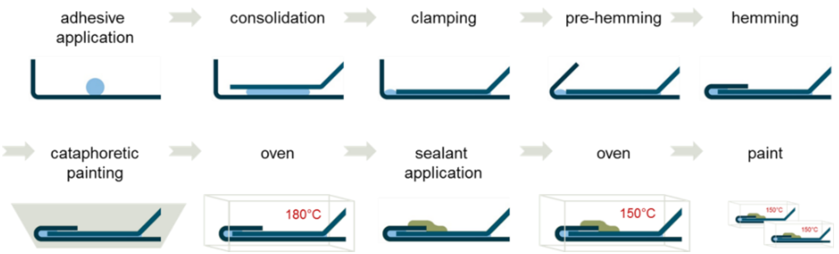

Fig. 6. Process chain [20].

2 Correlations between hemming and process parameters and quality

The described hemming process chain clearly demonstrates that the hem flange bonded joint stands at the end of a complex production process. The quality of a bonded hem flange is therefore not only dependent on the hemming process itself, but also on all influencing variables along this process chain, from the individual part to the painting process. With the example of the filling features used for quality evaluation, the most important influencing variables are briefly explained in detail.

In order to meet the filling feature requirements described in section 1.2, the applied adhesive volume must correspond exactly to the volume to be filled in the hem. This means that the design of the adhesive application must be based on the hem geometry. The hem geometry itself in turn depends on the individual part and hemming parameters. The sum of the four hem adhesive areas (a, b, c, d see Fig. 3) gives the adhesive section required for the particular hem geometry. The distribution of this adhesive section over the four hem adhesive areas determines the position of the adhesive application. The dilemma of hem filling becomes clear from this context: if one of the three parameters (hem geometry, adhesive quantity, adhesive position) deviates from the specification, the degree of filling changes (Fig. 7).

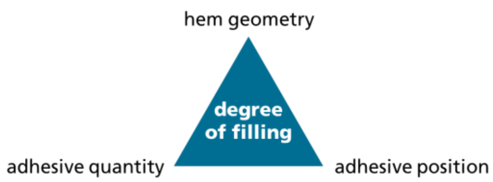

Fig. 7. Dependence of the hem filling features.

The adhesive quantity and adhesive position are mainly determined by the adhesive application, i.e. by the path programming of the robot as well as the dosing parameters of the dosing unit and the interaction of both [21]. However, even after application, the adhesive can still be influenced unintentionally by transport processes or during nesting. Even a deviation of the adhesive layer by 2 mm leads, depending on the direction of the deviation, to an adhesive leakage or an underfilling of the areas b and c. Furthermore, the surface condition of the sheets, especially the oiling, has an effect on the adhesive. [22]

The hem geometry is described by many parameters, which all depend on different variables (Table 4).

Table 4. Hem geometry parameters and influencing variables.

Hem geometry parameters	Influencing variables
Flange width of the inner part	Trimming
Adhesive gap thicknesses in a and b	Force and distance of the blank holder, force and distance of the hem tools, flange angle inner part
Hem position of the inner part (FL)	Flange width inner part, inner part position during nesting, roll-in, relative movements during / after hemming
Inner part position during nesting	Positioning of the outer part, positioning of the inner part, relative movements during nesting
Flange parallelism during nesting	Flange angle inner part, form deviations of the inner part and outer part
Hem overlap (FÜ)	Flange height outer part, hem position of the inner part
Sheet thickness inner part	Semi-finished product, deep drawing process
Bending radius inner part	Deep drawing process
Hem radius hight / length	Bending radius outer part, pre-strain outer part, force and geometry of the pre-hem and hem tools

It turned out that of these parameters, the thickness of the adhesive layer in the hem flange bonding area a and the flange tilting of the inner part in particular have the greatest influence on the adhesive distribution in the hem.

If, for example, the adhesive layer thickness in the area a is 0.05 mm higher than the nominal dimension used for the adhesive design (0.15 mm in this example), more adhesive is required to fill this area. If the adhesive application is not adapted to this deviation, the filling in the hem flange bonding area b is reduced to zero and in the areas c and d to below 80 %. This means that the hem flange bonded joint no longer meets the required filling features.

If the flange of the inner part is not plane-parallel to the outer part, this has various negative effects on the hem quality:

- The flow direction of the adhesive during consolidation and clamping is asymmetrical, as the following investigation shows. When the adhesive is pressed between plane-parallel flanges, the adhesive flow is approximately symmetrical. When pressing between non-plane-parallel flanges (flange angle inner part -3° or +3°), a larger proportion of the adhesive flows in the direction of the larger gap and a smaller proportion in the direction of the smaller gap:

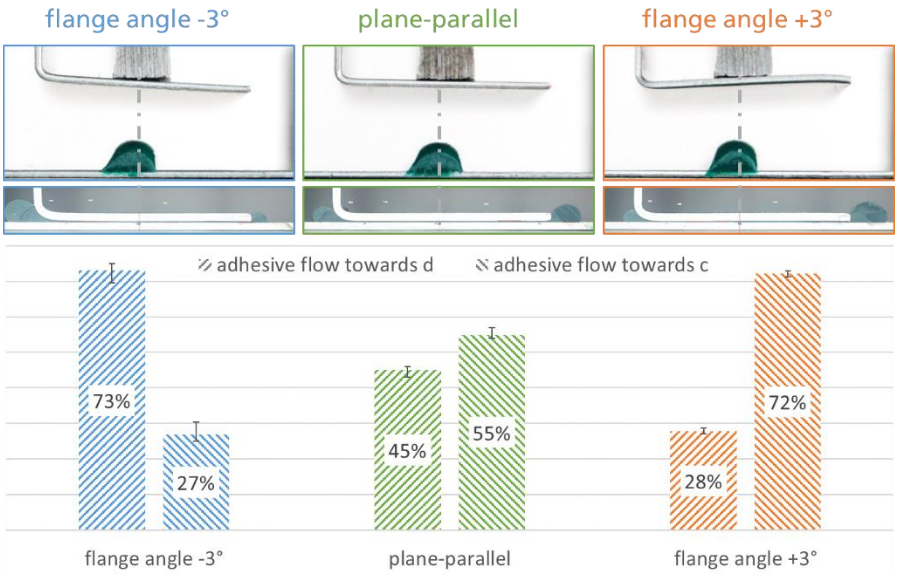

Fig. 8. Investigation of the adhesive flow direction with tilted inner part.

- The hem geometry is changed, since a non plane-parallel adhesive layer thickness in the hem flange bonding area a is produced. This changes the volume to be filled.
- After hemming, spring-back may occur when the blank holder is opened, causing the adhesive gap in area a to increase again. This leads to defects in the adhesive, which reduce the degree of bonding.

3 Current investigations at Fraunhofer IWU: Glass beads

The adhesives used for hem flange bonding are often filled with glass beads. The glass beads are used as spacers to ensure a minimum adhesive gap thickness [23]. The effectiveness of this method was investigated at Fraunhofer IWU. The basic idea of the spacer effect of glass beads is that they oppose the pressing of the inner and outer parts together with a force as soon as they come into contact with both parts. This force should be above the forces occurring in the hemming process and thus prevent a further reduction in the gap.

In order to determine this force, an FE model with a single glass bead between two metal sheets was built. While the lower sheet is fixed, the upper sheet is moved towards the lower sheet in a uniform movement while the force is recorded. This simulation was carried out for different glass bead diameters and sheet materials and verified experimentally. The results permit the following conclusions: A force increase occurs only from a gap height which is equal to the glass bead diameter. As long as the gap is larger than the glass bead, it has no effect (force = 0 N). As soon as the gap is smaller than the glass bead diameter, the glass bead is formed into the metal sheets because the glass is harder than the metal sheets and the contact surface is very small, especially at the beginning of the contact. The measured force effect results from this pressing of the glass bead into the two metal sheets. If two identical sheets are used, the glass bead is formed in half into each sheet at a gap of 0 mm. The force to press in the glass bead increases with increasing glass bead diameter and sheet hardness.

A measurement of different batches of glass beads showed that it cannot be assumed that all glass beads contained in hemming adhesives correspond to the nominal diameter specified. Instead, due to the manufacturing process, a frequency distribution of glass bead diameters exists, with the largest glass beads corresponding to the nominal diameter. The majority of glass beads are smaller than the nominal diameter.

In the example shown in Fig. 9, instead of one glass bead, there are four glass beads of different sizes in the gap. Since the single force-displacement curves for the four glass bead diameters are known from the FE simulations, the force-displacement curve of this group of glass beads can be analytically determined by summing up the four curves. From the resulting diagram the force, required to press the group of glass beads to a defined gap height, can be determined. Or vice versa: the gap height that will be reached with a given force. This model can be used to determine the amount of glass beads to be added to the hemming adhesive for a given glass bead size distribution, given blank holder force and defined required adhesive gap.

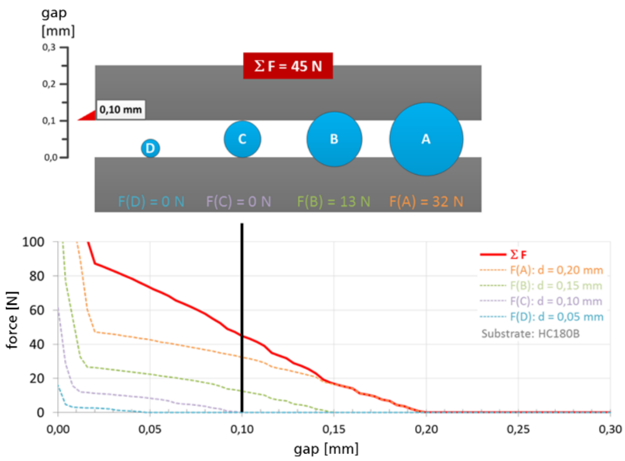

Fig. 9. Visualization of the glass bead calculation model.

In addition to the glass beads, the adhesive itself also has a gap-defining effect, i.e. it also counteracts pressing with a force. Since the adhesive is a viscoelastic material, this effect depends on time and viscosity. This means that the gap effect of the adhesive is primarily dependent on:

- The adhesive rheology: The higher the viscosity of the adhesive, the higher the counterforce and the larger the gap. The viscosity is temperature-dependent, that means the higher the temperature, the lower the viscosity and the smaller the gap.
- The velocity of pressing: The faster the gap is reduced, the higher the counterforce of the adhesive and the larger the gap. The slower the gap is reduced, the more time the adhesive has to relax and the lower the counterforce, i.e. the smaller the gap.
- The duration of the blank holder force: The adhesive creeps under the effect of the blank holder force. The longer the force is applied, the smaller the gap.

The creep behaviour under the force of the blank holder was investigated experimentally. In a test setup, the inner and outer part were pressed by a blank holder to a defined force with a subsequent time of holding the force and simultaneous measurement of the adhesive gap. Under constant conditions, the blank holder force and the amount of glass beads in the adhesive were varied (Fig. 10).

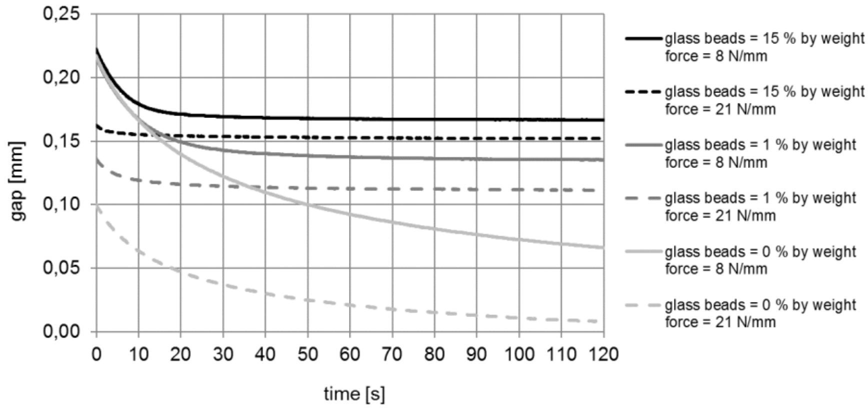

Fig. 10. Adhesive gap height with and without glass beads under constant load (amount of adhesive = 6.3 g/m, flange width inner part = 20 mm, nominal glass bead diameter = 0.2 mm, pressing speed = 0.1 mm/s)

The nominal diameter of the glass beads was 0.2 mm, i.e. the theoretical adhesive layer thickness should be 0.2 mm. The gap-time curves clearly show that the final adhesive gap is only achieved after a certain time of holding the blank holder force. If no glass beads are contained in the adhesive, the adhesive gap thickness decreases continuously over the holding time, whereby a greater blank holder force causes a smaller adhesive gap. If glass beads are added to the adhesive, the adhesive gap thickness also decreases over the first 20 to 30 seconds of the holding time, but then adjusts to a constant value. This value depends on the amount of glass beads in the adhesive and here, too, a higher blank holder force leads to smaller adhesive layer thicknesses.

The experimentally determined relationship between glass beads in the hemming adhesive and the resulting adhesive layer thickness is consistent with the preceding analytical considerations of the glass beads without adhesive influence. Due to the effects of the glass beads being pressed in the sheets and the size distribution of the beads described above, the final adhesive layer thickness is smaller than the nominal glass bead diameter even at a glass bead content of 15 percent by weight. It can be concluded that the behaviour of the hemming adhesive in the gap must be considered for two load cases:

The movement of the blank holder: The counterforce of the hemming adhesive against the pressing is determined by its rheological characteristics. Depending on the blank holder force and speed and the adhesive viscosity, no gap thickness in the size of the glass beads is achieved during closing. This only occurs during the holding time of the constant blank holder force.

Holding the constant blank holder force during the hemming process: The counterforce of the hemming adhesive against the pressing is determined by its rheological characteristics and the amount and size of glass beads. The adhesive gap decreases over the duration of the constant down holder force. Glass beads in the adhesive cause a stop in the reduction of the adhesive gap, whereby the final adhesive gap depends on:

- The size distribution of the glass beads
- The amount of glass beads
- The blank holder force
- The hardness of the parts to be joined.

4 Current investigations at Fraunhofer IWU: Hem flange pull-out test

Fraunhofer IWU has developed a method for measuring the pull-out strength of a hem flange bonded joint. This describes the maximum force required to pull the inner sheet out of the bonded hem flange. This test method can be used to determine the influence of various hemming specific variables such as hem geometry, adhesive layer thickness, degree of filling, degree of bonding, etc. on the strength of a bonded hem flange.

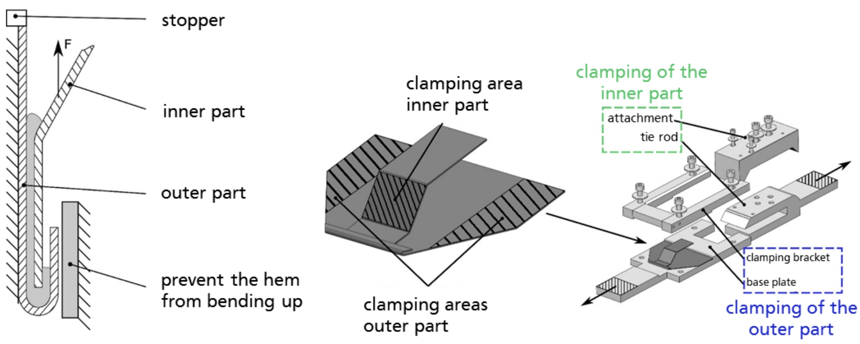

Fig. 11. Test principle, test specimen and test device.

In a series of tests, the influence of the degree of bonding on the pull-out strength of the hem flange bonded joint was determined. For this purpose, the degree of bonding was reduced by means of defects of various sizes. In addition, the influence of the location of a defect was tested in this test series by reducing the degree of bonding using Teflon tape in different locally defined areas. As a result of the test, the pull-out force for several test series as a function of the degree of bonding is shown in Fig. 12. The test series a represents the reference with a degree of filling of 100 % and a degree of bonding of approximately 100 %. In the test series b, the degree of bonding was reduced by different sized defects. In the test series c and d, the degree of bonding was reduced by approx. 50 % using Teflon tape. For the test series e, all surfaces were covered with Teflon tape to achieve a degree of bonding of 0 %. The forces measured at this test series are due to friction within the test device. Overall, there is an approximately linear relationship between the degree of bonding and the pull-out force.

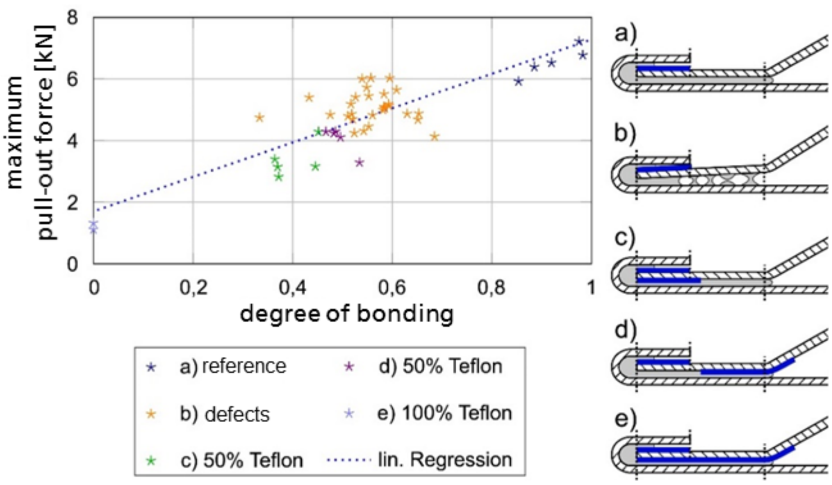

Fig. 12. Comparison of the pull-out forces as a function of the degree of bonding.

5 Summary and outlook

The paper presents the complexity of the hemming process. The hemming process chain begins with the production of the individual parts and ends with the painting of the car body. All parameters of these production, handling, transport and storage steps of the comparatively large assemblies have an effect on the circumferential hem seam, which is just a few millimetres in width. At the same time, the quality requirements for a hem flange bonded joint and the hem flange bonded assembly are extremely high. This inevitably leads to challenges. Considering, for example, the sensitivity of the quality criterion "degree of filling" to the smallest changes in the hem geometry or adhesive application, it can be seen that even deviations within the permissible tolerances for the single parts and the process lead to measurable differences.

In order to improve the quality of hem flange bonded assemblies, it is therefore necessary to understand the process more as a real interaction of the individual processes of bonding and hemming and to consider their mutual dependencies. When commissioning new hemming plants, sometimes only the hemming without adhesive is optimized. The adhesive afterwards has to adapt to the process. However, if the joining technology of hem flange bonding should exploit its full potential, then hemming and bonding must be taken into account with equal weight from the very beginning of design and all processes must be designed for hem flange bonding.

The current investigations at Fraunhofer IWU show that the glass bead filling of the adhesive must be designed precisely to the forces to be expected in the hemming process and the required adhesive layer thickness. Adhesive layer defects reduce the degree of bonding and thus the strength of the joint and should be prevented by ensuring an adhesive-oriented hemming process.

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