Original article

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Design criteria for the pin-foot ratio for joining adhesion-incompatible polymers using pin-like structures in vibration welding process

<https://doi.org/10.1515/polyeng-2021-0199>

Received July 12, 2021; accepted August 1, 2021;

published online August 30, 2021

Abstract: Joining technologies have a crucial role in the product development process, e.g. to achieve local part properties or functional integrations. This often requires multi-material joints, which are challenging for conventional joining processes. Therefore, innovative processes are needed to generate bonds between adhesion-incompatible material combinations, such as joining using pin-like structures in the vibration welding process. Investigations into this novel process have provided initial findings; however, a specific pin design is not possible at this time. For this reason, the influence of the pin-foot width of the two joining partners was analyzed numerically by simulation. The results of the simulation were validated by experimental tests. The investigations show, that the simulation model is suitable for predicting the bond quality as well as the fracture behavior of the multi-material joint based on pin-like structures. The developed correlations between material, pin-like structure, and resulting bond quality allow design criteria for the pin-like structures to be derived. These allow a specific dimensioning of the pin-foot ratio depending on the used material combination. Thus, for example, the fracture behavior of the multi-material connection can be selectively adjusted, as well as the bond strength can be maximally utilized.

Keywords: adhesion-incompatible; multi-material; pin-like structures; vibration welding.

1 Introduction

Joining technologies have a decisive role in the product development process. On the one hand, they allow the geometric limitations of primary forming processes (e.g. injection molding) to be overcome [1]. On the other hand, assemblies can be used to achieve locally adapted component properties as well as complex functional integrations. However, these advantages often require the combination of different polymer types. These multi-material joints present a major challenge for conventional joining processes. Cohesive bonds, such as by welding, are very limited due to the necessary adhesion compatibility of the used materials [2]. Adhesive bonds allow dissimilar materials to be joined, but the production process is very time- and cost-intensive due to the surface pretreatment that is often required [1, 3]. Also, there is no universal adhesive [4]. The adhesives often have to be adapted to the application and the material combination in question or even specially designed for this purpose. Many adhesives also contain hazardous substances [5]. Mechanical fasteners enable the combination of adhesion-incompatible materials, like adhesive bonds, but additional elements and an increased assembly effort are necessary [6]. In addition, the design of the joining zone (necessary overlap of the joining partners, space requirement for screws) restricts the geometrical freedom of the parts. For these reasons, novel joining processes are needed to generate joints between adhesion-incompatible material combinations, such as joining using pin-like structures.

The joining using pin-like structures in the vibration welding process is shown schematically in Figure 1a. In the first step, the structuring process, the pin-like structures are formed with the help of a structuring tool. The tool performs an oscillating frictional movement with a defined pressure. The structuring partner melts at the contact surface and the pin-like structures are formed. In the second step, the joining process, the structuring tool is exchanged for the bonding-partner and again a frictional relative movement takes place under defined pressure. The bonding-partner melts, flows into the cavities between the

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pin-like structures of the structuring partner and thus a form-fit connection is generated. Thus, a connection between adhesion-incompatible materials can be realized easily and without the use of additional elements (like screws) or complex pre-treatments.

The vibration welding technology is a friction-based joining process [7]. Thus, no additional heating techniques or additives are necessary to produce the bond. Furthermore, the vibration welding process is generally characterized by short cycle times, high reproducibility as well as high process stability [8]. Consequently, the use of vibration welding technology for joining using pin-like structures enables a very flexible and product-specific joint design.

Previous studies of the joining using pin-like structures in the vibration welding process show high suitability of pin-like structures for overlap- [9] as well as butt-joint [10, 11] connections. Investigations on the thermo-mechanical properties during the joining step show an influence of the bonding-partner on the process and the resulting bond quality [10]. The temperature in the joining zone should not exceed the melting temperature of the structured-partner, otherwise, the stability of the pin-like structures during the joining step cannot be ensured. If the melting temperature of the structuring-partner is exceeded, as for polycarbonate as bonding-partner, the pin-like structures of the polyamide 66 (PA66) are deformed. As a result, the undercut area can be reduced and the cavity between the pin-like structures can be partially closed, whereby a filling of the cavity by the bonding-partner is hindered. For bonds between PA66 and polypropylene (PP) as well as PA66 and polymethylmethacrylate (PMMA), no melting of the pin-like structures in the PA66 took place. Further investigations [11] for PA66–PP and PA66–PMMA joints show slight

differences in the achieved filling of the cavities between the pin-like structures. In combination with PP, the filling of the cavities is slightly lower than for PMMA as a bonding-partner. Nevertheless, almost a complete filling can be reached for both bonding-partners. Further, the investigations show a relation between the geometry of the pin-like structure, the material combination, and the resulting mechanical behavior of the form-fit connection (bond force and fracture behavior) [11]. Bond strengths of up to approx. 75% (PA66–PP) and 82% (PA66–PMMA) of the base material strength of the weaker partner were achieved, based on the pin-foot diameter. For the combination PA66–PP, failure always occurred by an adhesive pull-out of the PP out of the pin-like structures, whereas for the combination PA66–PMMA, failure occurred either by pull-out or by a cohesive break, depending on the form-fit geometry.

The investigations allowed influences on the form-fit joining process using pin-like structures to be identified and initial findings to be derived. However, pin dimensioning is currently not possible based on these results. For this reason, the influence of the pin-foot width of the two partners is investigated numerically by simulation in dependence of the material combination. The simulation model will be validated by experimental tests subsequently. This study shall allow identifying general interactions between the material combination, the geometry of the pin-like structures, and the resulting bond quality. As a result, it is supposed to be possible to specifically design the pin as a function of the selected material combination. Furthermore, an optimized pin design with regard to the achievable bond strength and/or the occurring failure behavior of the multi-material bond should be achievable.

Figure 1: Schematic illustration of (a) form-fit joining by pin-like structures in vibration welding process [9], (b) definition of the pin-foot width of the joining partners, and (c) joint geometry of the multi-material connection.

2 Materials and methods

2.1 Materials

As structured-partner, the semi-crystalline PA66, type Ultramid A3K (BASF AG, Ludwigshafen, Germany) was used. The semi-crystalline standard thermoplastic PP of the type Sabic 505P (Sabic Europe B.V., Sittard, Netherlands) and the amorphous thermoplastic PMMA, type Plexiglas 7N (Evonik Industries AG, Essen Germany) were used as bonding-partner.

With the help of a connection between the industrial widely used technical thermoplastic PA66 and a polyolefine (PP or polyethylene), cost-effective technical assemblies can be produced with locally adapted mechanical and chemical component properties. The combination of a semi-crystalline thermoplastic (PA66) with an amorphous thermoplastic (PMMA) enables an optical functionalization of a technical component that usually would not be possible with conventional welding processes due to the existing adhesion incompatibility.

For the experimental investigations, plates with dimensions of $115 \times 115 \times 4$ mm were produced by injection molding. The plates were produced according to the manufacturer's recommendations on a machine of the type Allrounder 370V/800-315 (Arburg GmbH & Co. KG, Lossburg, Germany). Subsequently, tensile bars according to DIN EN ISO 3167 [12] (for the mechanical characterization of the base material), as well as weld specimens with dimensions of 52×50 mm 4 mm, were milled out of the injection-molded plates.

2.2 Simulation

2.2.1 Material models: For all simulative investigations, ANSYS Academic CFD&Mechanical Teaching 19.2 (Ansys Inc., Canonsburg, Pennsylvania, US) was used. With the help of the numerical investigation, it shall be possible to develop the correlations between material, the geometry of the pin-like structure, and the mechanical behavior.

In the first step, the material models for the three materials used were created. Therefore, data of experimental tensile tests (i.e. stress, strain, and Young's-modulus) of the three materials were used. The Poisson's ratio shows a negligible effect on the result of mechanical simulations [13], thus literature values were used. The Poisson's ratio was set to 0.32 for PA66, 0.32 for PMMA, and 0.34 for PP.

To verify the material model, a uniaxial tensile load was simulated before the main study. For this purpose, a tensile bar was designed, which has the same geometry as the tensile bars used in the experimental base material characterization. The corresponding material models were assigned to these tensile bars and the mechanical behavior, analogous to the experimental tensile tests, was simulated. Finally, the results were correlated with the experimental stress-strain curves.

2.2.2 Simulation model of the multi-material joint: After the definition of the material models, the form-fit multi-material joint based on pin-like structures was set up in the simulation environment. Therefore, assumptions and simplifications must be made. Exact geometric dimensions of the pin-like structures (as defined by the structuring tool), as well as a complete filling of the cavities between the pin-like structures in the joining process, are assumed. Further, symmetry

effects are used and only a sample width of 2.325 mm and thus the form-fit of one pin structure is simulated to simplify the model, shown in Figure 1b. The investigations were carried out for two different pin-like structures (mushroom-like and trapezoidal). The geometric dimensions of the two structures were selected according to previous studies [11]; only the pin-foot ratio a/b was varied between 0.5 and 2.1. As structured-partner PA66 and as bonding-partner PP as well as PMMA was used to analyze the correlation between the material combination, the geometrical dimension of the pin-like structure, and the resulting mechanical behavior of the form-fit connection.

After building up the model of the multi-material joint and assigning the specific material properties a convergence study was carried out to define the mesh size. Subsequently, a tensile force was applied vertically to the form-fit connection. The maximum achievable bond force and the occurring failure behavior were evaluated as a function of the pin-foot ratio and the material combination. The resulting failure was divided into adhesive separation by pull-out of the bonding-partner (PP or PMMA), cohesive failure of the structure partner when exceeding the tensile strength of the PA66, and cohesive failure of the bonding-partner when exceeding the tensile strength of the PP or PMMA, respectively.

In order to further evaluate the quality of the joint, the bond factor (relation of bond stress to base material strength) was calculated. Therefore, the maximum bond forces are divided by the design area of the simulated bond (width 2.325 mm, thickness 2 mm). It should be noted, that not the complete design area contributes to the force transmission, but only the pin-like structures. Nevertheless, the design area is chosen as a reference surface because it represents the entire joining area and thus allows for a comparison with other joining methods such as welding or adhesive bonding. As base material strength, the value of the weaker partner of the material combination was used.

2.3 Experimental trials

2.3.1 Joining trials: The structuring, as well as the joining process, took place on a linear vibration welding machine of the type Branson M-112 HR (Branson Ultraschall, EMERSON Technologies GmbH & Co. OHG, Dietzenbach, Germany). The structuring of the PA66 was conducted with a resonance frequency of 235 Hz, an amplitude of 0.7 mm, a structuring force of 600 N, and a structuring path of 1.2 mm. For generating the pin-like structures, three different structuring tools were used. All tools have 16 pin structures and a total undercut volume of approximately 25.4 mm^3 . The tools differ in the resulting pin-foot width of the structured-partner, resulting in a varied pin-foot ratio, Table 1. After the structuring step, butt-joints, as shown in Figure 1c, were produced in the joining step. Therefore, the resonance frequency and the amplitude were equal to the structuring process. The joining force was set to 400 N and the joining path was 1.5 mm. To exclude any influence of moisture, the PA66 weld plates were dried to constant weight in a vacuum oven at 70°C before the joining tests were carried out. After the experimental tests, the multi-material connections were stored in a vacuum oven at 23°C until further analysis (optical or mechanical characterization). Thus, moisture absorption or a temperature influence on the multi-material connection can be avoided.

2.3.2 Optical characterization: The pin-like structures produced in the structuring step can deviate from the theoretical structure geometry, which is given by the structuring tool. To compare the simulated

Table 1: Theoretical pin-foot width and pin-foot ratio of the used structuring tools for the experimental trials.

Theoretical pin-foot ratio a/b	Theoretical pin-foot width (mm)	
	Bonding-partner a	Structured-partner b
0.67	0.88	1.32
0.96	1.08	1.12
1.44	1.30	0.90

and experimental results, however, the exact geometry of the resulting pin-like structures is crucial. For this reason, the PA66 specimens with introduced pin-like structures were analyzed optically by computed tomography (CT), and the real pin-foot width and pin-foot ratio of the experimental trials were evaluated. Therefore, rectangular samples with dimensions of $12 \times 20 \text{ mm}$ 4 mm were prepared out of the structured-partner, to achieve a high resolution of the pin-like structures. The CT investigations were conducted using a CT device of the type sub μ -CT (Fraunhofer-Institute for Integrated Circuits (IIS) e.V., Erlangen, Germany).

2.3.3 Mechanical characterization: The base material strength of the used materials was characterized according to DIN EN ISO 527 [14] using a universal test machine with computer-controlled test execution, type Zwick 1448 (Zwick GmbH & Co. KG, Ulm, Germany). Tensile bars according to DIN EN ISO 3167 [12] were used, the clamping length was set to 40 mm. The Young's modulus was determined with a test speed of 0.5 mm/min, followed by the determination of the tensile strength with a test speed of 25 mm/min. All tests were carried out under standard conditions according to DIN EN ISO 291 ($T = 23^\circ\text{C}$, relative humidity 50%) [15]. The stress–elongation curves of the three materials were used to validate the created material model of the simulation.

Besides the material characterization, the bond quality of the generated form-fit connections was analyzed. The tests were conducted with the same test machine under standard conditions with a pull-off speed of 1 mm/min. The maximum achievable bond force was evaluated to correlate the results of the experimental tests with the simulative results. To avoid moisture absorption, the specimens were stored in a vacuum oven at 23°C before the mechanical tests. After the mechanical testing of the form-fit connection, the fracture behavior was analyzed additionally.

3 Results and discussion

3.1 Simulation analysis

3.1.1 Material models

Figure 2 shows the elongation–stress curves of the simulated and the experimental tensile tests for the different materials. Using this comparison, the created material models for the model-based description of the mechanical behavior of the multi-material joint based on pin-like structures can be validated. It can be seen that the stress curves of the simulated tensile tests are identical to the experimental test up to the maximum tensile strength. Due to the brittle behavior of the PMMA, a fracture occurs when the maximum tensile strength is reached, Figure 2b. For the semi-crystalline PA66, Figure 2a, and PP, Figure 2c, a decrease in strength occurs at higher elongations because of a beginning of necking in the experimental tests. This necking cannot be fully reproduced by the generated material model. However, this behavior at higher elongations can be neglected for the simulative investigations. The simulated range is only in small elongation ranges. The failure criterion for the form-fit multi-material connection was defined as either a fracture of one partner when the maximum tensile strength is exceeded or an adhesive separation by pulling out the bonding-partner. In each case, the stress curve up to the maximum tensile strength is decisive, which is represented correctly by the material model. Besides, necking only occurs at an elongation of about 15% for PA66 and 20% for PP and thus well above the expected elongation of the form-fit joint.

3.1.2 Mechanical behavior

The evaluation of the resulting bond force for one pin of the simulated form-fit connection is shown in Figure 3 as a

Figure 2: Verification of the material models by correlation of experimental data with simulated tensile tests: (a) PA66, (b) PMMA, and (c) PP.

Figure 3: Simulated mechanical behavior of the form-fit connection as a function of pin geometry and bonding-partner.

function of the pin-foot ratio. For the material combination PA66–PMMA, a maximum of the achievable force within the selected pin-foot ratio can be seen for both pin geometries. For the mushroom-like pins, this maximum is at a pin-foot ratio of 1.0. For the trapezoidal tool, there is no clear high point; the achievable force shows a plateau-like course between a pin-foot ratio of 0.7 and 1.4. For both smaller and larger ratios, there is a drop in the achievable force. The maximum force for the joint between PA66–PMMA is in a similar range for both pin geometries. For mushroom-like pins, a force of about 180 N and for trapezoidal pins of about 160 N for one pin-like structure is achieved.

The PA66–PP joint shows different behavior, which is similar for both pin geometries. The maximum of the achievable bond strength is not yet reached in the selected range of the pin-foot ratio. Nevertheless, a flattening of the increase can be observed at a ratio of approx. 1.4 for both variants. While in the lower range up to a pin-foot ratio of approx. 0.7 similar forces result for both structures, at higher ratios higher forces are achieved for mushroom-like pins. The maximum achievable force for the PA66–PP combination is in a similar range of about 60 N (trapezoidal) and about 80 N (mushroom-like) for both pin geometries, but clearly lower than the bond force of the PA66–PMMA connection. This is analogous to previous experimental studies [11].

In order to assess the achievable bond forces in general, the bond factor was evaluated as a function of the

pin-foot ratio, the material combination, and the pin geometry, Figure 4. It describes the ratio of the achievable bond stress to the base material strength of the weaker partner and thus can have a maximum of 1.0. The bond factor for the simulative investigations is in the range between 0.31 and 0.57. For the material combination PA66–PMMA, a maximum of 0.47 (mushroom-like pins, pin-foot ratio 1.0) or 0.42 (trapezoidal pins, pin-foot ratio 0.8) is achieved. The multi-material connection PA66–PP shows a maximum bond factor of 0.57 (mushroom-like pins) or 0.45 (trapezoidal pins), in each case for a pin-foot ratio of 2.1. It has to be noted, however, that the stress applied locally at the pin is clearly higher than the stress used here for the evaluation, which was related to the entire design area. The local stresses in the pin-foot area partially reach the base material strength, resulting in a cohesive failure by fracture.

3.1.3 Fracture behavior

The simulated failure behavior of the form-fit joints based on pin-like structures is shown for both material combinations and both pin geometries as a function of the pin-foot ratio in Figure 5. The failure behavior of the pin-foot ratio for the combination of PA66 and PMMA is influenced by the pin-foot ratio. For the trapezoidal geometry, a fracture of the bonding-partner with a smaller pin-foot diameter (ratio of 0.5–0.6 and 1.7–2.1) results in the edge areas. For the range between 0.7 and 1.4, there is no exceeding of the maximum material

Figure 4: Evaluated bond factor (ratio bond stress to base material strength) for the design area of 4.65 mm².

Figure 5: Simulated fracture behavior of the form-fit joint as a function of pin geometry and bonding-partner.

strength of the partners, the bond is separated by pulling the bonding-partner out of the structure of the structured-partner. This wide range of adhesive separation explains the occurring plateau-like behavior of the maximum achievable bond strength. For the mushroom-like pins, separation by pull-out occurs in the simulation solely for a pin-foot ratio of 1.0. For lower as well as higher ratios, fracture takes place in the partner with a smaller pin-foot cross-section. The maximum bond strength can therefore only be fully used for a ratio of 1.0, which is also confirmed by the evaluation of the maximum achievable force in Figure 3.

For the material combination PA66–PP and a trapezoidal pin-like structure, adhesive separation by pulling out of the bonding-partner from the structured-partner can be seen for all pin-foot ratios. For the mushroom-like pins, failure of the bonding-partner occurs for pin-foot ratios below 0.8. Above a ratio of 0.8, adhesive separation of the bond always occurs. The upper limit at which a fracture of the structured-partner results, and thus the maximum achievable bond force, is not reached in the range of the pin-foot ratio investigated. This is also confirmed by the mechanical evaluation of the bond force.

3.1.4 Derived findings

The results show that the achievable strength and the failure behavior of the form-fit connection using pin-like structures depend on the material combination, on the pin geometry, and especially on the pin-foot ratio. If wanted, the failure behavior can be specifically adjusted (e.g. in which joining partner the fracture occurs) by adapting the pin-foot ratio. Furthermore, it is shown that higher strengths are achieved for the bonding-partner PMMA compared to PP. This is in agreement with previous investigations [11] and can be explained by the clearly higher strength of the PMMA compared to PP. It can also be seen that mushroom-like pins

lead to higher bond factors as well as a more frequent cohesive fracture in one of the joining partners compared to trapezoidal pins. This failure behavior correlates with a previous experimental study [11]. The reason is assumed the abrupt undercut increase at about the half pin height of the mushroom-like pins. This abrupt increase leads to a stress concentration in this region and makes a continuous pull-out of the bonding-partner more difficult. The assumed stress concentration in the area of the undercut increase can be seen qualitatively in the simulations, Figure 6, and thus confirms the hypothesis.

In addition to these relationships, the findings obtained from the simulation enable, in particular, a specific design of single pins or pins in line for multi-material connection (pin arrays may deviate due to further interactions). It can be stated that for material combinations with similar base material strengths, a pin-foot ratio of about 1.0 should be used to exploit the maximum achievable strength. For

Figure 6: Qualitative stress distribution for the combination PA66–PP: (a) trapezoidal structure and (b) mushroom-like structure.

combinations with clearly different material strengths, a larger pin-foot diameter is recommended for the partner with the lower strength. Simplified, the following relationship can be derived for the design of the pin-like structures:

$$\text{Pin-foot ratio}_{\text{idealized}} = \frac{a}{b} = \frac{\sigma_a}{\sigma_b} \quad (1)$$

with the pin-foot width of the bonding-partner a , the pin-foot width of the structured-partner b , the tensile strength of the bonding-partner σ_a , and the tensile strength of the structured-partner σ_b . This assumption can be used as a design criterion for the pin-like structures in multi-material joints and shall be verified for further material combinations and different pin arrangements in the future.

3.2 Experimental trials

3.2.1 Optical characterization

To evaluate the real pin-foot ratio, the experimentally generated pin-like structures were analyzed optically by CT. The results of the optical analysis are shown in Figure 7. The mushroom-like form of the pin-like structures can be seen for all variants. As in previous investigations, a rupture of the structure takes place [11]. This phenomenon is caused by the vertical removal of the structuring tool from the softened structured-partner. The vertical movement of the tool at the end of the structuring step is also responsible for the increase in pin height. This height is similar for all variants between 2.4 and 2.5 mm instead of the theoretic height of 2.0 mm, which is analogous to previous studies [11].

The pin-foot width of the structured-partner is very similar to the theoretical width given by the tool for all variants. Different behavior is observed for the cavity width between the pin-like structures, which later represents the pin-foot width of the bonding-partner. This width is clearly

wider than the theoretical width for all variants. The difference between the real and the theoretical width is between 0.4 and 0.7 mm. On the one hand, this increase is caused by the extraction movement of the tool, which elongates the pin in the vertical direction. On the other hand, a horizontal widening of the cavities takes place due to the oscillating movement during the structuring step. This widening should theoretically correspond to half the amplitude, and thus 0.35 mm. Due to the changed pin-foot width of the bonding-partner, the theoretical pin-foot ratio also deviates from the actual ratio. The real pin-foot ratios are 0.92, 1.54, and 2.00 instead of the theoretical values of 0.67, 0.96, and 1.44. For the further evaluation of the experimental tests, the real pin-foot ratio is used.

3.2.2 Mechanical and fracture behavior

To validate the simulation, the mechanical behavior, as well as the fracture behavior of the multi-material connection based on mushroom-like structures, was determined by experimental tests. The evaluation is shown in Figure 8. The failure behavior of the experimental tests, Figure 8b, matches the simulative investigations. For the bonding-partner PP, adhesive separation by pull-out takes place for all three variants. For the bonding-partner PMMA, failure occurs for a pin-foot ratio of 0.9 due to increased fracture in the bonding-partner and a ratio of 1.6 and 2.0 due to fracture in the structure-partner. Thus, a prediction or even design of the failure behavior of the multi-material bond can be obtained by the simulation.

The resulting bond force of the experimental multi-material connection with 16 pin-like structures was scaled to one pin (bond force divided by a number of pin-like structures) to allow a comparison with the model-based investigation, Figure 8a. The evaluation of the maximum achievable bond force for one pin-like structure shows no clear dependence on the pin-foot ratio for both material

Figure 7: Optical characterization of the mushroom-like pins produced by experimental trials with a theoretical pin-foot ratio of (a) 0.67, (b) 0.96, and (c) 1.44. Gray values: theoretical width, black values: real width.

Figure 8: Experimental results for the mushroom-like pins as a function of pin geometry and bonding-partner: (a) mechanical behavior and (b) fracture behavior.

combinations. For the PA66-PP combination, the bond force is around 50 N. For the PA66-PMMA combination, the resulting force is in the range of 140–160 N, although the high standard deviation does not allow a determination of the tendency. In comparison with the simulation, it can be seen that the experimental values for the bonding-partner PP are below the values obtained by simulation. This is also evident for the maximum force achievable in the simulation for the PA66-PMMA combination at a pin-foot ratio of 0.9. For higher pin-foot ratios, the experimental tests show slightly higher resulting bond forces compared to the simulation.

The evaluated bond factors (Figure 4) are in the range 0.36–0.42 (PA66-PMMA) and 0.31–0.35 (PA66-PP). The use of the base material of up to 57% for the PA66-PP combination achieved in the simulation is not reached experimentally. Here, utilization of the base material of up to 35% can be seen. For the PA66-PMMA combination, a similar situation is observed for a pin-foot ratio up to 1.5, although not quite as pronounced. The bond factor of the model-based investigation is slightly above the experimentally achievable value. The simulation shows a use of the base material of 42% (ratio 0.9) and 39% (ratio 1.4), whereas the experimental use is 37% (ratio 0.9) and 36% (ratio 1.5). Analogous to the achievable bond forces, a changed behavior is visible for the relation to the base material for a pin-foot ratio of 2. Here, the base material utilization in the

simulation is 30% (ratio 2.1), while experimentally a clearly higher value of 42% (ratio 2.0) results.

The reason for the increased bond forces and bond factors in the simulation are the simplifications made in the model. The bond strength achievable in the model cannot be reached in the experimental tests due to assumed boundary conditions, such as optimal filling of the cavities between the pin-like structures or the neglect of possible stress effects due to e.g. shrinkage. Furthermore, an optimal formation of the pin-like structures is assumed in the model-based investigation, which is not achieved experimentally, as shown. The experimentally resulting mushroom-like structures show defects as well as geometric and undercut deviations. An improved reproduction accuracy of the pin-like structures, as achieved for the trapezoidal pins [11], should lead to a better match between simulation and experiment.

The reduced bond strength of the simulations for the PA66-PMMA combination for a pin-foot ratio of 2.0, compared to the experimental tests, is due to the simplified representation of the pin-like structures of the structured-partner in the model. In the model, only the pin-like structure with a pin thickness of 2 mm is analyzed, Figure 9a. In the experimental tests, both joining partners have a plate thickness of 4 mm and the structures have a thickness of 2 mm, as in the model, and are introduced in the center of the plate, Figure 9b. Therefore, edge areas of

Figure 9: Schematic illustration of the joining partner geometry: (a) simulation model and (b) experimental tests.

approx. 1 mm are left. For the bonding-partner, these edge areas extend only up to the pin onset and therefore have no or only minor effect on the uniaxial tensile load. This is different for the structured-partner. Here, the edge areas are present over the entire pin height and thus provide an additional force absorption and possibly stiffening of the pin-like structure. Due to this additional support of the structured-partner, which is neglected in the model, the failure of the structured-partner results in reduced bond forces in the simulation model compared to the experimental model. Nevertheless, it can be assumed that the simulation model is sufficiently accurate for an initial design of the pin-like structures.

For an exact dimensioning of the pin-like structures, this additional force absorption and possibly stiffening of the structured-partner must be taken into account. On the one hand, the edge area can be integrated into the simulation model. However, this would clearly increase the processing time. On the other hand, this additional force absorption, which supports the structures of the structured-partner and thus leads to an earlier failure in the bonding-partner, can be implemented in the idealized calculation of the pin-foot ratio by means of factor X , Equation (2). This factor shifts the pin-foot ratio to higher values and thus compensates for the supporting effect. The value of factor X shall be investigated and approximated in further studies.

$$\text{Pin-foot ratio}_{\text{idealized, with side plate}} = \frac{a}{b} = \frac{\sigma_a}{\sigma_b} + X \quad (2)$$

4 Conclusion

With the help of this study, it was shown that the simulation model is suitable for predicting the bond quality of the multi-material joint based on pin-like structures. Due to simplifications made in the model, the bond strength is not exactly reproduced, but similar values are achieved. The failure behavior can be represented exactly. In addition to the verification of the model, the investigations enabled design criteria for the structures to be derived. These allow the pin-foot ratio to be specifically dimensioned as a function of the material combination for single pins or pins in line. For complex pin-arrays, the relationships between the pin-foot ratio and the bond strength as well as the failure behavior may deviate due to further interactions. Nevertheless, the single-pin approach provides an important basis and necessary fundamental correlations for the pin design.

The ratio of the achievable bond stress to the base material strength of the weaker partner shows utilization of the base material of up to 57% for the PA66–PP combination and 47% for the PA66–PMMA bond. For the bonding-partner PP, the highest possible utilization has not yet been achieved with the pin-foot ratios investigated. The experimental investigations show a lower utilization of the base material of 35% (PA66–PP) and 42% (PA66–PMMA). This can be attributed to simplifications in the simulation model, such as an optimal reproduction accuracy of the pin-like structures. For the bond strength of the multi-material connection, only the pin-like structures are responsible, which extend over just half of the joining zone (design area). It can therefore be assumed that for a combination with materials of similar strength, maximum utilization of the base material of up to 50% can be achieved. This is reached nearly for the combination PA66–PMMA, simulatively as well as experimentally. For material combinations with significantly different strengths, higher utilization of the material with lower strength should be possible, which is also shown by the simulative investigations of the PA66–PP combination. However, this has not yet been achieved experimentally.

Finally, the simulation provided a qualitative confirmation of the hypothesis of stress concentration at the abrupt undercut increase of the mushroom-like pins. This stress concentration impedes the pull-out of the bonding-partner from the structured-partner. For material combinations with low deformability, this leads to an increased failure due to cohesive fracture in one of the partners.

Author contributions: All the authors have accepted responsibility for the entire content of this submitted manuscript and approved submission.

Research funding: The authors thank the German Research Foundation (DFG) for funding this study within the project DFG-432470536 “Joining by using pin-like structures in welding processes”. The authors would also like to thank the BASF AG, the Evonik Industries AG, and the Sabic Europe B.V. for providing the used materials.

Conflict of interest statement: The authors declare no conflicts of interest regarding this article.

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