

Bonding of wood-plastic composites (WPC)—material and surface modification for special applications

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Abstract As part of the current research at the *Kunststofftechnik Paderborn (KTP)*, foundational experiments are being conducted on adhesive bonding of wood-plastic composites (WPC) with dispersion adhesives. The setting mechanism of this type of adhesive is characterized by the evaporation of the dispersion medium (water). The challenge is therefore to remove the water in the adhesive fluid from the joining plane. In conventional applications, dispersion adhesives are used to bond wood, paper, or other porous materials. Wood-plastic composites, however, which consist of wood particles in a polymer matrix, cannot absorb the necessary amount of water within the required time period, as they do not possess a similarly porous structure. Part surfaces are treated in various processes in order to expose the wood fibers. This is intended to improve the material's capacity to absorb water, which should lead to more rapid setting. In addition to surface treatments, the WPC formula is modified by the addition of hygroscopic additives. A further approach is to drill holes at regular intervals into the joining plane as additional points where evaporation can occur. The water in the adhesive layer migrates towards these holes through diffusion processes and then evaporates into the ambient atmosphere.

Keywords (IIW Thesaurus) Wood-plastic composites (WPC) · Dispersion adhesives · Adhesion · Surface modification

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1 Introduction

Wood-plastic composites (WPC) are composite materials which primarily consist of a typically thermoplastic polymer matrix, wood particles as filler or as a strengthening additive, and additional additives. Frequently used polymers include polypropylene, polyethylene, or polyvinylchloride. Examples of additives include coupling agents and UV stabilizing agents [1–3].

Although WPC represent a fairly young material type, they have already found application worldwide in decking, in fencing, in the automobile industry, in various technical applications, and in the furniture industry. In 2012, the production volume of WPC reached 1,100,000 tons in North America, 900,000 tons in China, and 260,000 tons in Europe. Together, these regions represent the majority of yearly production worldwide [4].

As part of the research conducted at the *Kunststofftechnik Paderborn (KTP)*, foundational investigations are being carried out on the bonding behavior of WPC with dispersion adhesives, which will have relevance for the furniture industry and, in particular, for interior door production. The adhesive most often used in these industries is a water-based, non-toxic polymer dispersion from polyvinyl acetate, also known as “white glue.” In such dispersion adhesives, polymer particles are finely dispersed in a medium (water) and form a transparent film either via evaporation of the water into the atmosphere or via absorption by the joined parts [5–8].

2 Motivation

One reason for these investigations is the efforts of the interior door industry to replace costly solid wood pieces with WPC. The outer frame of an interior door is produced of solid wood

for stability reasons, onto which is glued a top layer (see Fig. 1).

WPC can, for example, be substituted for the solid wood frame; a hollow square profile can be used instead, which can be produced in a continuous extrusion process. The advantages of a WPC profile in comparison to solid wood include weight reduction and increased mechanical stiffness, as well as lower production costs.

However, the economic benefits in particular which result from using WPC in door production can only be taken advantage of if existing production units can be used to produce door panels. This also concerns processing units for the dispersion adhesives that are most commonly used in the furniture industry. It follows that it is critical to ensure that bonding WPC parts with this type of adhesive is possible, and that these joints provide sufficient strength.

In terms of their setting mechanism, dispersion adhesives are unsuitable for bonding WPC due to their low permeability to water compared to pure wood. The wood particles in the WPC are entirely surrounded by the polymer, which prevents that wood from absorbing water. A further challenge when bonding WPC is the low surface energy of polypropylene and polyethylene, which are the most frequently used matrix materials in Europe. This leads to poor wetting of the parts to be joined by the adhesive, and consequently to insufficient adhesion.

In order to enable bonding with dispersion adhesives despite these challenges, fundamental investigations are being conducted on adhesive film formation when bonding WPC. The main focal points of these investigations on how to improve of the setting behavior are the surface treatment of the parts to be joined, the modification of the WPC formula, and design techniques to modify joining surfaces.

3 Film formation of dispersion adhesives in conventional applications

Dispersion adhesives contain polymer particles, ranging in size from 0.05 to 10 μm , which are finely dispersed in a dispersion medium (water). The small size of the particles results in large surface area in the dispersion, which in turn results in a high total surface energy. Such systems strive

towards a lower energetic state, which leads to a surface reduction in the dispersion and thus to a union among the particles themselves. In order to prevent this coagulation of the polymer particles before the application of the adhesive on the desired parts, emulsifiers or protective colloids are used [10].

The decisive process to obtain a solid adhesive layer is the formation of a film in the dispersion, a process which occurs under specific conditions. A minimum (film) formation temperature (MFT) must be maintained, below which the dispersion is unable to form a coherent film, and where cracks may appear in the adhesive layer after setting.

The formation of this film is a complex process which can be explained in a simplified form by the following model (Fig. 2).

Initially, the polymer particles are finely dispersed in the watery medium. In the first phase, the water evaporates from the freshly applied adhesive. After joining, the water may also be absorbed by the substrate, depending on the latter's chemical composition. This results in the polymer particles moving closer together. As a result of the ensuing capillary pressure between the converging particles, the latter are deformed (phase II). In the following phase, the unification of the polymer particles, known as coalescence, takes place as the polymer particles are destabilized by the bursting of their membranes. Lastly, the molecule chains form a transparent, mechanically stable film by interdiffusing among one another.

Brown [11] describes film formation with the help of forces acting in the adhesive layer, listed as follows:

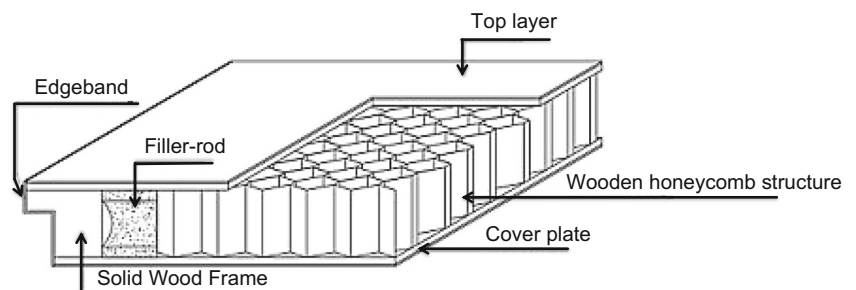
- Surface tension of the polymer particles F_s
- Capillary forces due to the interface water/air F_c
- van der Waals forces between the particles F_v
- Force of gravity which leads to settling of the polymer F_g

The forces which hinder film formation are:

- Particle resistance to deformation F_G
- Coulomb repulsion force between the particles F_e

With the exception of the capillary forces and the particles' resistance to deformation, all of the forces are of small enough

Fig. 1 Structure of an interior door [9]



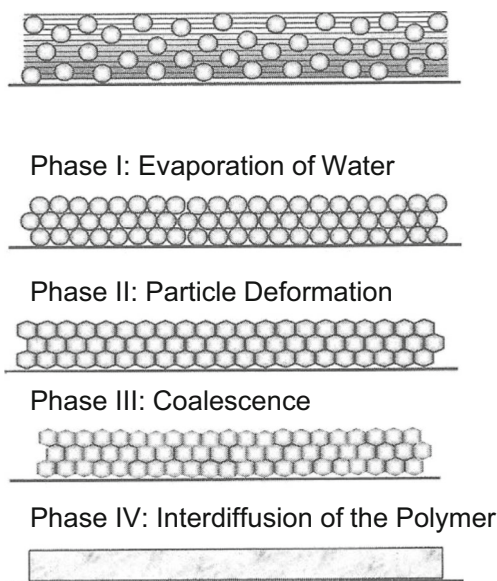


Fig. 2 Model of film formation in dispersion adhesives according to [10]

magnitude that they can be neglected. According to Brown, film formation occurs when the following inequality is fulfilled:

$$F_c > F_G$$

4 Bonding WPC with dispersion adhesives

One primary feature of bonding wood with dispersion adhesives is the permeation of the dispersion medium into the wood, which is a prerequisite for film formation. Bonding WPC also requires the removal of the dispersion medium from the adhesive layer, which can be accomplished by the absorption of water into the WPC parts and/or by diffusion of the water in the adhesive layer.

Commercially available dispersion adhesives on the basis of polyvinyl acetate (PVAc) typically have a water content of roughly 50%. Thus, normal application quantities of 170–200 g/m² contain some 85–100 g/m² of water which must

be removed from the joint [12]. Each of two WPC joining parts must thus account for up to 50 g/m².

4.1 Absorption by WPC joining parts

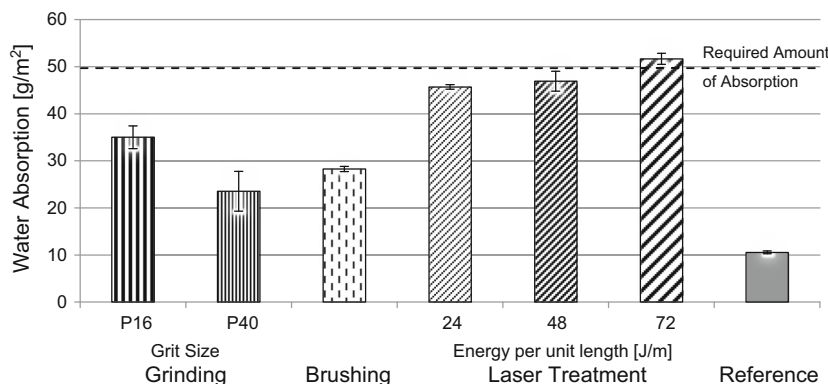
As wood constitutes one part of the WPC and behaves hygroscopically in its raw form, making use of the wood particles as water-absorbent material to encourage film formation (as when bonding wood itself) is an obvious choice. Unfortunately, WPC parts produced by extrusion or injection molding possess an obstructing surface layer of the pure polymer as a side effect of the production process. Therefore, it is necessary before bonding such parts to prepare them by exposing the wood particles in order to increase the water absorption capability of the WPC. As shown in Fig. 3, grinding and brushing the surface with a round steel brush, with both procedures using a contact force of 80 N, increase the 24-h water absorption capability of the part in comparison to untreated reference samples. The WPC used here consists of 48% polypropylene, 2% coupling agent, and 50% wood with a particle size of 300–500 μm. After grinding with a coarse-grade grit (size P16, according to FEPA, Federation of European Producers of Abrasives), absorption is 3.5 times greater.

Laser pretreatment of the surface using a fiber infrared laser and a 3D scan head allows the process to be configured such that the obstructing surface layer can be burned away [13]. By varying the parameters laser power, scanning speed, and number of lasering cycles, a clearly defined amount of energy can be applied to the surface, transferring a substantial amount of heat to the part and causing the polymer molecules to sublimate. The applied energy per unit length, given in Fig. 3, is defined as follows:

$$\text{Energy per unit length} = \frac{\text{Power of the laser} \times \text{Number of lasering cycles}}{\text{Scanning speed}}$$

At an energy level per unit length of 72 J/m, the laser-pretreated specimens absorb more than five times as much

Fig. 3 Water absorption of pretreated WPC specimens according to ISO 62:2008 after 24 h



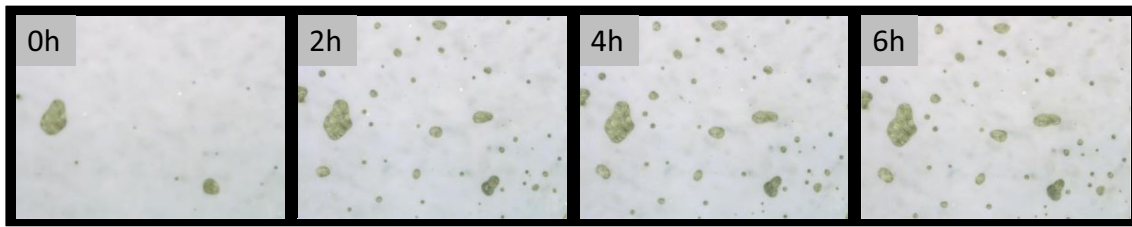


Fig. 4 Setting behavior over time while bonding laser-pretreated WPC to glass

water per surface area as the control specimen. As the energy level increases, the water absorption capability increases correspondingly.

As shown in Fig. 3, only after a laser treatment with an energy level per unit length of 72 J/m does the specimen's water absorption reach the desired concentration of 50 g/m^2 , meaning that bonding with the help of this process would be theoretically possible within a 24-h time frame.

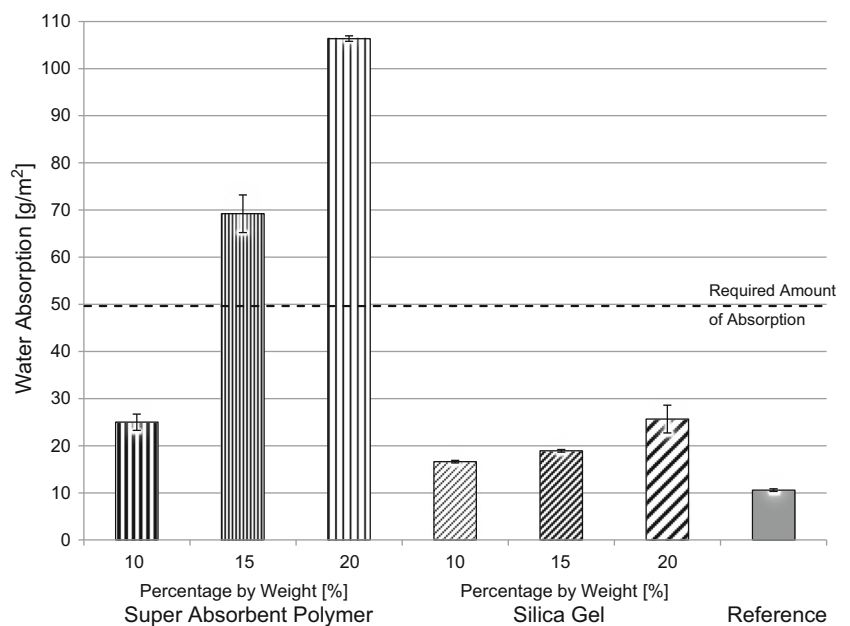
The setting behavior of dispersion adhesives when bonding WPC can be investigated over time by bonding a WPC specimen to a glass plate with a defined thickness of the adhesive layer ($20 \mu\text{m}$). The chosen thickness corresponds to an approximate application density of 250 g/m^2 , which is somewhat higher than the typical maximum density of 200 g/m^2 [13]. However, the setting behavior can be better assessed on the basis of a longer-lasting white adhesive layer. Due to the phase boundaries between the polymer particles and water, and the resulting refraction of light waves, PVAc-based adhesives appear white while they are still wet and form a transparent film after setting. This allows the time of setting to be precisely determined through the glass.

The images below show a laser-pretreated WPC specimen which has been bonded to glass. In the first 6 h, the setting of the adhesive can be seen in the appearance of vacuoles, which can be explained by the decrease in adhesive volume resulting from the removal of the dispersion medium (Fig. 4).

An additional possibility of increasing water absorption by the joining parts is to modify the formula of the WPC itself; the inclusion of hygroscopic additives is intended to increase water absorption capability. Super-absorbent polymers (SAP) are weakly cross-linked polymers which can absorb several times their weight in liquids. In doing so, they form a hydrogel, resulting in swelling of the polymer. Another possible additive, silica gel, is an amorphous form of silicon dioxide with a large internal surface area. It is strongly hygroscopic and is therefore frequently used as a desiccant. Figure 5 shows the results of water absorption by WPC with a wood content of 50% and varying percentages of the abovementioned hygroscopic additives.

Adding silica gel does not increase water absorption sufficiently; while increasing the percentage of the additive does increase the amount of water absorbed, even 20% silica gel by weight absorbs only 25 g/m^2 —half of the amount necessary to

Fig. 5 Water absorption by WPC with hygroscopic additives according to ISO 62: 2008 after 24 h



be effective. In contrast, modifying the WPC formula to include SAP particles leads to a tenfold increase in the amount of water absorbed as compared to the control specimen. Increasing the proportion of the super-absorber thus markedly increases absorption capability. With 15% or more by weight of SAP particles, bonding with dispersion adhesives is theoretically possible in terms of setting behavior.

The setting progress of the WPC specimens with 20% super-absorber (Fig. 6) exhibits more rapid setting behavior compared to the laser-pretreated specimen. However, despite the generally more rapid setting behavior, more water is clearly absorbed within the first 2 h, compared to later in the course of setting, as was the case with the laser-pretreated specimen shown in Fig. 4.

In sum, it can be said that water absorption by the joining parts is only marginally accelerated by mechanical pretreatment, while laser pretreatment leads to more water absorption over time only with application of comparative high energy levels. A modification of the WPC formula to include super-absorbent additives will lead to rapid setting of the joint. However, both the costs of laser pretreatment as well as material costs for the addition of SAP particles must be taken into account and considered for individual applications on a case-by-case basis.

In terms of cost-benefit, the expenditure necessary to accelerate film formation is therefore fairly high here. However, with simple surface grinding alone, the water remains in the joining plane and setting within the given time period is not possible.

4.2 Diffusion in the adhesive layer

An additional possibility of ensuring adhesive setting is to drill holes through the WPC part which then function as points of evaporation along the adhesive layer. Within these holes, as described above, the initial film forms (Fig. 7).

The resulting difference in concentration between the layer of already-set adhesive and the still-wet adhesive in contact with it triggers diffusion processes in the interior of the adhesive layer. The water molecules diffuse towards the holes and evaporate at the interface between adhesive/air.

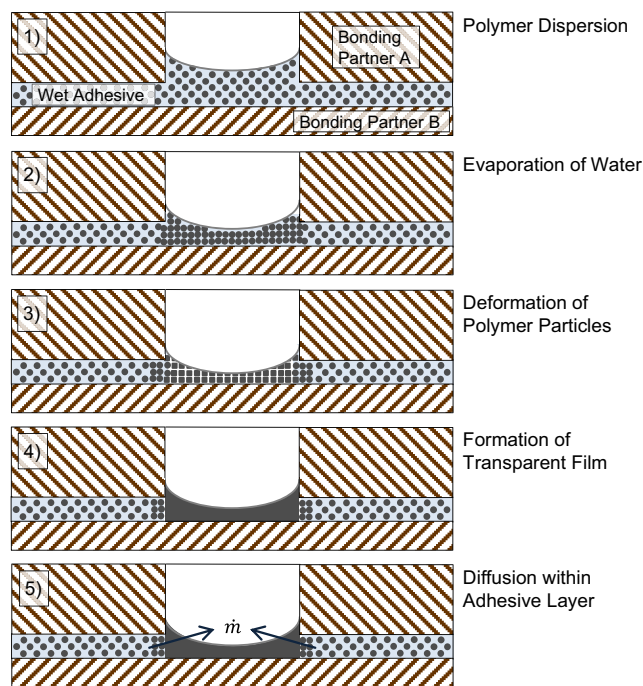


Fig. 7 Model of film formation in the joining plane between perforated WPC parts

The images of the adhesive layer taken through the glass over a period of time can be evaluated in terms of a threshold-value correction, which allows the degree of setting to be qualitatively evaluated.

Figure 8 shows the setting behavior of the adhesive when bonding WPC specimens perforated by holes with three different diameters. These holes are arranged in an equilateral triangle and the ratio of hole surface area to the total adhesive area is constant.

In comparison to the results from the prior experiments on the absorption behavior of WPC, the removal of the dispersion medium is significantly faster. It appears as well that a smaller hole diameter produces more rapid setting behavior. This could indicate capillary effects due to the holes, which would be greater for smaller holes. However, the distance between the holes is not constant for different diameters as a consequence of maintaining a constant ratio between hole surface area and total adhesive area.

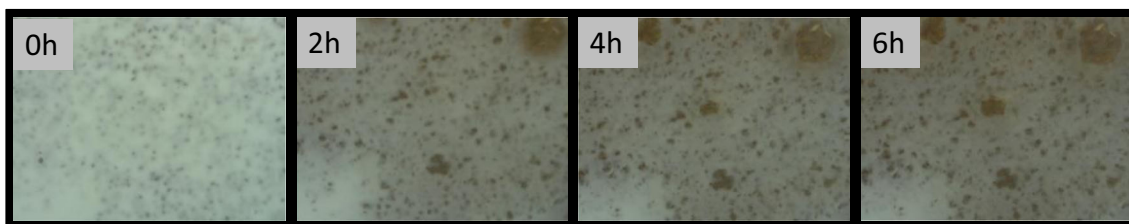
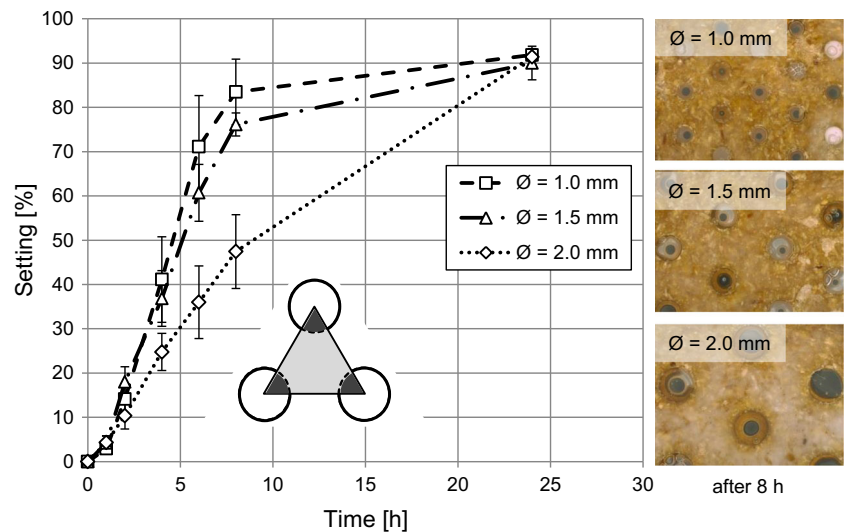


Fig. 6 Setting behavior over time while bonding WPC with 20% SAP on glass

Fig. 8 Setting behavior over time while bonding perforated WPC specimens to glass with constant ratio of hole surface area to total adhesive area



With smaller holes, the number of holes per unit of area rises and the maximum distance required for diffusion decreases (see images of specimen in Fig. 8). This could also result in accelerated setting of the adhesive.

The setting progression shown in Fig. 9 represents specimens in which the maximum diffusion distance within the adhesive layer is constant. It can be seen that the adhesive requires a roughly similar amount of time to set regardless of diameter.

This contradicts the theory of capillary action due to the holes and instead supports the assertion that the maximum diffusion distance is decisive for setting behavior.

Figure 10 shows the effect of varying the maximum diffusion distance. It can be derived from the results shown that the adhesive takes longer to set when the maximum distance is increased.

It is also clear that the setting speed decreases after some 7 h, which indicates, in addition to a greater diffusion distance

for the remaining water, an increasingly strong barrier effect of the already-set adhesive.

The relationship between diffusion behavior and the temperature can be seen in Fig. 11. The diameter of the holes in the specimens used is 2 mm; the maximum diffusion distance is constant. Taking the altered scale of the diagram's x-axis into account, the significantly faster diffusion at 65 °C is conspicuous.

The higher temperature generates a higher degree of mobility among the molecular chains; the probability is therefore higher that diffusing water molecules will be able to enter the resulting spaces between the polymer chains.

In addition to curing the joining parts in a drying oven while pressing, additional acceleration of the setting process can be achieved with a permanent convective flow of hot air perpendicular to the joining plane. However, an industrial-scale application of such a solution can be eliminated on economic grounds.

Fig. 9 Setting behavior over time while bonding perforated WPC specimens to glass with constant maximum diffusion distance

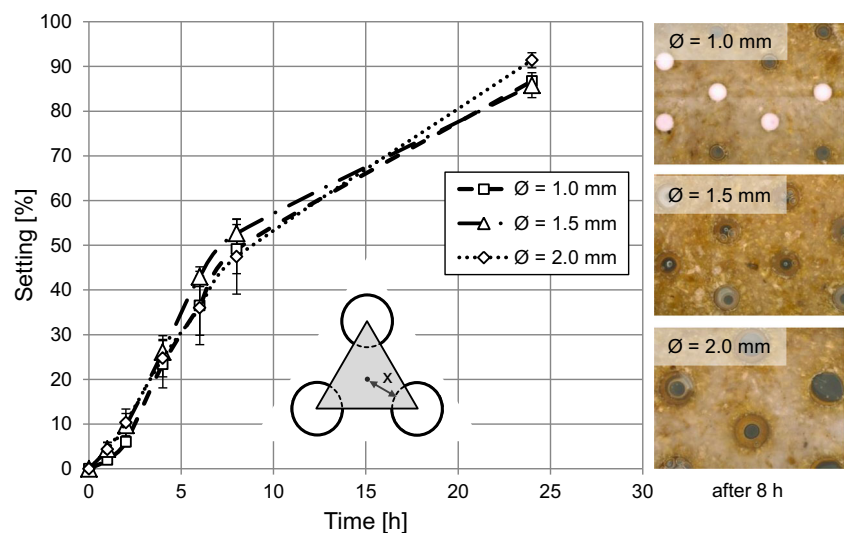
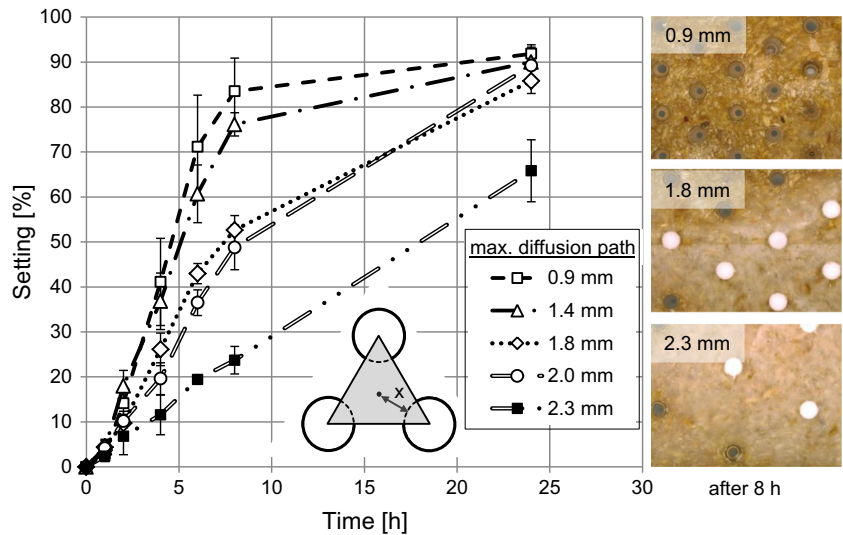


Fig. 10 Setting behavior over time while bonding perforated WPC specimens to glass with varying maximum diffusion distance



The amount of water in the applied adhesive film can be reduced before bonding by, for example, evaporation caused by exposure to infrared light. Accordingly, in such a case, there is less water remaining to be removed from the adhesive layer, which leads to a shorter setting time. However, the tackiness of the adhesive after an IR-treatment must be considered to avoid possible adhesion difficulties.

In sum, perforation of one of the parts to be joined can substantially accelerate setting. In combination with a surface treatment or a modification of the WPC formula, setting times of under 24 h can be realistically achieved.

5 Bond strength experiments

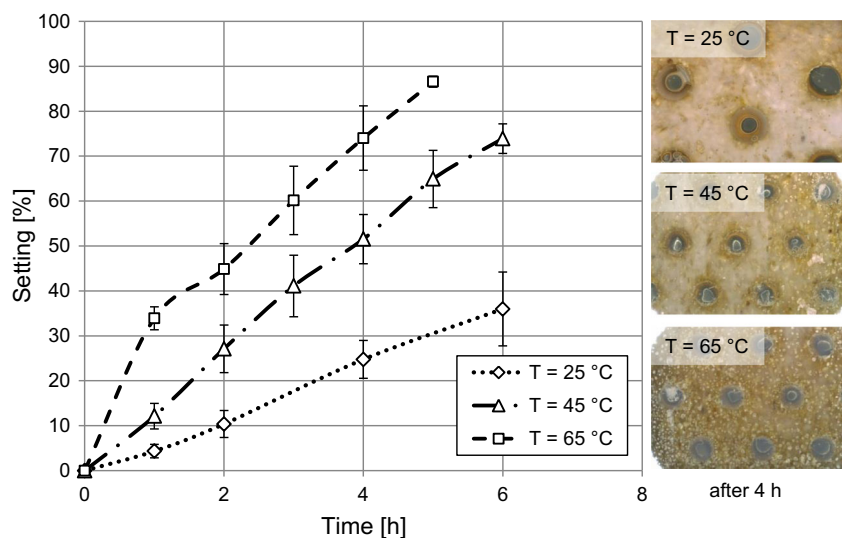
Apart from the time needed to set, another crucial measure of bond quality is the joint strength. In contrast to bonding with

adhesives on polar wooden materials, bonding WPC materials which have a polyolefin matrix produces only insufficient wetting and therefore poor adhesion. A mechanical surface treatment and the resulting partial exposure of wood fibers can significantly improve the adhesion, as shown in the following diagram (Fig. 12).

The increased surface roughness of the ground parts has a positive influence on bond strength as well. For the experiments discussed here, conducted in order to determine the shear strength in a lap shear test, the compression time was 72 h in each case in order to be able to accurately measure bond strength for the untreated reference sample as well as for the treated specimens. As in the experiments on setting behavior, the adhesive used was a PVAc-based dispersion adhesive with roughly 50% solids. The molding pressure was 0.125 MPa.

As seen in the investigations of laser pretreatment, increasing the energy per unit length leads to an increase in water

Fig. 11 Setting behavior over time while bonding perforated WPC specimens to glass with constant maximum diffusion distance and at varying temperatures



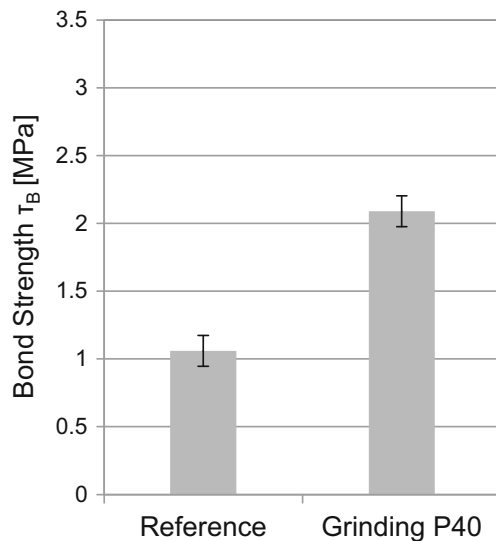


Fig. 12 Influence of surface grinding on bond strength

absorption. The laser pretreatment has the additional effect of increasing surface roughness; therefore, as can be seen in Fig. 13, the measured average surface roughness increases as the energy per unit length is raised.

Within the range of energy levels investigated, the roughness increases by roughly $60 \mu\text{m}$. The results also show an improvement in shear strength to almost 3 MPa, an increase of some 0.5 MPa. This can be firstly traced to a higher degree of mechanical interlocking due to the higher surface roughness, as well as to improved specific adhesion due to the exposed wood fibers at the surface.

As shown in Fig. 5, modification of the WPC formula to include super-absorbent additives leads to accelerated setting

behavior. However, Fig. 14 shows that the bond strength is still below that which can be obtained using a laser pretreatment. This is a consequence of the untreated surfaces of the specimens, as their surface roughness is comparable to that of the polished surface in the injection molding tool cavity ($<1 \mu\text{m}$). The increase in bond strength which comes with higher quantities of SAP is connected to the polar structure of the super-absorber; the SAP particles are exposed at the surface in larger quantities, which leads to better adhesion.

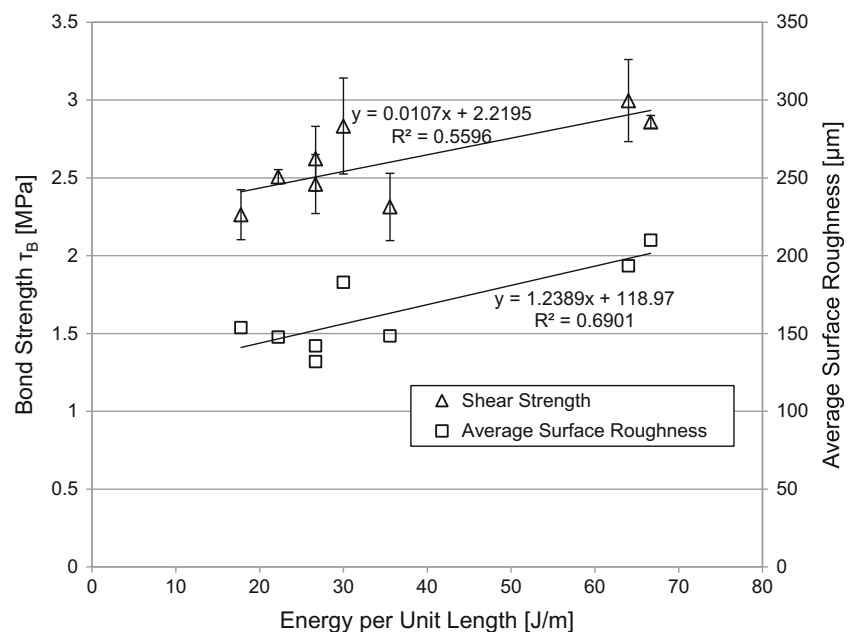
Figure 15 shows the strength of bonds with targetedly roughened surfaces and one joining part perforated with holes having diameters of 1, 1.5, and 2 mm. The ratio between hole surface area and total adhesive area is constant; as a consequence, it was necessary to drill four times as many holes to the adhesive layer with a 1-mm diameter, as with a 2-mm diameter. In comparison to the results shown above, higher bond strengths were obtained here. This can be explained, for one, by the use of a modified adhesive system (WPC formula); it can also be explained by the fact that the roughness and the undercuts offered by the holes when pressing the adhesive layer both contribute to better mechanical adhesion.

As there is a higher number of holes and consequently a larger amount of undercuts provided by the 1-mm holes, higher bond strengths could be observed here than those obtained with 2-mm holes.

6 Summary

Bonding WPC parts with dispersion adhesives is possible with a modification of the WPC formula and of the surface condition of the parts to be joined. However,

Fig. 13 Influence of laser pretreatment on bond strength and average surface roughness R_z



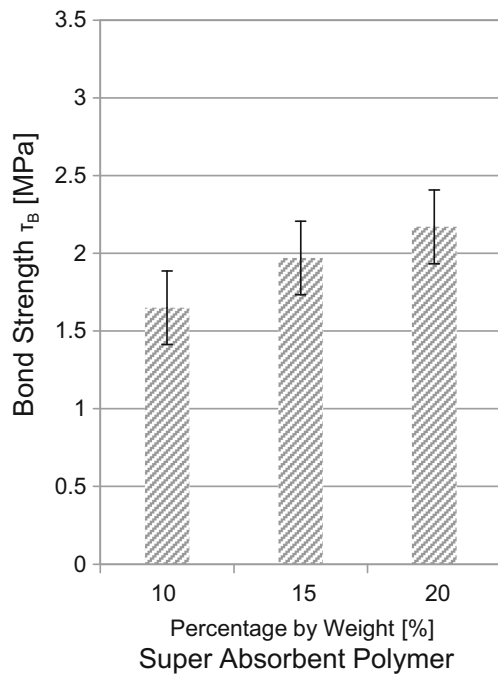


Fig. 14 Effect on bond strength of modifying the WPC formula to include super-absorbent additives

exposure of the wood particles by a purely mechanical treatment is not possible to the extent that would be necessary to produce an effective bond by absorption

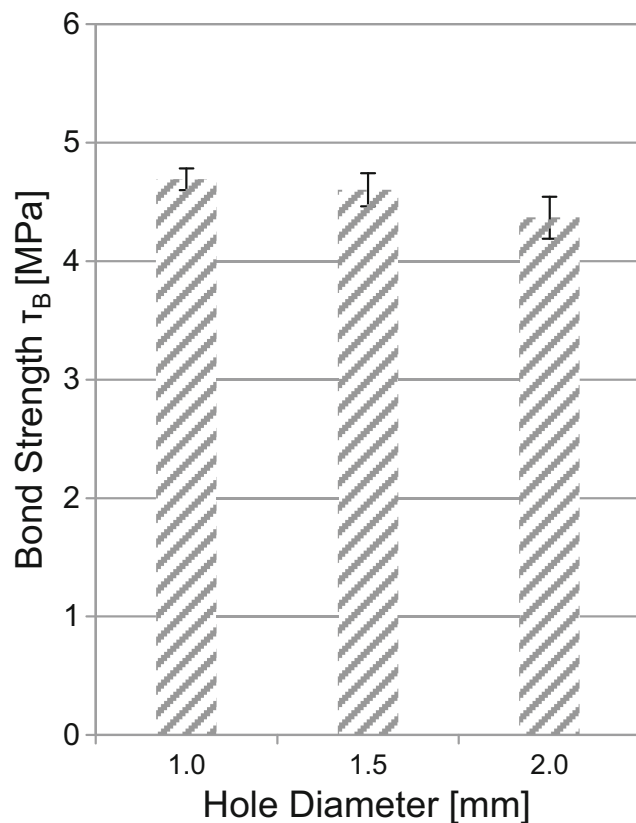


Fig. 15 Influence of perforation on the bond strength

of the dispersion medium into the joining part. This can, however, be accomplished by a laser pretreatment with high energy density. Both pretreatment methods produce an increase in surface roughness, which leads to higher bond strengths. Modifying the WPC formula to include hygroscopic additives leads to accelerated setting of the adhesive. When doing so, however, a further increase in surface roughness must be obtained with additional grinding in order to obtain the desired higher bond strengths.

Perforating the WPC is a second method of encouraging film formation in the adhesive layer. The holes provide specific points at which an initial transparent adhesive layer appears. Water travels through the adhesive layer to the holes by diffusion, where it leaves the adhesive as it evaporates into the atmosphere. The maximum diffusion distance should be as small as possible during this process. An acceleration of the diffusion process can be obtained by increasing the temperature in the adhesive layer. In addition, the holes generate an increase in bond strength by producing undercuts in the holes as the adhesive is pressed into them.

7 Future prospects

To implement bonding of WPC with dispersion adhesives on an industrial scale, further experiments must be conducted and the solution strategies described here must be combined. Further acceleration of the setting behavior is desirable for realistic, practical industrial use.

Obtaining an increase in bond strength by optimizing the composition of the WPC and the adhesive will be investigated further. In this context, the influence of plasma pretreatments and other pretreatment possibilities will be analyzed in terms of their effect on adhesion [6, 13].

To conduct further-reaching experiments on the possible use of a WPC profile to produce frames for interior door leaves, the tensile loading of the joint must be taken into consideration. For commercially available interior doors, the surface soundness of the top layer is, in most cases, the weakest element in the entire unit. The carrier material for the veneer surface is typically grade P2 particle board; according to European industrial standards, this must possess a surface soundness of 0.8 N/mm^2 [14]. Mechanical loading of the sort occurring here would correspond to tensile loading in the adhesive layer between the particle board and the WPC profile; therefore, the bond strengths previously shown are not comparable. Shear loading can be regarded as more favorable for adhesives than tensile loading, due to the typically low tensile strengths of adhesives in general.

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