Influence of Glue Line Thickness on the Strength of Joints Bonded with PVAc Adhesives

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Abstract

The purpose of this study was to evaluate the impact of glue line thickness on joint strength properties while using two types of PVAc adhesive (i.e., one-component Rhenocell 3W, 4B Plus, resistivity class D3, and two-component Protovil VP244/2C, resistivity class D4) belonging to the group of thermoplastic adhesives intended for nonconstruction joints. Joint strength testing was carried out using the transverse tensile test for estimation of the joint strength method. It was proven that if specimens were conditioned for 7 days at 20°C ± 2°C and a relative air humidity of 65 ± 5 percent, when testing one-component Rhenocell 3W, 4B Plus (D3) adhesive, increasing thickness of the glue line results in falling strength of the bonded joint. When testing the two-component Protovil VP244/2C (D4) adhesive, increasing thickness of the glue line always results in increasing joint strength, even under conditions when water is directly affecting the joint or under increased temperatures.

Synthetic adhesives are used in many branches of industry because of their ability to bond a wider range of materials. They are used mainly during production of wood-based materials in the wood processing industry. Use of adhesives has enormous potential not only in the wood processing industry, and we can assume further development and an increasing scope of utilization in this field in the future. As a result, it is appropriate to examine the individual parameters affecting the resulting properties of these adhesives.

Polyvinyl-acetate adhesives (PVAc) are one of the most frequently used synthetic adhesives in the wood processing industry because of their versatility. They are used mainly to bond joints and finish edges and are also used for veneering, particularly due to their price, safety, polymerization under normal pressure, and ease of application. PVAc adhesives are distinguished by their good affinity with wood and provide very strong and flexible joints (Liptáková and Sedliačík 1989, Tout 2000, Altinok et al. 2009). They are capable of achieving up to 50 percent bonding strength within an hour after application (Eisner et al. 1983, Bomba et al. 2014a). The relative flexibility of PVAc adhesives (typical for thermoplastic adhesives) enables relative movement within the joint, which means much better distribution of the interior stress within the joint (Tankut 2007, Ratnasingam and Ioras 2013). On the other hand, they have low resistance to moisture, heat, and low temperatures and are mechanically unstable and distinguished by their poor rheological properties. However, the previously mentioned deficiencies can be improved by the addition of special additives (Zhao et al. 2011, Aydemir 2014). The greater flexibility of PVAc adhesives enables greater tolerance in relation to the thickness of the glue line, which also encourages use of PVAc adhesives for series production of furniture (Ratnasingam and Ioras 2013).

Glued joints are currently one of the key methods of joining wood and wood-based materials. Adhesives are used in more than 70 percent of products made from wood (Zhao et al. 2011). An incorrectly chosen type of adhesive and bonding parameters can negatively affect the strength of the glued joints. Several studies on the strength of joints glued using PVAc adhesives have already been performed. Bomba et al. (2014a) examined the effect of a rise in strength of a rabbet joint on hardening times. Other studies have examined the effect of moisture (Bomba et al. 2014b) and temperature (Elstner 2013) on the strength of joints. Geometric factors defining the glued joint are also important, and their design significantly influences the

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results of bonding. One of the most important factors is the thickness of the glue line. It influences the mechanical properties of the joint and has a clear economic impact on the production process (Arenas et al. 2010). Classic flexible analysis assumes that strength increases with the rising thickness of the glue line (Arenas et al. 2010). In spite of this, research generally shows that the strength of rabbet joints increases with the falling thickness of the glue line. However, in general, the highest strengths were determined on the basis of literary research and resulted from glue lines of thicknesses between 0.05 and 0.5 mm (da Silva et al. 2006). Other studies generally give a glue line thickness ranging between 0.1 and 0.5 mm (Gleich et al. 2001). However, this hypothesis is not applicable in all cases; it always depends on the type of stress, the properties of the adherent, and the type of adhesive (da Silva et al. 2006).

The issue of the thickness of the glue line has been specifically researched in several works. One study examined the effect of the type of adhesive and thickness of the glue line on the fatigue strength of a rabbet joint in furniture (Ratnasingam and Ioras 2013). The following glue line thicknesses were used: 0.1, 0.05, and 0.01 mm. PVAc adhesive showed better results than urea-formaldehyde (UF) adhesive; joints of a thickness of 0.1 mm had the best strength properties. Another study examined the effect of the type of adhesive (PVAc, UF, and polyurethane [PUR]), thickness of the glue line (0.012, 0.063, and 0.095 mm), and moisture content on the strength of a mortise and tenon joint in beech (*Fagus orientalis* L.) specimens. The research confirmed that strength depended on the type of adhesive and thickness of the glue line. PVAc adhesive with a glue line thickness of 0.063 mm demonstrated the best results (Tankut 2007). Kurt (2006) examined the effects of the thickness of the glue line using phenol-resorcinol adhesive in wooden elements. The critical thickness of the glue line was shown to be 0.25 mm; if this was exceeded, a fall in joint strength was registered. Another study researched the effect of the thickness of the glue line (0.2, 0.5, and 1 mm) on the strength of a rabbet joint in metal using three types of adhesive. The conclusion was that shear strength increases with decreasing glue line thickness. This significant dependence may be explained by the stress placed on the interface between the adhesive and the adherent (da Silva et al. 2006). Brožek (2003) also examined the problematic issue of bonding metal and devoted his work to fast-acting adhesives. He tested seven various adhesives to establish how the strength of the glued joint changes depending on the thickness of the glue line. He tested five various thicknesses for each adhesive (0.05, 0.10, 0.15, 0.20, and 0.25 mm). His results indicate that the maximum joint strength differs for each type of adhesive, but it can be stated that the greatest strengths were achieved when the glue lines were of thicknesses ranging between 0.05 and 0.15 mm.

Joint strength is also affected by other factors. It is generally affected by the roughness of the glued surface or the preparation of the surface before bonding. Joint strength depends not only on the size of the glued surface but also on its shape (Brožek 2003). In general, it holds true that the larger the glued surface, the stronger the bonded joint. This is why glued joints are structurally modified using pegs, plates, or nibs (Osten 1975, Brockmann et al. 2009).

The main goal of the following experiment was testing of a rabbet joint according to the EN 204 (European Committee for Standardization 2001) and EN 205 (European Committee for Standardization 2003) standards. The rabbet joint is one of the most frequently used types of joint, and it is important in determining the effect of the thickness of the glue line on its strength from the aspect of design (da Silva et al. 2006).

Materials

The specimens for the experimental testing were made using the procedure defined in standard EN 205. Twelve test specimens were made for each test group. The samples were made from thick, steam-conditioned boards, initially dried naturally and then kiln dried, from beech wood (*Fagus sylvatica*) with straight fibers of a nominal density of 700 ± 50 g and a moisture content of 12 ± 1 percent (Fig. 1). The angle between the annual rings and the surface panel ranged between 30° and 90°. The panels were conditioned for a period of 7 days under standard conditions at a temperature of 20°C ± 2°C and a relative air humidity of 65 ± 5 percent so that the wood moisture content was maintained at values of 12 ± 1 percent.

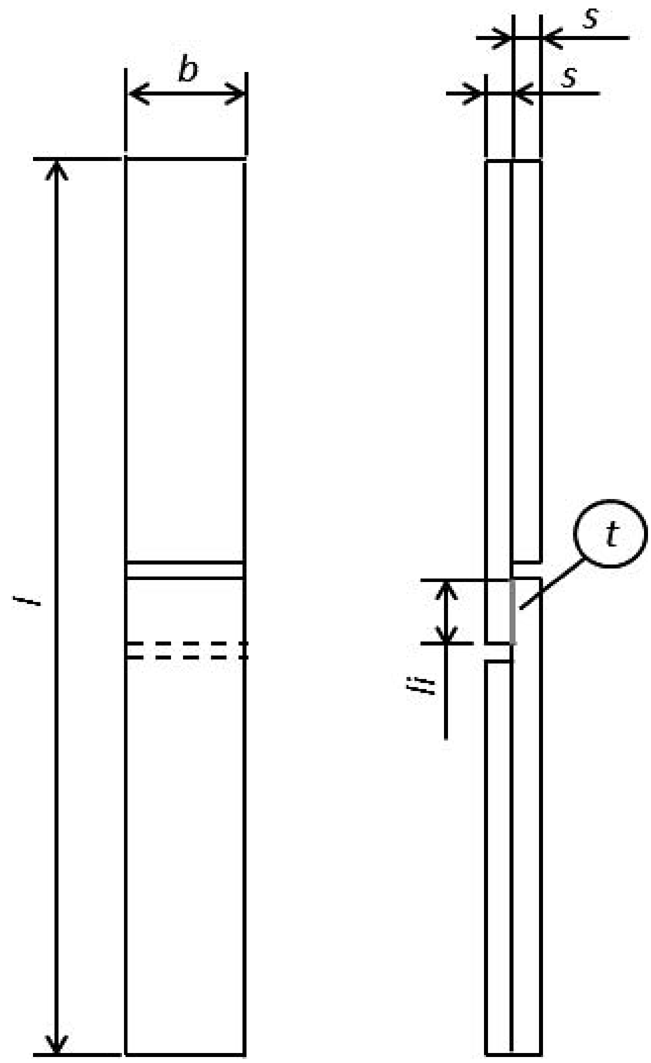

Figure 1.—Test specimens according to EN 205; l = *150* ± *5 mm,* li = *10* ± *0.2 mm,* b = *20* ± *0.2 mm,* s = 5.0 ± 0.1 mm, t = *different thickness of glued joint.*

Methods

Testing was realized in compliance with standard EN 205 and EN 204 (Fig. 1). Two types of PVAc adhesive from various manufacturers were used for the glued joint elements. The glued joints were constant loaded using a pressure of 1 MPa for 60 minutes. The samples were subsequently conditioned for 7 days in a standard environment at 20°C ± 2°C and relative air humidity 65 ± 5 percent in full cure (EN 205). The bonding strength tests of the specimen were performed according to EN 205 at a crosshead constant speed of 5 mm/min. The testing velocity by lapping joints for PVAc adhesives of the D3 resistivity class is defined at 5 mm/min.

The first adhesive was one-component Rhenocoll 3W, 4B Plus (Rhenocoll-Werk, Konken bei Kusel, Germany). Rhenocoll 3W, 4B Plus is a polyvinyl-acetate adhesive in water dispersion. The properties of this adhesive comply with EN 204-D3. It has been certified to comply with DIN EN 14257:2010 by IFT Rosenheim (Window Technology Institute) and features excellent bonding properties at higher temperatures.

The second adhesive was two-component PVAc Protovil VP244/2C (Collanti Concorde, Vittorio Veneto, Italy). Protovil VP244/2C is a synthetic resin–based polyvinyl-acetate adhesive in water dispersion, and the properties of this adhesive comply with EN 204-D4. Refer to Table 1 for the parameters of these adhesives.

The resulting bond strength values by adhesive were evaluated at a significance level of $\alpha = 0.05$ using an analysis of variance, and the difference between individual groups was determined using a post hoc test (Tukey honest significant difference test; STATISTICA, version 12, StatSoft CR, Prague, Czech Republic).

Table 1.—Properties of tested adhesives (Rhenocoll 3W, 4B Plus 2004 and Protovil VP244/2C).

Property	Adhesive: Rhenocoll 3W, 4B Plus	Adhesive: Protovil VP244/2C
Resistivity class (EN 204)	D3	D4
Application quantity (adhesive applied on both adherents) (g/m^2)	120–150	150–300
Viscosity at 20°C (mPa)	9.000–15.000[a]	18.000 ± 4.000[a]
Minimum processing temp. (°C)	+3	+6
Open time (min)	5–8	5
Wood moisture content (%)	10–12	8–12
Pressure (MPa)	0.2–0.5	0.3–0.5
Density (g/cm^3)	1.03	1.10
Pressing time at 20°C joint bonding (min)	Minimum 6[b]	Minimum 4[b]

[a] Type of viscosity measured by the Brookfield method.
[b] The pressing time of the test specimens was 3 hours.

Test principle

Two adhesives were used for the test: one-component class D3 and two-component class D4. The test samples were divided into nine groups for each adhesive (each group included 12 samples with a requirement of achieving a minimum of 10 valid values), and a total of 108 samples were tested for each adhesive. The samples were prepared so that they had three different glue line thickness values: thin (0.1 mm), medium (0.3 mm), and thick (0.5 mm). The appropriate glue line thickness was ensured by grooves of appropriate depth milled to the surface of wood used to the manufacturing of samples.

The conditions for bonding (deposition, open time, pressing pressure) complied with the data specified by the manufacturer of the adhesives (see Table 1). Bonding was carried out at a temperature of 18°C ± 2°C and a relative air humidity preventing any changes in the wood moisture content. The moisture content was measured using the weight method.

Batches of 216 test specimens were produced with wood moisture contents of 8 ± 1, 12 ± 1, and 20 ± 1 percent. Each group of specimens was bonded using two types of adhesive: 108 specimens using Rhenocoll 3W, 4B Plus (D3) and 108 specimens using PVAc Protovil VP244/2C (D4).

Because the adhesives used were in the D3 and D4 resistivity class (interior with frequent, long-term effects of water or exterior exposed to weather), three tests were carried out for each adhesive with sequential numbers 1, 2, 3, and 4 (prescribed in accordance with EN 204).

The first test was carried out 7 days after bonding (test sequence number 1). For each test, the parameters of the environment in which the samples were conditioned for 7 days were 20°C ± 2°C and a relative air humidity of 65 ± 5 percent, which prevented changes to the wood moisture content (hereinafter referred to as the standard environment).

The second test was carried out in such a way that after 7 days, the samples were immersed for 4 days in water at 20°C ± 5°C and then immediately tested (test sequence number 2).

The third test was carried out only on D3-class samples by, after 7 days, immersing the samples in water for 4 days at 20°C ± 5°C and then placing them in a standard environment at 20°C ± 2°C and a relative air humidity of 65 ± 5 percent (which prevents changes to the wood moisture content) for 7 days (test sequence number 3).

Only samples in the D4 resistivity class were used for the fourth test. These were placed in a standard environment at 20°C ± 2°C and a relative air humidity of 65 ± 5 percent for 7 days. They were then placed in boiling water at 100°C ± 5°C for 6 hours and subsequently placed in water at 20°C ± 5°C for 2 hours (test sequence number 4).

The number of test specimens was chosen so that at least 10 valid values were measured for each test. Results where there was a breach in the wood rather than in the adhesive layer or where it was visually apparent that the adhesive had not been properly applied were considered invalid.

Test equipment

The test device used was a tensile testing machine type SM50.61-5,0-0, UTS (Testsysteme, Denkendorf, Germany) with a constant feed rate described in ISO 5893 (International Organization for Standardization 2002).

Transverse tensile test according to EN 205

Both ends of the specimens were clamped in the jaws of the machine at a length of 45 ± 5 mm. The test specimens were burdened by a tensile force until they were breached, and the highest exerted force F_{max} in newtons (N) was recorded. The feed rate of the tensile testing machine was a constant 5 mm/min. Simultaneous measurements were also conducted on the surface of the bonded joints in each specimen.

Expression of results according to EN 204

The bond strength of a bonded joint (τ) is expressed in MPa and calculated according to the equation

$$\tau = \frac{F_{max}}{l_2 \times b} \quad (1)$$

where F_{max} is the ultimate force (N), l_2 is the length of the bonded test surface (mm), and b is the width of the bonded test surface (mm).

Results and Discussion

The measurements determined the degree of strength at maximum load of the bonded joint under the effects of bonded wood moisture content (Test 1) and moisture in the external environment (Tests 2 through 4). The measured values are specified in Tables 2 and 3. Two-factor analyses of variance of strength of bonded joints tested during executed tests are depicted in Figures 2 through 4.

During Test 1, when the samples were conditioned for 7 days at 20°C ± 2°C and a relative air humidity of 65 ± 5 percent, increasing thickness of the glue line resulted in decreasing joint strength when testing one-component Rhenocoll 3W, 4B Plus (D3) adhesive. When testing the two-component Protovil VP244/2C (D4) adhesive, the opposite effect occurred (Fig. 2). However, none of the differences are statistically important; trends can only be assumed on the basis of development of the median values of the monitored group. One-component Propellerleim 3W, 4B Ples adhesive contains a built-in hardener that is reactive at low and high temperatures. The hardener ensures the strength and hardness of the bonded joint, but due to this additive, the adhesive is less flexible than the two-component Protovil VP244/2C adhesive. The two-component Protovil VP244/2C adhesive has high strength and resistivity, even in environments with increased moisture. During these measurements, some of the specimens were breached in the wood rather than the joint bond, and these values were eliminated from the tests.

The strength of the bonded joint is significantly affected by penetration of the adhesive into the wood (there is also an issue of how to define the thickness of the glue line with regard to penetration) (Kurt and Çil 2012, Ratnasingam and Ioras 2013). The rate of penetration of adhesive into the wood is also affected by its viscosity and density as well as the pressing pressure. The viscosity and density of Protovil VP244/2C adhesive is significantly higher than the viscosity and density of Rhenocoll 3W, 4B Plus adhesive. It can therefore be assumed that Rhenocoll adhesive will penetrate the wood more deeply than the Protovil adhesive, and therefore the glue line thickness will be greater than when Protovil is used (even though the target thickness was given by a groove machined to 0.1, 0.3, or 0.5 mm) (Mendoza et al. 2012, Voulgaridis et al. 2012). We are therefore probably comparing various thicknesses of glue line within the scope of one glue line category. The glue line consequently consists of a zone of pure adhesive and a transitional zone of adhesive penetrating into the wood (Xu et al. 2016). The ratio of the transitional zone to the entire thickness of the glue line decreases the thicker the glue line is. We are therefore comparing glue lines of various structures.

During Test 2, in which the joint was also subject to the effects of cold water, the shear strength of the joint was reduced compared with Test 1 (Fig. 2). Class D4 adhesives showed greater strength than did the class D3 adhesives. Degradation of the PVAc adhesive joint is caused by hydrolysis of the PVAc (Minelga et al. 2013). It is therefore possible that class D4 adhesive degrades as a result of the effects of water and less because of the lower content of free

Table 2.—Overview of measured values for adhesive Rhenocoll 3W, 4B Plus PVAc.[a]

	Bond line thickness (mm)								
	0.1			0.3			0.5		
	Test 1	Test 2	Test 3	Test 1	Test 2	Test 3	Test 1	Test 2	Test 3
$\bar{x}$ (Mpa)	14.52	3.18	3.08	13.28	3.37	3.71	12.82	3.58	3.81
Max. (MPa)	17.81	4.80	5.12	15.40	5.38	5.67	17.21	6.01	5.84
Min. (MPa)	9.89	0.75	1.12	11.97	2.83	2.66	12.91	3.64	3.72
SD	2.69	1.11	1.26	1.06	0.45	1.04	1.68	0.50	0.63
CV (%)	20.90	35.42	36.00	7.76	13.69	23.85	11.45	13.99	13.68

[a] $\bar{x}$ = average value; Max. = maximum measured value; Min. = minimum measured value; SD = standard deviation; CV = coefficient of variation.

Table 3.—Overview of measured values for Protovil VP244/2C.[a]

	Bond line thickness (mm)								
	0.1			0.3			0.5		
	Test 1	Test 2	Test 4	Test 1	Test 2	Test 4	Test 1	Test 2	Test 4
$\bar{x}$ (MPa)	12.87	3.92	11.26	13.65	5.14	11.98	14.63	5.27	12.39
Max. (MPa)	17.48	4.46	14.33	15.74	6.47	14.89	16.79	6.96	14.71
Min. (MPa)	11.83	1.96	8.04	12.12	3.32	9.37	11.25	3.89	9.43
SD	1.88	0.69	2.13	1.13	0.98	1.64	1.78	0.80	1.87
CV (%)	12.96	23.12	19.49	8.57	19.93	14.80	13.88	16.04	15.03

[a] $\bar{x}$ = average value; Max. = maximum measured value; Min. = minimum measured value; SD = standard deviation; CV = coefficient of variation.

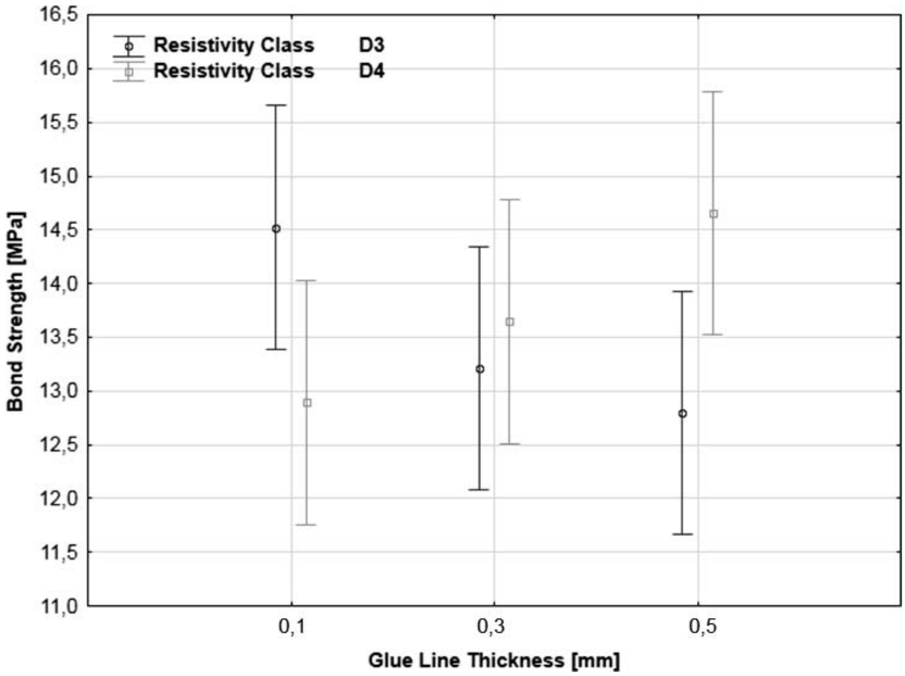

Figure 2.—Bond strength by adhesive and wood moisture content after 7 days in a standard environment (Test 1).

links. The strength of the joint increased with increasing thickness of the glue line in both types of tested adhesive. When testing the Rhenocell 3W, 4B Ples (D3) adhesive, there was only a slight increase in strength with the rising thickness of the glue line. When testing Protovil VP244/2C (D4), the increase in joint strength resulting from the rising thickness of the glue line was found to be statistically significant.

Joints bonded using Protovil VP244/2C (D4) were subjected to Test 4, according to the procedure defined by standard EN 2014 when in contact with boiling water. Because of the increased temperature affecting joints bonded using two-component adhesive, there may be more intensive cross-linking between the macromolecules of the adhesive polymer, resulting in an increased joint strength up to values of 11 to 13 MPa ($P < 0.05$), which does not correspond to theory. According to theoretical assumptions,

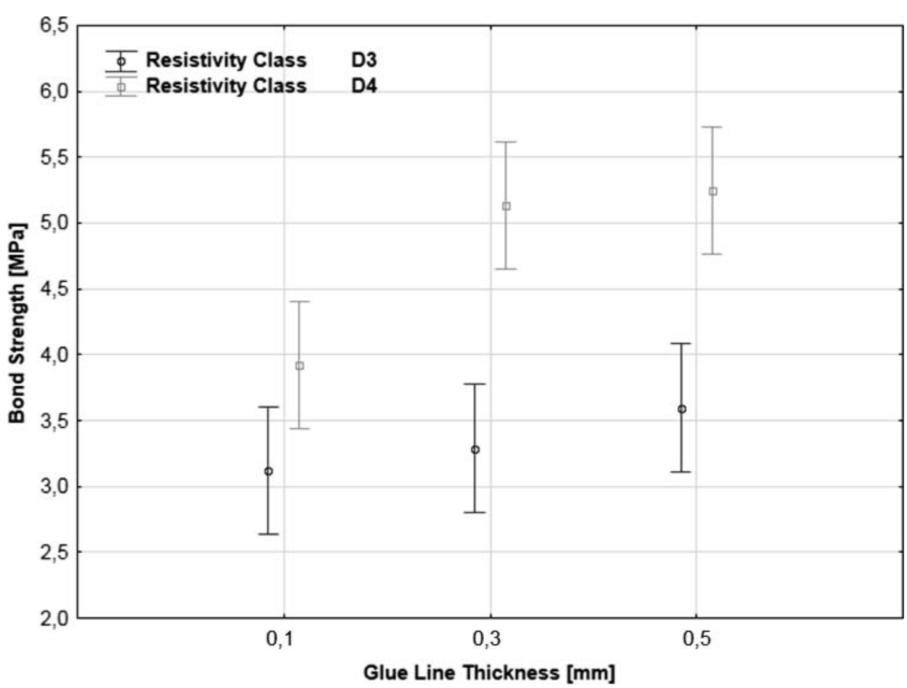

Figure 3.—Bond strength of a joint after 7 days in a standard environment and then 4 days in water at a temperature of 20°C ± 2°C (Test 2).

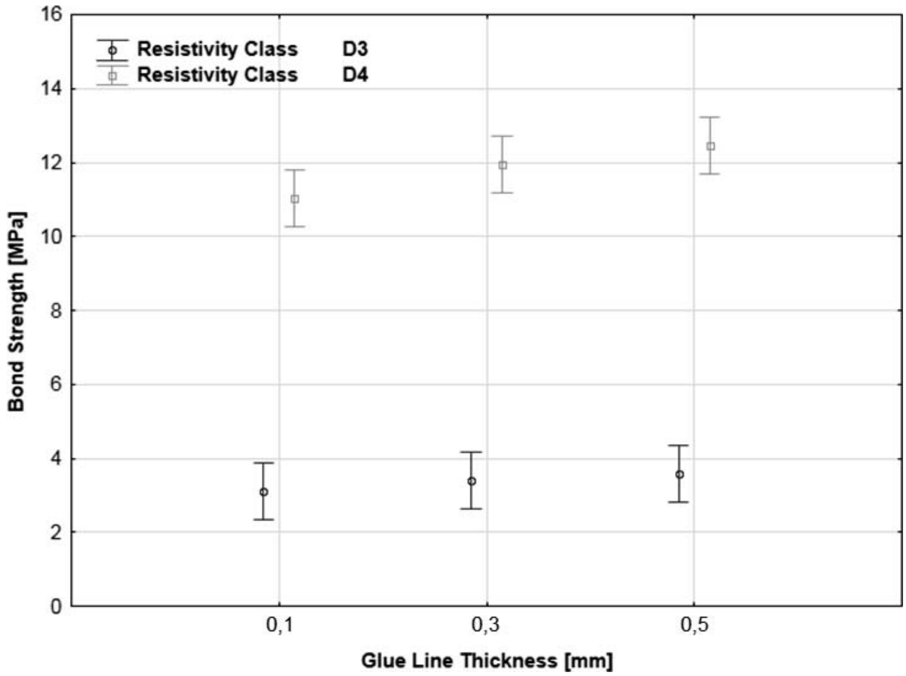

Figure 4.—Bond strength by adhesive and moisture content during bonding (Test 3 for resistivity class D3 adhesive and Test 4 for resistivity class D4 adhesive).

the temperature has no effect on cross-linking of PVAc adhesive. PVAc adhesives harden as a result of coagulation of dispersed adhesive particles after water is released into the surrounding material, not as a result of increased temperatures. On the contrary, with regard to the fact that PVAc adhesives are thermoplastics, higher temperatures result in softened joints (Lu et al. 2011, Bomba et al. 2014a); subsequent reduction of the temperature means that the joint strength increases again but is no longer as great as it was before the changes in temperature (Beech 1977). During testing of the Rhenocoll 3W, 4B Plus (D3) adhesive, the rising thickness of the glue line resulted in only a slight increase in strength (again statistically insignificant), the same as in Test 2.

However, when evaluating the various thicknesses of glue lines, we must be aware that in regard to all of the glued joints, the manufacturer's application instructions were not followed. In relation to glue lines thicknesses of 0.1, 0.3, and 0.5 mm, Rhenocoll was applied at 103, 309, and 515 g/m^2, and Protovil was applied at 110, 330, and 550 g/m^2, which does not correspond to application recommendations and can therefore result in the glued joint strength falling above or below the interval given for a recommended application.

The majority of cracks (defects; about 95%) were cohesion fractures. The defects occurred in the adhesive material itself (mass), and traces of the adhesive on both surfaces of the substrate could be seen. The minority of cracks (defects; about 5%) were adhesion fractures on both surfaces of the substrates. The defect occurred in the joints between the adhesive and the substrate. The adhesive was partially separated from both fastener substrate surfaces.

Conclusions

1. During the first test, when specimens were conditioned for 7 days at 20°C ± 2°C and a relative air humidity of 65 ± 5 percent, increasing thickness of the glue line was accompanied by falling joint strength when Rhenocoll 3W, 4B Plus (D3) was tested. On the contrary, when testing Protovil VP244/2C (D4), the opposite effect occurred (Fig. 2).
2. During the second test, when one-component Rhenocoll 3W, 4B Plus (D3) adhesive was subject to direct contact with water for a period of 4 days at a temperature of 20°C ± 5°C, the joint showed a lower strength within a range of 3 to 4 MPa (Figs. 3 and 4) than when tested under dry conditions during the first test (Fig. 2). Joints showed an inconsiderable rise in strength with rising glue line thickness.
3. Joints bonded using the two-component adhesive Protovil VP244/2C (D4) demonstrated rising joint strength along with rising glue line thickness.
4. During the fourth test, when two-component Protovil VP244/2C (D4) was subject to direct contact with boiling water for a period of 6 hours and was subsequently placed in water at 20°C ± 5°C for 2 hours, the joints demonstrated higher strength within a range of 11 to 13 MPa (Fig. 4) along with increasing thickness of the glue line. The high temperature probably resulted in increased cross-linking of adhesive polymer molecules and an increase in strength in joints bonded using the two-component adhesive.

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