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**Jürgen Follrich · Oliver Vay · Stefan Veigel · Ulrich Müller**

# Bond strength of end-grain joints and its dependence on surface roughness and adhesive spread

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**Abstract** The effect of different machining processes on surface roughness and on adhesive tensile strength of end-grain-bonded spruce wood specimens was studied. Surfaces that had been cut with two different circular saws containing 48 and 96 teeth were compared with those that had been further processed by smoothing with a microtome, machine planing, or sanding. Two different adhesives and two different spreading quantities were used to join the test specimens by their end-grain surfaces. Increasing tensile strength of the bonded specimens was observed with increased surface roughness, which was ascribed to an enlarged bonding area in the case of circular-sawn samples with a rough surface. On the other hand, more pronounced starving of the bond line and thus decreased bond strength was observed in the more open cells of the smoothed end-grain surfaces. A positive effect regarding tensile strength was further observed with increased spreading quantity of the adhesives. Machining was found to particularly affect early-wood tracheids, whereas surface roughness of latewood tracheids was comparable for the differently treated end-grain surfaces.

**Key words** Adhesion · Bonding · End grain · Surface roughness · Tensile strength

## Introduction

Bonding technology is one of the key technologies for producing wood-based materials such as particleboards and fiberboards, plywood, light-weight panels, and load-bearing constructions, or glulam. Bonding of wood with glue, e.g., bone or casein glue, is known to date back to the times of the Egyptian pharaohs.[1,2] In recent decades, bonding technology has been associated with great efforts to improve existing resins and to design and fabricate novel condensation resins.

Adhesive is commonly applied to bond two wooden parts oriented in parallel, which means that the joint parts contact on their radial or tangential surfaces; this form of bonding has been extensively studied. Mechanical stability of adhesive joints is typically influenced by some critical factors such as wettability of the wood surface, adhesive and cohesive strength of the bond line, and penetration of the adhesive into the wood tissue.[3,4] Penetration of a liquid adhesive into the porous structure of wood can either occur on the micro scale (penetration into cell lumina) or on the nano scale (penetration into the cell wall). Hydrodynamic flow and capillary action are the main causes for penetration[5] and are influenced by the formulation of the adhesive (molecular weight distribution or solid content), its viscosity,[6] and temperature.[7] Additionally, process parameters such as specific adhesive spread, applied pressure, and surface properties resulting from machining processes including surface cleanliness, structural damage, and surface roughness, may exhibit major effects on the resulting bonding.[8]

In terms of surface roughness, the most obvious effect is a reduction in the size of the actual surface and thus in the contact area, leading to a diminishment of the effective bond line. Gaps can occur more easily in the bond line, which may act as points of crack initiation and propagation, thereby lowering the cohesive strength of the bond line. Furthermore, rough surfaces may promote desiccation, overpenetration, or starving of the adhesive.[9,10] On the other hand, mechanical interlocking of the adhesive may be facilitated on a rough surface.

In the special case of machine processing of end-grain surfaces, latewood fibers are cut and earlywood fibers are pulled out of the earlywood tissue, and hence a rough surface is formed.[11,12] Simultaneously, by machining, a mechanically weak boundary layer is created in the form of

J. Follrich (✉) · O. Vay · S. Veigel · U. Müller
Wood K plus – Competence Centre for Wood Composites and Wood Chemistry, Peter Jordan Strasse 82, A-1190 Vienna, Austria
Tel. +43-147654-4265; Fax +43-147654-4295
e-mail: j.follrich@kplus-wood.at

U. Müller
BOKU – University of Natural Resources and Applied Life Sciences, Department of Material Sciences and Process Engineering, Institute of Wood Science and Technology, Vienna, Austria

loosely adhered cells and cell wall fragments, which can negatively influence the bond line firmness. These fragments, stemming from and adhering to the damaged surface, can act as a barrier to the adhesive penetrating into the intact wood.[13–15] In order to improve the penetration of the adhesive into the wood pores and to get a smooth surface on the macro scale, the damaged cells and cell wall fragments can be removed by a microtome[16] or by laser light.[13,14] Alternatively, an increase in the spreading quantity of the adhesive has also been shown to exhibit a positive effect, e.g., on the tensile strength of polyurethane-bonded butt end joints.[17]

In the present study, the influence of surface roughness, created by five different machining processes, as well as of the spreading quantity of two different adhesives was studied by investigating the tensile bond strength of an end-grain joint.

## Materials and methods

### Treatment of end-grain surface

Flawless spruce wood boards (*Picea abies* Karst.) with regular annual rings (average ring width 1.358 ± 0.724 mm and a ratio of 0.60:0.40 ± 0.09 of earlywood:latewood), a density of 477 ± 37 kg/m$^3$, and a moisture content of 12.9 ± 0.3% were used to fabricate the dumbbell-shaped tensile specimens as shown in Fig. 1. For the two longitudinally oriented outer layers, straight grained boards were machine-planed to a thickness of 20 mm and sawn into pieces 90 mm long and 35 mm wide. The end-grain surface of these pieces was created by using a circular saw with previously unused saw blades with 48 teeth or 96 teeth, the former yielding a rougher surface compared to the latter. The geometry of both saw blades was an alternated top bevel (ATB) tooth that is usually used for crosscutting wood in the wood industry. One side of the pieces cut with the 48-tooth circular saw was further treated by hand planing with a microtome to get a smooth and open end-grain surface for bonding. Additionally, the end-grain surface of two other cut pieces was planed with a conventional planing machine (four HSS blades, feed speed approx. 6.0 m/min) and with a sander (grit 50).

### Bonding of test specimens

Two consecutive parts from one board which underwent the same surface treatment, i.e., microtome-smoothed surface (MI), planed surface (PL), sanded surface (SA), circular-sawn fine surface ($CS_f$, 96 teeth), or circular-sawn rough surface ($CS_r$, 48 teeth), were adhesively bonded by their end-grain surfaces (Fig. 1a) with either polyvinyl acetate emulsion (PVAc, solid content 49.5%–51.5%, viscosity 7450 ± 1050 mPas) (Prefere 6415, Dynea, Norway) or phenol-resorcinol-formaldehyde (PRF) adhesive (Aerodux 185, Hardener HRP 150, Friebe, Mannheim, Germany, solid content 50%–53%). Viscosity of the PRF

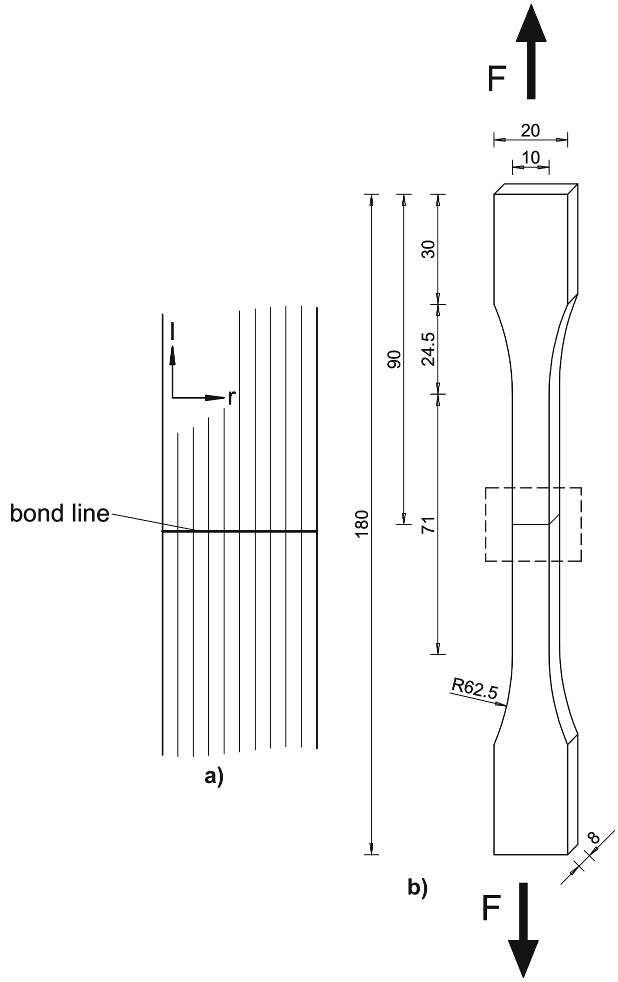



**Fig. 1.** Tensile test sample showing **a** overview of the bond line and anatomical direction of the wood and **b** geometry of the dumbbell shaped tensile sample with reduced midsection. Dimensions are in millimeters

mixture was measured with a Brookfield laboratory viscometer LVDV II+ (Brookfield, Middleboro, MA, USA) at 23°C (LV4, 30 rpm) after 15 min of mixing resin and hardener and was 8750 ± 100 mPas, which corresponds well to values found in the literature (8000–10 000 mPas[18]). The adhesive assemblies were prepared with a spreading quantity of 400 or 800 g/m$^2$ applied on both surfaces. Adhesive joints were cured at a temperature of 20°C and a pressure of 0.7 MPa following the instructions of the manufacturers for the pressing time (120 min for PVAc and 420 min for PRF). A ratio of 5:1 (w/w) of resin and hardener was chosen for PRF. The 180-mm-long cured adhesive-bonded assemblies were cut to their final shape on both sides with a circular saw resulting in a thickness of 8 mm, and the dumbbell shape of the tensile samples (Fig. 1b) was mill cut resulting in a reduced width of 10 mm in the region of the bond line. In total, 480 samples were produced, i.e., twenty-four samples for each surface treatment, type of adhesive, and spreading quantity. All samples were stored at 20°C and 65% relative humidity until equilibrium moisture content was reached.

Determination of surface roughness by three-dimensional optical surface metrology

The roughness of the variously treated surfaces was investigated with optical software 3D Infinite Focus (Alicona Imaging, Austria). This measurement technique is based on the small depth of focus variation with vertical scanning which provides topographical as well as color information.[19] The specimens were mounted on a motorized stage and were illuminated with modulated white light.

The surface roughness of each surface preparation was measured three times on five specimens ($n$ = 15) with the 3D Infinite Focus (5x magnification, field of view 1.6 × 2.1 mm and resolution of 800 nm) along a path (tangential direction) in early- and latewood in the same annual ring and across the annual ring. The average and SD of surface roughness were calculated and compared by two-way ANOVA as well as by the $t$ test for independent samples.

Mechanical testing

Tensile tests were performed on a Zwick/Roell Z020 universal testing machine equipped with a 5-kN load cell. The specimens were tested to failure at a cross-head speed of 0.5 mm/min, and tensile strength was calculated by dividing the maximum load by the cross section. For the individual groups of samples, average values and SDs were calculated and compared by two-way ANOVA.

## Results and discussion

In Fig. 2, average tensile strength values ($n = 24$) for the two different adhesives PVAc (Fig. 2a) and PRF (Fig. 2b) and the different spreading quantities are plotted against the surface treatment. In general, tensile strength was significantly influenced by the adhesive spreading quantity as well as by the different machining processes (two-way ANOVA, $P \leq 0.05$). Increasing tensile strength (2%–30%) was observed for the differently processed end-grain surfaces in the order MI < PL < SA < $CS_f$ < $CS_r$, as well as with the higher adhesive spreading quantity for the circular-sawn surfaces $CS_f$ and $CS_r$ and for microtome-smoothed surfaces (MI), whereas for the planed (PL) and the sanded (SA) surfaces, no significant influence of higher adhesive spreading quantity was observed. For MI surfaces, a strong effect of increased spreading quantity was observed for PRF-bonded samples, for which tensile strength was approximately 3.5 times higher when 800 g/m$^2$ adhesive was used compared to 400 g/m$^2$ (Fig. 2b).

Average surface roughness ($n = 15$) across an annual ring and data separated into early- and latewood of the annual ring plotted against the surface treatment is shown in Fig. 3. Surface roughness across the annual ring (Fig. 3a) was significantly influenced by the different machining processes (one-way ANOVA, $P \leq 0.05$) and increased in the order MI < PL < SA ~ $CS_f$ < $CS_r$. Furthermore, a significant difference in surface roughness was observed for early- and

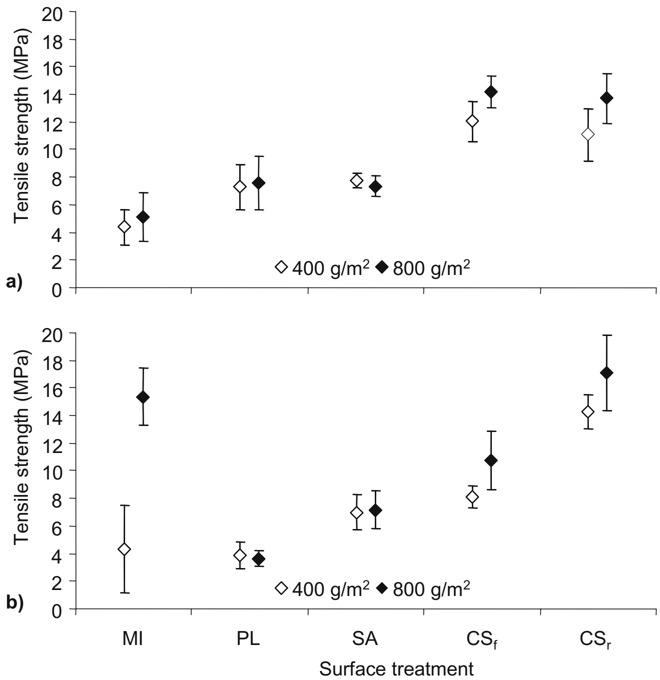



**Fig. 2.** Average tensile strength of end-grain specimens bonded with different spreading quantities of two adhesives. **a** Bonded with polyvinyl acetate emulsion (PVAc) and **b** bonded with phenol-resorcinol-formaldehyde adhesive (PRF). Twenty-four samples ($n$ = 24) were tested for each surface treatment: *MI*, microtome-smoothed surface; *PL*, planed surface; *SA*, sanded surface; $CS_f$, circular-sawn fine surface (96 teeth); and $CS_r$, circular-sawn rough surface (48 teeth). *Error bars* represent SDs

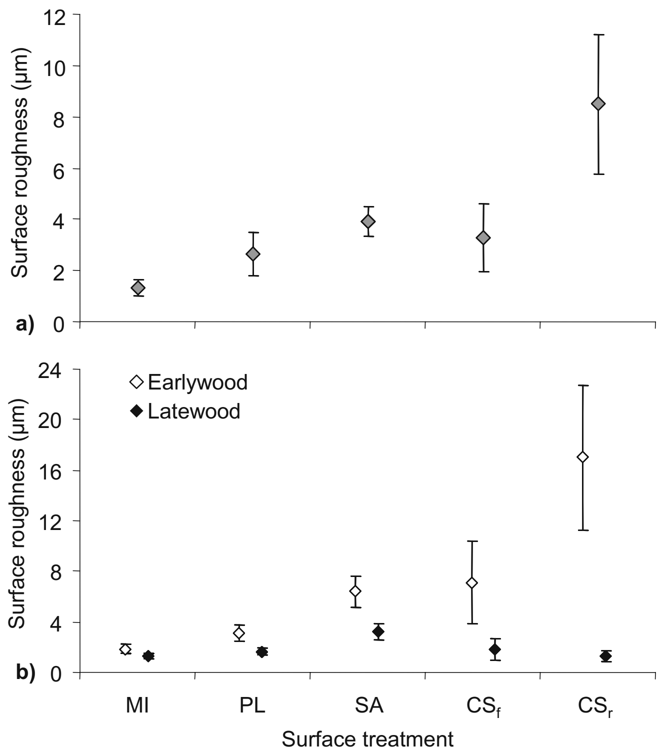



**Fig. 3.** Average surface roughness for the different mechanical treatments of end-grain surfaces: **a** across the annual ring and **b** data separated for early- and latewood. Surface roughness was measured on five specimens three times ($n$ = 15) for each surface

latewood (two-way ANOVA, $P \leq 0.05$) for all five different surfaces (Fig. 3b).

Depending on the wood species and the adhesive used, the strength of butt end joints was reported to range from 16% to 70% of that for adhesive joints parallel to the grain.[20] In general, bond line formation and the resulting quality of the adhesive bond depend on some basic factors. These include the properties of the adhesive, the wood substrate,[4,21] and process parameters.[2] For instance, effects of adhesive viscosity, surface roughness, and processing pressure on tensile shear strength of soybean protein adhesive-bonded specimens were investigated by Cheng and Sun.[22] The authors stated that the most important factor determining adhesive strength was the processing pressure and that adhesive viscosity had a greater effect than surface roughness. Concerning surface roughness resulting from machining processes, the following points should be considered: machining leads to a weak boundary layer with nonfixed or only slightly fixed cell wall fragments which compromise formation of a stable bond line since cell wall fragments that adhere to the surface act as a barrier to the adhesive penetrating into the intact wood.[13–15] On the other hand, this barrier could also help to prevent starving of the adhesive bond line. In comparison, the rough and open end-grain surface enhances penetration of adhesive into wood pores[23] and constitutes a possible source of mechanical interlocking by enlarging the bond area, which improves the tensile strength.[12] Such mechanical interlocking is most probably the explanation for our findings, which show increasing tensile strength with increasing surface roughness and highest strength values for sawn surfaces of high roughness (Fig. 4). It can be assumed that the damaged cell walls of the tracheids as well as the cell wall fragments were reinforced by the low-molecular-weight fractions of the adhesives,[13] which are able to diffuse into the cell wall where their curing leads to an increased hardness of the cell wall.[24,25] This is the case for phenol-formaldehyde (PF) or melamine-urea-formaldehyde (MUF) adhesives, for example, but is less applicable to PVAc. PVAc adhesives consist of long fibrous molecules which exhibit a reduced mobility, resulting in a lower penetration ability of PVAc compared to PRF adhesive.[26,27] In other words, while PRF is able to penetrate into cell lumina and cell walls (leading to a stiffening at the micro as well as the nano scale), PVAc can only penetrate into the lumina but not into the cell walls (stiffening effects only at the micro scale). This could explain the somewhat low bond strength observed for the roughest surface ($CS_r$) bonded with PVAc, for which a further increase in surface roughness has no beneficial effect on tensile strength. On the other hand, the lower penetration ability of PVAc results in a higher amount of this adhesive being available in the bond line, which would explain the higher bond strength of PVAc-bonded specimens with PL, SA, and $CS_f$ surfaces compared to PRF-bonded samples.

The effect of enhanced penetration into an open end-grain surface in the sense of improved mechanical interlocking was especially observed for the microtome-smoothed surface with increased spreading quantity (800 $g/m^2$) in PRF-bonded samples (Fig. 5b). The low tensile strength observed for MI samples and for the circular-sawn samples ($CS_f$, $CS_r$) bonded with a lower amount of adhesive points to a starving of the bond line, i.e., less adhesive was concentrated in the bond line, which led to insufficient bonding and/or thin bond lines (Fig. 5a). In comparison, if the amount of adhesive spread is increased, more adhesive is available for penetration into the open surface leading to the creation of a penetrated cured adhesive network that supports the firmness of the bonding by mechanical interlocking (Fig. 5b). Bröker and Korte[28] found similar results for butt end joints with thick bond lines bonded with epoxy resin. In comparison, for planed and sanded surfaces, the lumina of earlywood tracheids are possibly closed by damaged cell wall fragments as well as swarf and less adhesive could thus penetrate into the wood.

In general, by sanding, sawing, planing, or milling, machined end-grain surfaces show a deformed characteristic to a depth of up to 0.2 mm.[29] Due to the cutting process with a circular saw, earlywood tracheids are partly pulled out and defibrillated as well as crushed, whereas latewood tracheids are clearly cut off. An inverse procedure happens during the machining process with a milling or planing machine, i.e., earlywood tracheids are crushed and compressed, whereas latewood tracheids are clearly cut off. In our study, different roughness was observed across an annual ring depending on the type of processing (Fig. 3a) and between early- and latewood (Fig. 3b). The observed surface roughness of latewood tracheids resulting from the

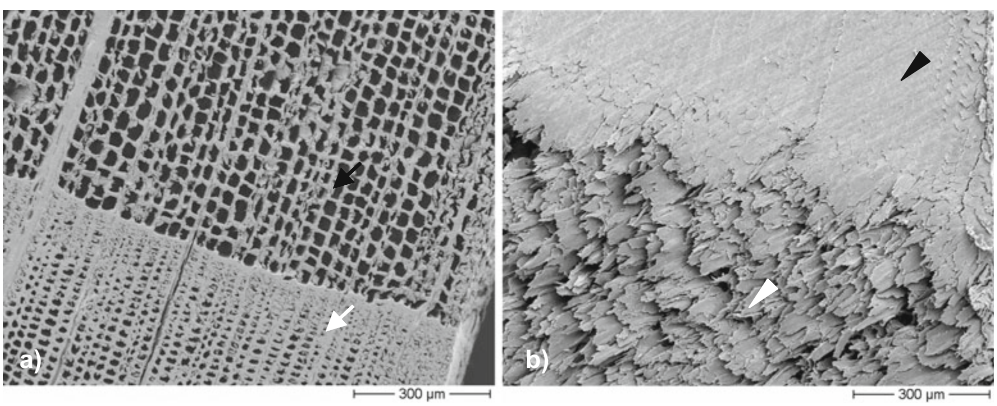



**Fig. 4.** Micrographs of the treated end-grain surfaces for **a** microtome-smoothed surface (MI) and **b** for rough surface ($CS_r$) created by a circular saw with 48 teeth. An open end-grain surface (*black arrow*, earlywood; *white arrow*, latewood) was formed by the microtome, whereas a closed (*black arrowhead*, latewood) and rough (*white arrowhead*, earlywood) surface was created by the sawing process

Fig. 5. Micrographs of bond lines of microtome-smoothed end-grain surfaces (MI) bonded with different spreading quantities of PRF: **a** 400 g/m$^2$ and **b** 800 g/m$^2$

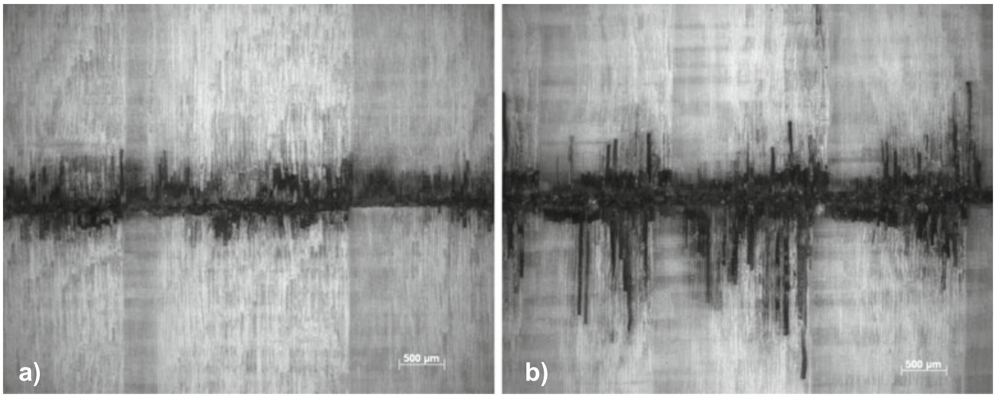
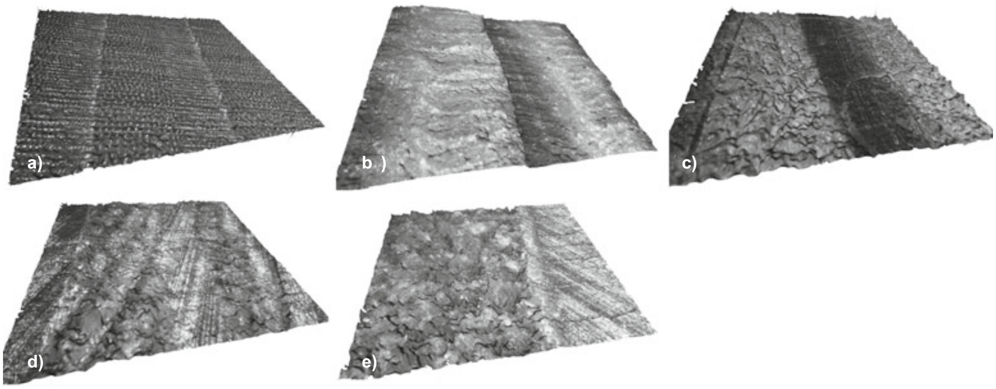



Fig. 6. Three-dimensional images of the surface roughness created by different machining processes: **a** microtome smoothed, **b** planed, **c** sanded, **d** sawn with 96 teeth, and **e** sawn with 48 teeth. In general, a higher roughness was observed for earlywood than for latewood




different machining processes was found to be in the same overall range. Only the sanded latewood tracheids exhibited a slightly higher surface roughness. In Fig. 6, surface roughness created by the different machining processes is illustrated as 3D images.

## Conclusions

It was shown that for the investigated spruce wood samples that were bonded either with PVAc or PRF adhesive after different mechanical surface treatments, the tensile strength of end-grain joints significantly increased with increasing surface roughness. Machining processes were found to especially affect earlywood tracheids, whereas surface roughness of latewood tracheids across an annual ring was widely the same for the differently treated end-grain surfaces. For both adhesives studied, highest bond strength was observed for samples with rough end-grain surfaces resulting from processing with a circular saw; this finding was attributed to the enlarged surface and hence the enlarged bonding area facilitating mechanical interlocking of the adhesive and the wood surface. For more open surfaces, resulting for instance from microtome smoothing, lower tensile strength was observed most probably due to a more pronounced starving of the bond line. Such starving, however, could partly be counteracted by increasing the spreading quantity of the adhesive, which was observed for microtome-smoothed as well as circular-sawn surfaces, whereas for planed and sanded surfaces, loosely adhering cell wall fragments probably impeded penetration of the adhesive. The differences in tensile strength found for the two adhesives were attributed to their different penetration ability resulting from their chemical structures as well as their physicochemical characteristics such as rheological properties.

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