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Bonding of birch solid wood of sawmill surface roughness with use of selected thermoplastic biopolymers

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Abstract: *Bonding of birch solid wood of sawmill surface roughness with use of selected thermoplastic biopolymers*. The aim of the research was to determine the shear strength and in-wood damage share of the birch lamellas of the surface shaped by rotary saw cutting and bonded with use of selected thermoplastic biopolymers, like polylactide (PLA) and polycaprolactone (PCL), as well as with use of polypropylene (PP) as a reference bonding material. The results show that the highest mechanical properties have been achieved in case of PLA used as a binder.

Keywords: solid wood, bonding, pla, pcl, surface roughness, shear strength

INTRODUCTION

In wood plastic composites (WPC), traditionally used thermoplastics are: polyethylene (PE), polypropylene (PP) and polyvinylchloride (PVC), which are not biodegradable. Conventional synthetic and inorganic fibers commonly used as fillers in composites, including nanocomposites, are: glass fiber, carbon fiber, carbonate ($CaCO_3$), silica, talc, calcium, kaolin and aramid. The advantage of these fibers is their high strength and stiffness (Premalal et al. 2002). However, the disadvantages include: no biodegradation, the high cost of pre-processing and no recycling option (Battegazzore et al. 2016). These fillers can be used in the form of powder and fibrous, while ensure favorable mechanical properties. Therefore, in recent years there has been growing interest in polymer composites, which are biodegradable and / or derived from lignocellulosic plants, due to this there are therefore called "biocomposites" or "green" composites (Zheng et al. 2015).

In the 21st century, it is becoming possible to obtain materials, which will have similar properties to the properties of structural material with one difference – they will come from renewable raw materials. Biopolymers obtained from agricultural raw materials, such as polyhydroxybutyrate (PHB) and poly(lactic acid) (PLA) are increasingly used as polyolefin replacements (Nagarajan et al. 2016).

Current research on the application and modification of PLA focuses on the production of partially renewable goods with a wide range of applications, that can compete with typical plastics. Unfortunately, PLA has low toughness and ductility, therefore it isn't used in durable-requiring applications (Nagarajan et al. 2016). One solution is to modify by PLA blending with various additives. Raghu et al. (2018) conducted investigations on PLA blends with thermoplastic starch (TPS) and wood fibers (WF). They stated, that the combination of TPS and PLA shows weak mechanical properties – weak adhesion between TPS and PLA, and weak properties of starch. Wood fibers in amount of 20% and 40% have been added in order to improvement of mechanical properties. A 10% maleic anhydride grafted PLA (MA-g-PLA) copolymer was used for all variants with TPS. At 20% WF and 10% MA-g-PLA, tensile strength increased by 86%, and flexural strength showed about 106% improvement over TPS / PLA blends. Increasing the content WF up to 40% additionally increased the tensile strength by 128% and bending strength by 180% in relation to the TPS / PLA blends. Other researchers tested the PLA combination - semi-crystalline PLA (PLA3052D) and amorphous PLA (PLA 4060D) with a wood surface bonding (Luedtke et al.

2019). They used beech *(Fagus sylvatica)* and maple *(Acer pseudoplatanus)* veneers with dimensions of 100x20x0.6 mm^3. The variable was press temperature (140 - 160°C) and test temperature (45, 60, 80, 100°C). For two PLA variants, with increase the pressing temperature, the viscosity of the biopolymer decrease, give rise to a better interference with the wood structure, which converts into higher mechanical properties. The lower test temperature, the bond strength is higher. The best results of mechanical parameters have been achieved for 45°C, where the PLA was still in the glassy state. The mean values of bond strength were higher for layered composites produced from beech veneers. Exactly biocomposites are considered to promising alternatives to commonly used (petro, oil-based) polymers. "Green" composites are products that can minimize the negative impact on the environment throughout their entire life cycle. Specifically, they comply with current environmental problems such as: environmental pollution, depletion of fossil resources and greenhouse gas emission (Yu et al. 2006, Bugnicourt et al. 2014). The above mentioned biopolymers have also potential to become a real replacement of conventional wood binders, as they are mostly produced from oil-based raw materials. Moreover, in the light of research of Liu et al. (2019), the wood-polymer adhesion can be supported by mechanical fixing/anchoring of these materials, which supports the connection strength. This can be improved by applying of wood with non-perfectly smooth surface, but with specific roughness.

The aim of the research was to determine the shear strength and in-wood damage share of the birch lamellas of the surface shaped by rotary saw cutting and bonded with use of selected thermoplastic biopolymers, like polylactide (PLA) and polycaprolactone (PCL), as well as with use of polypropylene (PP) as a reference bonding material.

MATERIALS AND METHODS

Bonding of the lamellas

Not less than 20 overlap samples made of air dry birch (*Betula pendula* Roth) lamellas of dimension of 110x22x7 mm^3 have been prepared for every thermoplastic polymer mentioned below: industrially pure polylactide (PLA) and polycaprolactone (PCL) in the form of 3 mm diameter drops, and polypropylene (PP) in the form of 0.25 mm thick mat as a reference material. The overlap (bonding line) nominal size was about 22x17 mm^2. The polymers have been heated to the temperature of 180°C, and, when the consistence of dense liquid able to produce the continuous threads when pulled out of the cup has been achieved, the excessive amount of polymer was applied onto the lamellas, which has been also pre-heated to above mentioned temperature to avoid the rapid cooling of the polymer. Then, the two lamellas with the polymer spread out on one lamella, have been connected and pressed with use of hand carpentry clamp to remove the surplus of polymer and cool down the bonding line to room temperature.

Shear strength testing and in-wood damage evaluation

The shear strength of the produced samples has been measured on standard universal testing machine, where the samples have been loaded by tension to be broken within 60±30 s, and the maximum load [N] has been registered. Prior to the loading, the real dimensions of the bonding line have been measured. The shear strength was calculated as a maximum load [N] referred to the bonding line area [mm^2]. After the break of the sample, every destroyed zone was analyzed if the break occur in wood structure, and the area of in-wood destruction was in organoleptic way estimated (in % of total bonding line area) with accuracy of ±10%.

Surface roughness

The surface roughness parameters have been measured with use Mitutoyo portable roughness tester SJ – 201. The following roughness parameters were measured: Ra, Ry and Rq. As many as 12 samples of dimensions 110x22 mm^2 have been used, where one measurement has been done on every wide face side of the sample. The surface of the samples has not been sanded and/or planed, but the lamellas' surface was shaped in industrial conditions (sawmill) by rotary saw blade cutting.

All the tested samples were conditioned prior to the tests in 20°C/65% RH to constant weight.

On the basis of above mentioned measurements, the average values (mean) of tested parameters, as well as standard deviation (sd) of these, have been calculated and displayed on graphs or in tables.

RESULTS

Surface roughness

The results of calculation of arithmetical mean and standard deviation of Ra, Ry and Rq of the lamellas used to test the wood bonding with use selected polymers, are displayed in table 1. When compare the achieved results of Ra parameter measurement to EN ISO 1302:2004 roughness classes, it can be found that the registered average value of Ra=13.66 μm, corresponds to 4th class of roughness, described as precise cutting processing. The achieved results of Ra are close to results of research, where the sawn, planed and sanded surface roughness of aspen and beech wood has been characterized (Kilic et al. 2006). The mentioned authors noted that Ra for sawn aspen wood is between 10.7 and 13.26 μm, for tangential and radial cross-cut, respectively, and, 11.05 and 12.77 μm for beech wood, respectively. According to another (Zhong et al. 2013), the Ra value about 8 μm is reachable for furniture plywood (wood specie unavailable), which indicates that the roughness of tested birch lamellas is significantly higher than the surface of furniture plywood. The analysis of the mean value of Ry (98.63 μm), which provide the information about maximum height of the profile, can be useful when the further surface processing is planned (like finishing or gluing). It can be commented, that the achieved result of Ry is about 25% higher that Ry value for surface of raw (unfinished) MDF panel (Kowaluk and Wronka 2018). In case of tested birch lamellas the relatively high Ry parameter should influence positively on the strength of prepared connection with use selected thermoplastic polymers, since the wood-polymer adhesion can be supported by mechanical fixing of these materials. This was confirmed when bonding poplar wood with HDPE with use chlorinated PP (Liu et al. 2019). The influence of the roughness parameters (Ra, Rz and Rmax) on the bonding strength have been confirmed for pine, oak and nyatoh wood (Hiziroglu et al. 2014). The researchers found that for oak and nyatoh the bonding strength increases with the Ra increase.

Table 1. Roughness parameters of the birch lamellas surface used in tests

Ra		Ry		Rq	
[μm]					
mean	sd	mean	sd	mean	sd
13.66	1.87	98.63	13.26	18.13	2.21

Shear strength testing and in-wood damage evaluation

The results of shear strength measurement of birch lamellas bonded with use of selected thermoplastic polymers, are presented on figure 1. The highest average value of shear strength is 5.88 N/mm^2 for birch lamellas bonded PLA, while the lowest strength value is obtained for reference samples. This investigation confirmed the possibility of obtaining interfacial adhesion between PLA and wood substrate. Considering the values of standard deviations, it can be noted that the mean values of shear strength are statistically different between each variant of the thermoplastic polymer. The spread of particular results around the average (sd) is at a similar level for all variants. Raghu *et al.*, 2018 in their investigation also confirm the possibility of bonding wood in the shape of fibers with PLA. Gaugler *et al.*, 2018, presented in their research the bonding of wood veneers: maple *(Acer pseudoplatanus)*, beech *(Fagus sylvatica)* and spruce *(Picea abies)* using PLA and PP as a binder. The shear strength values for the samples with the PLA bonding material were higher than for the polyolefin polymer, such as polypropylene (PP).

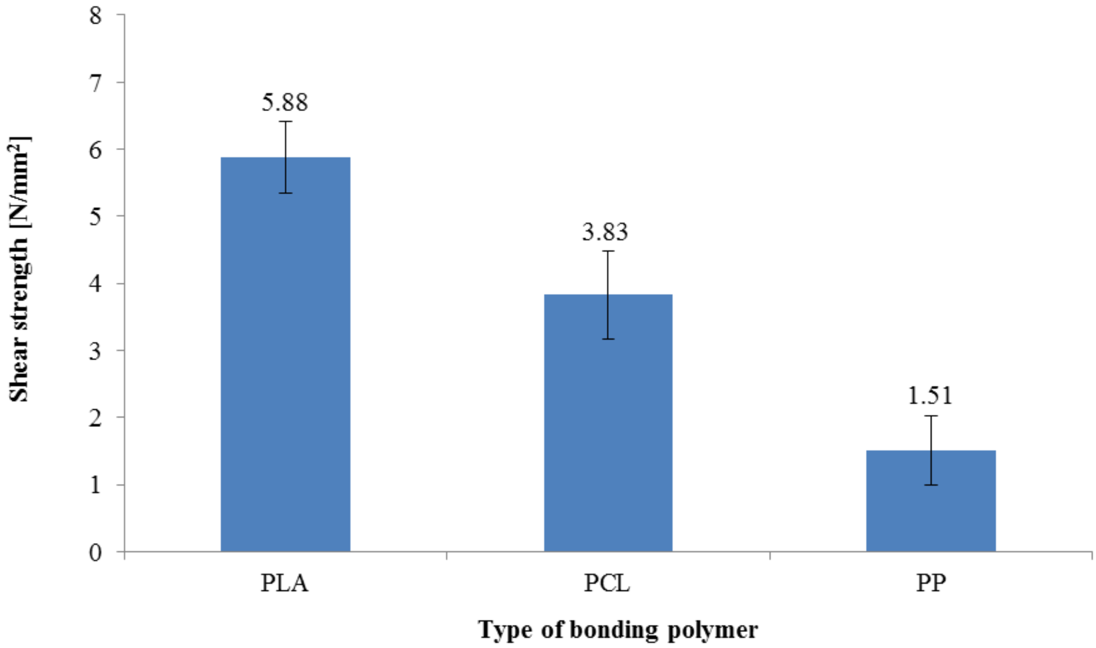

Figure 1. Shear strength of tested samples

On the figure 2 the examples of the break zone of tested samples are presented. As it is shown in the case of PLA, it cannot be concluded that the damage occurred to a large extent in the wood zone, but it should be added that it is not zero, is best illustrated on figure 2a. This means that there was interfacial adhesion between the bonding material and the wood substrate. In-wood damage evaluation results for PLA samples was 10% and for PCL and PP samples - 0%.

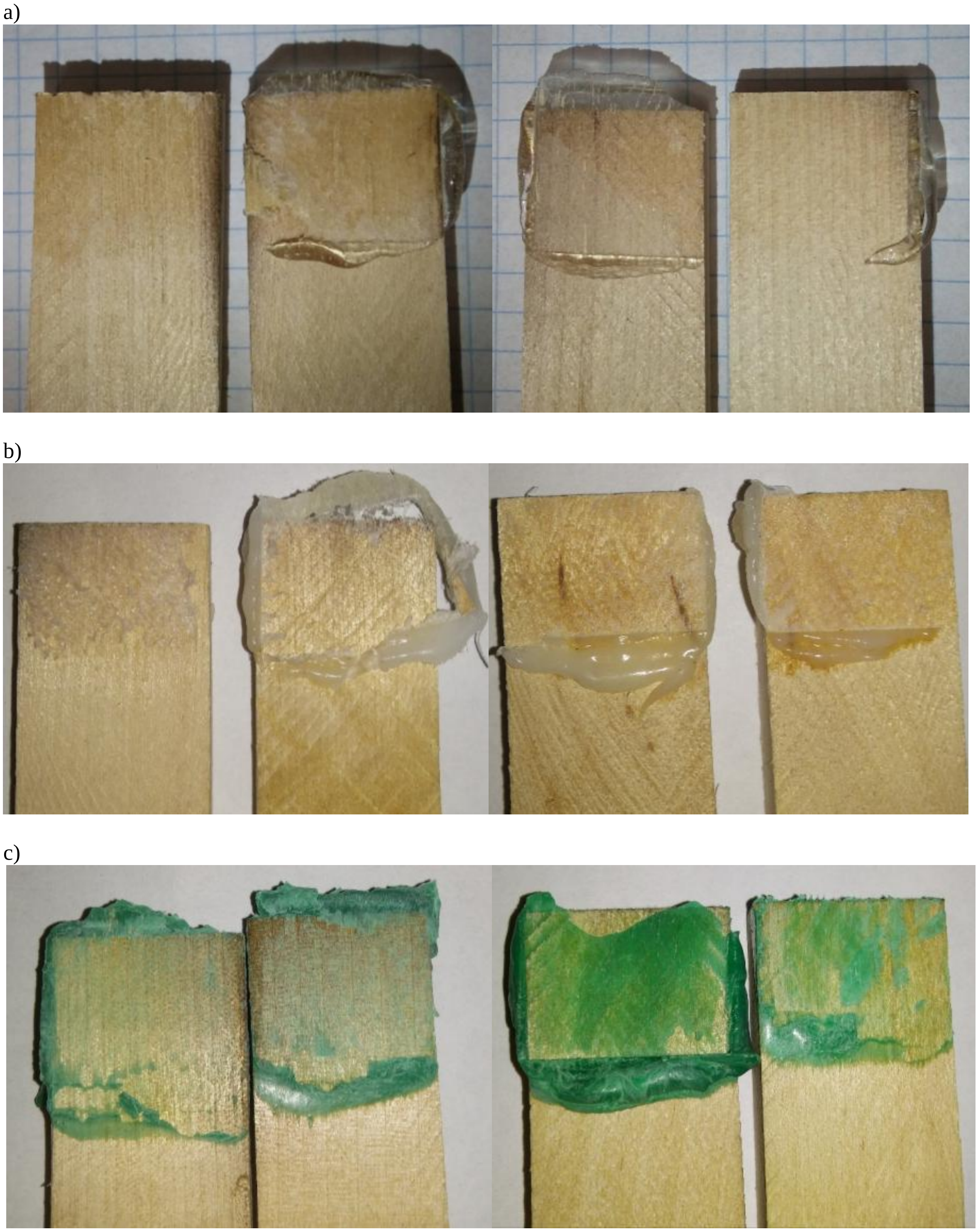

Figure 2. Examples of break zone of tested samples bonded with PLA (a), PCL (b) and PP (c)

CONCLUSIONS

According to the conducted research and the analysis of the achieved results, the following conclusions and remarks can be drawn:

1. The roughness of the birch lamellas can support the high strength of connection of wood with PLA, PLC and PP.
2. The shear strength of birch lamellas bonded with PLA is the highest, since the strength of connections achieved by PCL and PP are lower.

3. There is small in-wood damage (about 10%) in case of wood bonded with PLA.
4. There is no in-wood damage of samples bonded with use PCL and PP, what can be the reason of low bonding line strength.
5. The further research towards strength increase of wood bonded with use of biopolymers should be focused on improvement of adhesion of PLA and PCL to wood surface.

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Streszczenie: *Łączenie drewna brzozy o chropowatości drewna tartacznego z wykorzystaniem wybranych biopolimerów termoplastycznych.* Celem badań było określenie wytrzymałości na ścinanie i udziału zniszczenia w drewnie lameli brzozowych o powierzchniach ukształtowanych na pilarce tarczowej i sklejonych przy użyciu wybranych biopolimerów termoplastycznych, takich jak polilaktyd (PLA) i polikaprolakton (PCL), jak również z zastosowaniem polipropylenu (PP) jako referencyjnego materiału wiążącego. Badania wykazały najwyższą przydatność PLA do łączenia litego drewna brzozy, podczas gdy pozostałe wykorzystane w badaniach polimery dawały spoinę o niższych od wspomnianego polimeru wytrzymałości.

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