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Using Taguchi Optimization to Increase Machining Quality and Efficiency when CO_2 Laser Structuring Thermally Modified Beech Wood Veneers

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Due to the increasing demand in sustainable goods and products, wood and wood-based materials are used in a wide range of applications. For large scale cutting, marking, structuring and engraving of wood devices, lasers are applied to an increasing degree. Against this background a parameter study on thermally modified beech wood veneer was carried out to investigate the impact of process speed and laser power on CO_2 laser structuring quality. The goal was to obtain both a high aspect ratio and low surface roughness as well as an increased process efficiency. The optimal values of laser power and velocity were determined based on Taguchi optimization using the approach of highest possible aspect ratio and lowest possible surface roughness and subsequent improvement of the found parameters. It is shown that structuring the investigated veneer using the optimal values led to an increase in aspect ratio by 27.7% and a decrease in surface roughness of 12.3% with respect to the initial values before optimization was obtained. This improvement occurred after increasing the process speed by a factor of 2.82 and decreasing the laser power by a factor of 1.45. The applied optimization thus not only led to an improvement in laser machining quality, but also a reduction in required laser power and process duration. These data prove the high potential of the Taguchi method for increasing both the quality and efficiency of laser-based wood processing.

Keywords: CO_2 laser, beech wood, Fagus sylvatica L., laser structuring, veneers, laser beam-wood interactions, optimization, Taguchi

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1 INTRODUCTION

Due to its renewability, biodegradability and sustainable accessibility, wood and wood-based materials are essential substances in a large number of different application fields such as furniture construction, architecture, and vehicle construction. This is mainly driven by its impressive mechanical properties such as high stability and comparatively low weight. It is thus an appropriate alternative to plastics in various applications [1-3]. Against this backdrop extensive research is being carried out on different wood materials, covering a wide range of aspects such as chemical composition, influence of external factors, improvement of adhesion, and interaction with laser radiation.

Because of the inhomogeneous nature of wood, its comprehensive characterisation is a complex task, making it difficult to generalize its properties. Variations in wood properties can be attributed to a number of different factors such as the particular tree species, systemic or random material inhomogeneity such as growth rings (early wood/late wood), branch wood or compressed wood areas, the grain orientation, and the moisture content. Consequently, these factors lead to noticeable differences in the mechanical and optical properties of wood, including its strength and absorption properties [4-6].

For the manufacturing process of wood products, several methods of wood processing have been established. Since the invention of the laser, laser processing has been proven to be a superior manufacturing process to mechanical processing methods as seen in sawing and sanding. Thanks to the high degree of precision, the non-contact processing, and the control of intensity of the incident laser beam, the processing of wood can be freely controlled. Through focussing the laser beam, high intensities can be achieved by reducing the beam diameter – an advantage, which is not achievable by conventional methods [7, 8].

An essential aspect for realising a repeatable machinability of wood by lasers is understanding and predicting the interaction between optical radiation and wood. Thus, extensive research is being carried out on wood bulk material to investigate the interaction between lasers and the material. In this study, investigations were performed on thin veneers. The low material thickness of just a few millimetres poses a challenge for laser-induced structuring without cutting through the material. The present work thus strives to investigate the structural behaviour on veneer surfaces by laser radiation where the final goal and thus technical application, could be the gluing of wood veneers to substrates. Here, the adhesion of glues can be enhanced by creating surface structures that increase the effective surface area, which can be covered by adhesives. Therefore, the aim of this work is to identify suitable parameters to produce accurate structures with a high aspect ratio and low surface roughness without cutting through the material. For this purpose, a systematic parameter study was carried out and an established optimization algorithm was applied in order to identify the optimum laser parameter settings for improved laser structuring performance.

2 BASIC CONSIDERATION OF LASER BEAM-WOOD INTERACTIONS

Wood consists of three main components: lignin, cellulose and hemicelluloses [4,9]. The composition and content of these can vary not only from species to species but also depending on growing conditions. [5, 10]. These differences in composition and the naturally occurring inhomogeneities within the same species can have a significant influence on the general behavior and especially on the thermal and optical parameters.

Several studies have been carried out to investigate the thermal processing of wood using lasers [4, 5, 9, 11]. A recent study by Gusts *et al.* [5] investigated the effect of different laser parameters on the dimensions of laser-induced structures. They discovered a dependence of the depth of the structures on the laser power. In the study a laser cutting process was used on beech plywood and pine wood samples with a thickness of 3 mm. The laser cutting process was started at a laser power of 35 W and a feed rate of 50 mm/s. The results showed a significant difference in the depth of the structures depending on the particular wood and wood-based material. Specifically, an engraving effect was observed in natural pinewood, whereas clear cutting was observed in beech plywood composed of several glued veneers when applying the same laser parameters. These differences were attributed to the different mechanical and chemical properties of each material.

Barcikowski *et al.* [4] conducted a study to characterize the heat affected zone (HAZ) during laser material processing of wood using a CO_2 laser. The HAZ was found to depend not only on the material but also on the age of the wood. The thermally-induced modification was analysed on the basis of lignin and its derivatives. Lignin derivatives were defined as the reduction of lignin in the wood before and after processing, which is a clearly measurable quantity due to the fact that the surface of the wood is predominantly composed of lignin [10, 12, 13]. Their study concluded that, in addition to a dependence on annual rings, grain orientation has a significant influence on thermal behaviour since it influences heat conduction and the temperature distribution during processing. The results showed that when the cutting direction aligns with the grain direction, the temperature is increased at a greater cutting depth. This is attributed to the higher thermal conductivity along the grain direction, resulting in a higher energy input. It was also observed that the width of the cut varied depending on the age of the wood, ranging from early to late wood. In addition, the chemical structure and ultraviolet (UV) absorption of the tracheids, which are responsible for water conduction and mechanical support in wood, underwent changes as a result of the thermal treatment.

Kacik and Kubovsky [11] have investigated the effect of CO_2 laser radiation on the chemical structure of beech wood and subsequent changes in UV absorption properties of the wood. The study shows that the electromagnetic radiation from the laser caused the degradation of lignin, hemicellulose and extractives in the wood, resulting in the formation of chromophoric groups that contribute to wood discolouration. In another study, Haller *et al.* [9] have investigated the influence of laser radiation on the morphology of wood surfaces. The experiments were performed at a wavelength of 308 nm and 10.6 μm. These wavelengths were chosen since in the UV and far infrared (FIR) wavelength range, beech and pine wood exhibit comparatively high absorption, i.e. higher than 80% [14]. CO_2 lasers established themselves as a standard laser source by their emission wavelength of 10.6 μm for wood processing.

3 EXPERIMENTAL DETAILS

3.1 Sample material

Laser engraving experiments were carried out on thermally modified beech wood veneers. This wood species, scientifically known as *Fagus sylvatica L.*, was chosen because it is an abundant species in European mid-latitudes and is mainly used for construction and furniture [15]. Thermally modified beech wood veneer was produced by heating natural beech wood in a preheated oven at 200°C for 24 hours. This type of wood is chemically characterised mainly by the loss of hemicelluloses [16]. Prior to the experiments, the samples were stored for 24 hours at 20°C and 65% relative humidity (RH), resulting in an equilibrium moisture content of 7.7% [17]. The thickness of the veneers was 1.2 mm.

3.2 Laser structuring and sample analysis procedures

The laser structuring was performed using a continuous wave (CW) CO_2 laser (Lasermax Maxi 9060; Henrik Winter Holztechnik GmbH) emitting a Gaussian beam with an emission wavelength, λ, of 10.6 μm, a maximum output power of 100 W and a focus diameter, $2w_o$ of 100 μm. This laser is embedded in an arrangement with a motorized *xy*-linear stage. The maximum cutting velocity of this setup is 36 m/min and its maximum engraving velocity amounts to 72 m/min.

In order to avoid accidental intersection of this thin material, laser engraving was carried out perpendicularly to the grain direction. This resulted in a lower laser energy input and cutting depth, respectively, as suggested by [4]. For engraving grooves in the investigated wood veneer surfaces, the laser power and process speed and thus the applied energy *per* unit length were varied. The applied power range as adjusted via the laser's control panel was 20 to 40 W, varied in steps of 5 W, and the process speed range was 50 to 500 mm/s, varied in steps of 50 mm/s.

After laser structuring the quality parameters of interest, the aspect ratio of the grooves and the square arithmetic mean roughness of the surface S_A, were evaluated and measured *via* light microscopy using a digital three-dimensional (3-D) microscope (VHX-6000; Keyence Corporation).

3.3 Optimization procedure

Based on the measured data, the well-established optimization procedure developed by Taguchi and Konishi was applied in order to identify the optimum machining settings for the investigated types of beech veneer. This algorithm (the Taguchi method) allows for the determination of the effect of influencing parameters on any process by introducing orthogonal arrays [15, 18]. It aims to reduce the scatter around the target value and thus to increase the robustness of the considered process. The mathematical approach is to calculate the signal-to-noise (S/N) ratio as a statistical measure of performance to analyse the results [15]. This approach has already been used successfully in the past for improving laser-based materials processing techniques such as cutting [19], engraving [20, 21], and welding [22]. In contrast to the above works, very thin veneers were investigated. With a thickness of 1.2 mm, it will be a challenge to determine the appropiate laser parameters for structuring without cutting through the veneers. This thickness is quite close to the Rayleigh length, z_R, of the used laser of 740 μm.

For analyzing an ideal system or process, the existing noise (e.g. energy dissipation, friction, vibration etc.) must be minimised. There are several approaches for calculating the S/N ratio, depending on the desired results: Smaller the better (STB) aims for values that need to be as small as possible, such as noise in engines, toxic residues in drugs, or defects in manufacturing processes. Larger the better (LTB) aims for the opposite; that is, for maximum values of parameters of interest such as the hardness of coatings or the bond strength of adhesives. Nominal the better (NTB) is a special case, which aims at a mean value of 0 in cases of scattering of numerical values.

In the present case, two approaches were taken into account for the laser structuring of beech wood veneers by controlling two parameters of interest. The goal was to achieve the lowest possible surface roughness, while still having a high aspect ratio which implies a high depth and a minimal width; therefore, the STB value for surface roughness and the LTB value for aspect ratio were calculated as shown schematically in Figure 1. For this purpose, equations derived from the Taguchi analysis

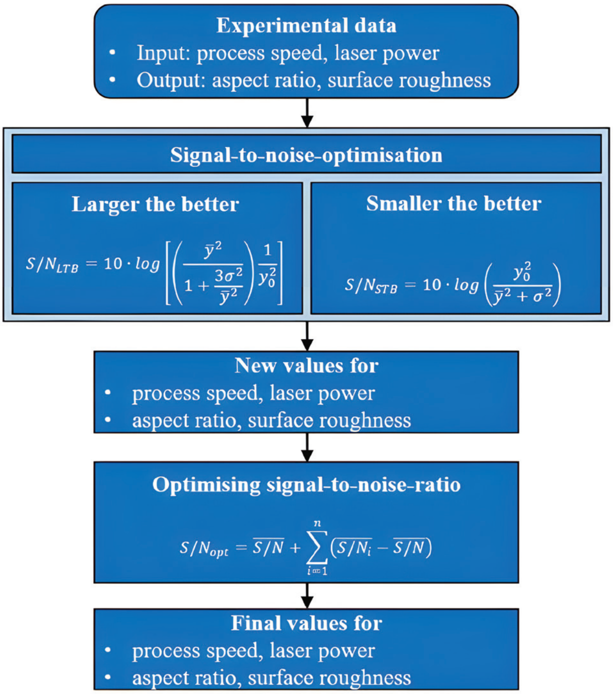

FIGURE 1
Flow chart of the approach used for optimizing the input values (laser parameters of process speed and laser power) and the resulting output values (aspect ratio and surface roughness).

approach to calculate the given values are in hand [15]. The equation for STB, S/N_{STB}, is defined as

$$S/N_{STB} = 10 \cdot log\left(\frac{y_0^2}{\bar{y}^2+\sigma^2}\right) \tag{1}$$

where σ is the standard deviation and $\bar{y}$ is the mean value of the target parameter. The corresponding unit of measurement is defined as y_0^2 with a numerical value of 1. The S/N ratio is given in decibels. The LTB, S/N_{LTB}, is calculated according to

$$S/N_{LTB} = 10 \cdot log\left[\left(\frac{\bar{y}^2}{1+\frac{3\sigma^2}{\bar{y}^2}}\right)\frac{1}{y_0^2}\right] \tag{2}$$

These equations were used in the course of the present investigations to determine the S/N ratios for the surface roughness according to Equation (1) and the aspect ratio according to Equation (2). The goal was to allow a better understanding of the influence of the different laser parameters, and to identify and select suitable parameters for the optimization of the machining results. Once the optimal S/N_{STB} and S/N_{LTB} values were determined, further optimization of the process parameters was carried out as suggested by Yung *et al.* [15] and Fidan *et al.* [23]. For this purpose, the theoretically optimal S/N value, S/N_{opt}, was calculated by

$$S/N_{opt} = \overline{S/N} + \sum_{i=1}^{n} \left(\overline{S/N_i} - \overline{S/N} \right) \tag{3}$$

It thus follows from the total mean value of the S/N ratios, $\overline{S/N}$, and the individual mean values of the S/N ratios, $\overline{S/N_\iota}$.

4 RESULTS AND DISCUSSION

The highest S/N_{STB} value of surface roughness was achieved at a process speed of 300 mm/s and a laser power of 35 W, as can be seen in Figure 2. In

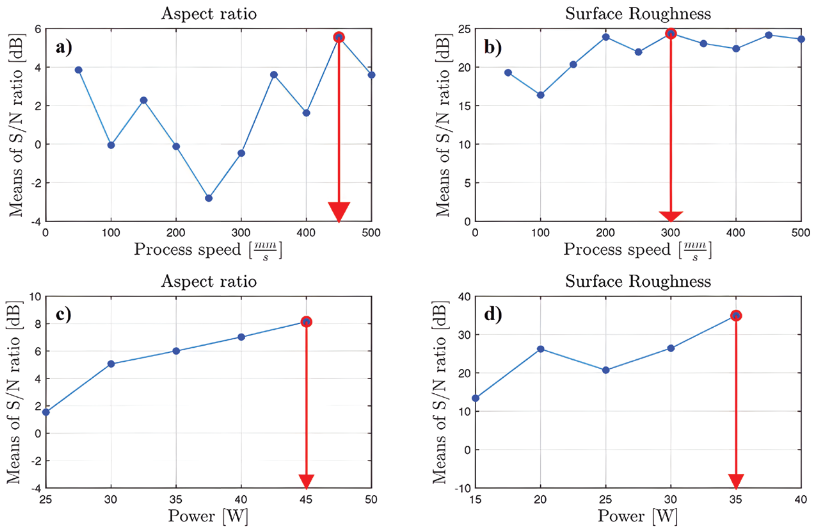

FIGURE 2
Graphs showing mean *S/N* values determined for thermally modified beech wood veneer indicating the theoretically optimum speed for (a) maximum aspect ratio, (b)minimum surface roughness, (c) optimum power value for maximum aspect ratio and (d) minimum surface roughness. The red arrows indicate the particular optimal laser process parameters.

contrast, the best S/N_{LTB} value, was obtained at a process speed of 450 mm/s and a laser power of 45 W. Therefore, the given experimental results show that the optimal parameters for laser structuring of thermally modified beech wood considering the two quality parameters of interest are (300 mm/s + 450 mm/s)/2=375 mm/s for the process speed, $v_{process}$, and (35 W + 45 W)/2=40 W for the laser power, P_{laser}.

Starting with an initial *S/N* value of 5.554 dB for the aspect ratio, an optimal value S/N_{opt} of 20.931 dB was calculated. This corresponds to quite a notable increase in *S/N* value by more than 14 dB or a factor of 3.77, respectively. For surface roughness, the *S/N* ratio was increased by about 10 dB, corresponding to a factor of 1.40. Here, the starting and end values before and after optimization were 24.366 and 34.023 dB, respectively. These increases clearly indicate a theoretical improvement of the relevant values due to a decrease in noise. Applying the particular values for S/N_{opt}, optimized process parameters were thus determined as listed in Table 1. It turns out that by such optimization, the process speed was drastically increased by a factor of 2.82, whereas the laser power was notably reduced by a factor of 1.45. Further samples were cut with these new process parameters, and the quality parameters of interest were measured. As shown in Figure 3, the aspect ratio was increased by a factor of 1.28, from 1.77 to 2.26, whereas the surface roughness was reduced. This result prooves an

TABLE 1
Optimized laser structuring parameters for machining the thermally modified beech wood veneer.

Parameter	Process Speed (mm/s)	Laser Power (W)
S/N	375	40
S/N_{opt}	1057.4	27.5

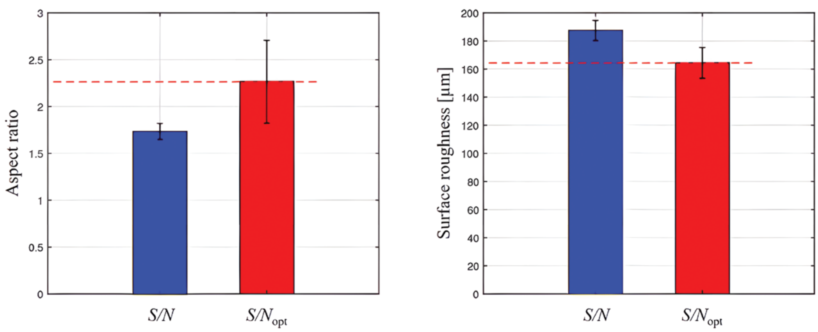

FIGURE 3
Bar charts showing aspect ratio (left) and surface roughness (right) of laser structured lines machined into the thermally modified beech wood veneer before and after optimization.

actual enhancement of the laser structuring process in terms of surface structure geometry by applying the theoretically determined optimized laser parameters.

Concerning surface roughness, a mean reduction by a factor of 1.12, from 187.36 to 164.36 µm, was obtained by applying the optimized laser parameters. Even though the observed changes feature weak statistical significance due to the inhomogeneous nature of wood, and its partially unpredictable laser-matter interaction behaviour, a clear trend can be observed since the error bars feature marginal intersection. It can thus be stated that a higher machining quality due to an optimization of the laser process parameters was achieved. This effect is also visualised by the comparison of the cross-sections of laser structured lines shown in Figure 4. Prior to optimization, a larger width and lower depth compared to the structure after optimization is observed, highlighting the increase in aspect ratio. The 3-D plots qualitatively confirm the reduction in surface roughness of the laser cut surfaces. This reduction is also shown by the qualitative comparison of the cross sections measured at the bottom of laser structured lines along the laser path direction in Figure 5. As indicated by the difference, Δ, in the peak-to-valley (PV) value of the surface profile and considering the appear-

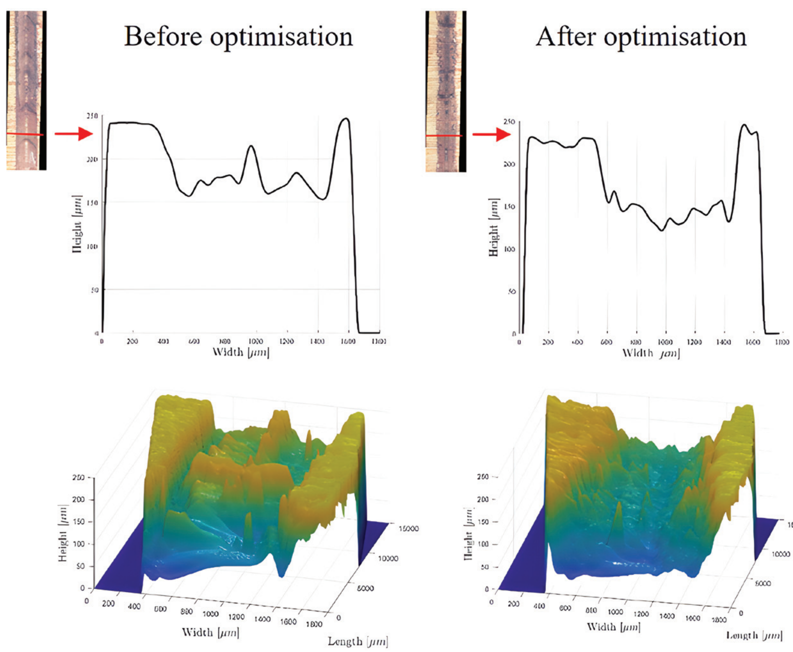

FIGURE 4
Cross-sectional laser structured line profiles and inserts showing plan view orthogonal to the direction of laser structuring (top) and 3-D plots (bottom) before (left) and after (right) optimization.

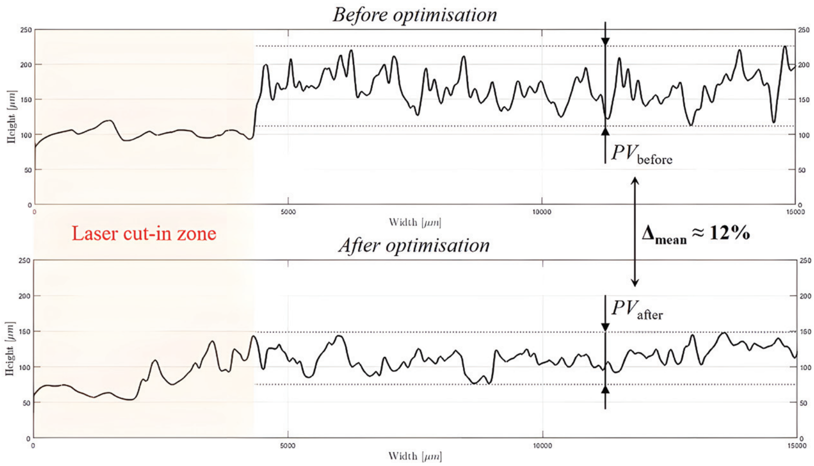

FIGURE 5
Surface profile cross-sections along the direction of laser structured lines before (top) and after (bottom) optimization.

ance shown in Figure 4 it turns out that roughness is reduced both; orthogonally and along the laser path direction in all cases, the laser structuring was performed perpendicularly to the wood's grain direction in order to foreclose a potential falsification of the machining results by differences in grain orientation. This approach reduces the penetration depth of laser-induced heat [4].

This aspect is of particular relevance for the observed improvements of the machining results that can preferentially be explained by the reduction in heat input, and thus the prevention of heat-induced disturbing effects such as stress in the wood material. As a result of the optimization, the energy *per* unit length, $E(P,v)$, provided by the laser beam was significantly reduced. This value can be calculated based on the laser power, P, and the process speed, v, according to

$$E(P,v)=\frac{P}{v} \tag{4}$$

For the initially determined laser parameters listed in Table 1, $E(P,v)$ amounts to 106.7 J m^{-1} whereas after optimization, it is reduced to a value of merely 26 J m^{-1}, meaning, the thermal impact on the wood veneer surface was reduced by a factor of 4.1. Such reduction of thermal load and heat-induced damage likely respectively, most probably explains the observed differences or improvements in laser machining quality and the reduction in surface roughness. This also confirms the work by Tiryaki *et al.* [24] who applied

Taguchi optimization for reducing the surface roughness during laser machining of wood. The results obtained in this contribution are in good accordance with work of several other authors who investigated the suitability of the Taguchi method for the optimization of laser matching of wood [21, 25, 26] or wood-based materials [26].

5 CONCLUSIONS

Using Taguchi analysis, a parameter study on thermally modified beech wood veneer was carried out to investigate the impact of process speed and laser power on CO_2 laser structuring quality where the goal was to obtain both a high aspect ratio and low surface roughness, as well as an increased process efficiency.

The results of the Taguchi analysis indicate that higher process speeds and lower power levels are required to achieve low surface roughness and high aspect ratios. The final process parameters for thermally modified beech wood veneer are obtained after an optimization process with a process speed of 1057.38 mm/s and a laser power of 27.5 W, which results in a mentionable increase in aspect ratio and a decrease in surface roughness. A significant reduction in the time requirement and energy consumption was realised from process speed reduction by a factor of 2.82, significantly shortening the machining time. At the same time, the laser power was decreased by a factor of 1.45. Such possible savings were also identified for non-thermally modified (untreated beech wood veneer) in comparative studies. Allthough, no significant improvement of<3% of the quality parameters of interest was obtained in this case, the process speed was reduced by a factor of 3.10 and the required laser power could be decreased by a factor of 1.11 by applying the Taguchi optimization procedure.

Such saving of time and laser energy, combined with an enhanced machining quality in the case of thermally modified beech wood veneer is of potential interest for large scale industrial laser structuring of wood and wood-based materials. For instance, the intended application of improved gluing of veneers to substrates, could benefit from these findings. The approach used in this work could easily be adapted to the optimization of any other quality parameter of interest.

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