Saadettin Murat Onat¹, Serkan Özdemir²

Optimization of Production Parameters of Densified Laminated Veneer Lumber Produced by Using Urea-Formaldehyde Resin

Optimizacija parametara proizvodnje ugušćene lamelirane furnirske građe proizvedene upotrebom urea-formaldehidne smole

ABSTRACT • This research aims to optimize densified laminated veneer lumber production parameters of compression ratio, press temperature, press time, and adhesive spread rate to maximize their mechanical properties. In the manufacturing process of densified laminated veneer lumber, I-77/51 American poplar clone (Populus deltoides) veneers and urea formaldehyde adhesive are used. The results showed that the compression rate and press time had the most significant impact on the mechanical properties of densified laminated veneer lumber. The optimal production conditions were determined as follows: 38 % compression, press temperature of 170 °C, press time of (10±3) minutes, and spread rate of 150 g/m². Modulus of rupture, modulus of elasticity, tensile shear strength, and tensile strength perpendicular to panels surface of densified laminated veneer lumbers produced under these conditions increased by 49 %, 8 %, 71 %, and 23 %, respectively, compared to the control group of laminated veneer lumber. So, it can be said that the production parameters of densified laminated veneer lumbers can be optimized safely and effectively using Taguchi method-based grey relational analysis.

KEYWORDS: densification, laminated veneer lumber, urea formaldehyde, processing parameters, Taguchi method based grey relational analysis

SAŽETAK • Cilj ovog istraživanja bilo je optimiziranje parametara proizvodnje ugušćene lamelirane furnirske građe: stupnja ugušćenja, temperature prešanja, vremena prešanja i količine nanosa ljepila kako bi se povećala mehanička svojstva lamelirane furnirske građe. U procesu proizvodnje lamelirane furnirske građe upotrijebljeni su furniri drva klona američke topole I-77/51 (Populus deltoides) i urea-formaldehidno ljepilo. Rezultati su pokazali da su stupanj ugušćenja i vrijeme prešanja imali najveći utjecaj na mehanička svojstva ugušćene lamelirane furnirske građe. Uvrđeni su ovi optimalni uvjeti: stupanj ugušćenja 38 %, temperatura prešanja 170 °C, vrijeme prešanja 10±3 min i količina nanosa ljepila 150 g/m². Modul loma, modul elastičnosti, smična čvrstoća i vlačna
čvrstoća okomito na površinu ploče ugušćene lamelirane furnirske građe proizvedene uz navedene uvjete povećali su se za 49 %, 8 %, 71 % odnosno za 23 % u usporedbi s kontrolnom skupinom lamelirane furnirske građe. Dakle, može se reći da se parametri proizvodnje ugušćene lamelirane furnirske građe mogu sigurno i učinkovito optimizirati uz pomoć sive relacijske analize utemeljene na Taguchijevoj metodi.

**KLJUČNE RIJEČI:** ugušćivanje, lamelirana furnirska građa, urea-formaldehid, parametri procesa, siva relacijska analiza utemeljena na Taguchijevoj metodi

**1 INTRODUCTION**

1. **UVOD**

The mechanical properties of wood, such as strength, hardness, and abrasion, can be improved by densification due to the compression perpendicular to grain under high temperature and pressure (Haller and Wechsener, 2004; Kollmann et al., 1975; Seborg et al., 1956; Ülker and Burdurlu, 2016). Thus, it is possible to use the wood of fast-growing species with low density and low mechanical properties as structural material instead of high-value wood (Kutnar and Sernek, 2007). Wood surface roughness is also reduced by densification, which provides lower press time, press pressure, press temperature, and less glue, especially in the production of laminated materials such as plywood and laminated veneer lumber (LVL) (Bekhta and Marutzky, 2007; Bekhta et al., 2012; Bekhta and Salca, 2018; Bekhta et al., 2018; Fang et al., 2012; Ugovšek et al., 2013; Ülker and Burdurlu, 2016).

In the literature, there are many studies on the production of laminated materials such as plywood and LVL from pre-densified veneer (Bekhta and Marutzky, 2007; Bekhta et al., 2012; Bekhta and Salca, 2018; Bekhta et al., 2018; Ugovšek et al., 2013; Ülker and Burdurlu, 2016). However, the densification of veneer as a separate step before lamination increases production time and cost.

Both densification and lamination require high press temperature and pressure. So, the production of laminated material by combining the densification and lamination in the same step may provide significant cost advantages. However, the vapor pressure, caused by the water in the adhesive, and wood moisture create the risk of blistering and blowing. A higher temperature (more than 100 °C) and pressure, which are needed for softening of wood, increase these risks even more (Wang and Dai, 2005). In contrast, spring-back and dimensional stability improve with increasing condensation temperature and time (Fang et al., 2012; Kádela et al., 2018). Therefore, it is necessary to apply the press pressure, press temperature, press time, and adhesive spread rate (SR) more carefully, if densification and lamination are used in the same step.

The Taguchi method is a powerful analysis method that reduces the number of experiments using orthogonal arrays to optimize production parameters. Several studies have used the Taguchi method to optimize the parameters such as press pressure, temperature, time, and adhesive amount in the production of composite materials. (Alade et al., 2022a; Alade et al., 2022b; Buddi et al., 2018; Hamzaçebi, 2016; Shafie and Zarea-Hosseinabadi, 2019).

Taguchi method allows for determining the effect of production parameters and optimizing them on a single product feature. However, it is often insufficient to evaluate the quality of a product by adhering to a single feature. In such cases, multi-response optimization techniques are used. In several studies, the Taguchi method and grey relational analysis (GRA) were successfully used together to determine the optimal production conditions for multiple quality features (Gupta et al., 2019; Kavimani et al., 2022; Khan et al., 2021; Kopparthi et al., 2021; Onyekwere et al., 2021; Velmurugan and Babu, 2020).

In this study, the effects of compression ratio, press temperature, press time, and adhesive spread rate on the mechanical properties of densified laminated veneer lumber (dLVL) were investigated. In this context, the parameter levels were determined using Taguchi-based GRA to maximize the modulus of rupture (MOR), modulus of elasticity (MOE), tensile shear strength (TSS), and tensile strength perpendicular to panel surface (TSPS) of dLVL.

**2 MATERIALS AND METHODS**

2. **MATERIJALI I METODE**

The veneers to produce dLVLs were peeled from I-77/51 American poplar clone (Populus deltoides) logged at an altitude of 250 m in Düzce, Turkey. American poplar wood was chosen as wood of low value with lower mechanical properties (Candan et al., 2013) and with great potential of improvement by densification. The veneers were peeled in thicknesses of 1.8, 2.1, and 2.4 mm to produce dLVLs and 1.2 mm to produce LVLs for the control group. They were cut in dimensions 55 cm × 30 cm, conditioned at (20±3) °C and (65±1) % relative humidity until they reached a constant weight. Their equilibrium moisture content reached approximately 13 % before the production of panels. A commercial urea-formaldehyde (UF) adhesive (Poliuire 2265, Polisan Kimya San. A.Ş., Kocaeli, Turkey) was used in the production of dLVLs. 10 % by weight hard-
ener (10 % NH₄Cl/water solution) and 20 % wheat flour by weight were added to prepare UF adhesive solution.

Equilibrium moisture content and air-dry density (\(d\)) were measured according to standards TS EN 322 (1999) and TS EN 323 (1999), respectively. The spring-back ratios (\(SB\)) of the produced test panels were calculated according to Eq. 1, respectively:

\[ SB = \frac{t_{dLVL} - t_{ms}}{t_{ms}} \times 100 \]  

Where \(t_{dLVL}\) is the thickness of dLVL panels in air-dry condition, \(t_{ms}\) is the thickness of panels compressed state, i.e., of a mechanical stop.

\(MOR\) and \(MOE\) were determined according to TS EN 310 (1999), while \(TSS\) was determined according to TS EN 314-1 (1998) standard. For each experimental group, five samples were tested. The universal test machine with 50 kN capacity (UTEST 7012) was used to determine these mechanical properties of dLVLs.

### 2.1 Experimental design

#### 2.1. Postavke eksperimenta

Parameter design is the first step of the Taguchi method. Here, the parameters that affect product quality and their levels are determined. As a result of the literature review and preliminary experiments, four production parameters, compression rate (\(CR\)), press temperature (\(PT\)), press time (\(Pt\)), and spread rate of adhesive (\(SR\)), and three levels of each suitable to L9 Taguchi orthogonal array were determined (Table 2). Parameter levels are determined by the low-normal-high principles. In addition, to compare the dLVLs, control group (non-densified) LVL panels were produced in conditions shown in Table 1.

### 2.2 Production of dLVLs

#### 2.2. Proizvodnja ugušćene lamelirane drvne grade

The UF adhesive was applied to one side of the veneers of various thicknesses (1.8, 2.1 and 2.4 mm) to create nine layers of dLVL drafts with 16.2, 18.9, and 21.6 mm thicknesses, respectively. In the same way, 10.8 mm thick control group LVL drafts were created from 1.2 mm thick veneers. There are four main stages in the dLVL pressing process, as shown in Figure 1. Initially, the prepared drafts were cold-pressed under 0.8 N/mm² pressure for 1 minute. Subsequently, the panels were placed in the laboratory hot press with a capacity of 180 tons (Cemil Usta SSP 180 T) and pressed under a pressure of 0.8 N/mm² for 10 minutes to reach the desired temperature of all veneer sheets. In the compression stage, the press pressure was increased.
to 4 N/mm² and the panels were brought to 10 mm. To ensure that all panels produced are of the same thickness, 10mm thick mechanical stops made of stainless steel were used. Thus, dLVLs were compressed at the rates of 38 %, 47 %, and 54 %. The compression step was not applied in the production of the control group LVL. The production parameters of the different experimental groups are presented in Table 2.

2.3 Single and multi-response optimization

In this study, single responses are optimized by the Taguchi method, in which the functions called signal-to-noise ratio (S/N) are used and expressed in decibels (dB). The S/N for the SB was calculated according to the “smaller is better” principle using Eq. 2. In contrast, density, modulus of rupture (MOR), modulus of elasticity (MOE), tensile shear strength (TSS), and tensile strength perpendicular to panels surface (TSPS) were calculated according to the “larger is better” principle using Eq. 3, where $S/N$ was calculated according to the “larger is better” principle using Eq. 3, where $\Delta_{\text{min}}$ and $\Delta_{\text{max}}$ are the minimum and maximum value of absolute difference between $P(k)$ and $P_{\text{max}}(k)$ and $P_{\text{min}}(k)$ are the minimum and maximum value of absolute difference between $P_{\text{max}}(k)$ and $P(k)$. $\xi$ is the distinguishing coefficient and commonly assumed to be 0.5 (Kavimani et al., 2022; Kopparthi et al., 2021; Onyekwere et al., 2021; Velmurugan and Babu, 2020).

$$\Delta_{\text{max}}(k) + \xi \Delta_{\text{min}}(k)$$

In the fourth step, the grey relational degree (GRD) was calculated by summing the weighted grey relational coefficients (Eq. 6) and ranked as the largest best. In this study, equal weights $r(k)$ are given for MOR, MOE, TSS, and TSPS.

$$GRD = \sum_{i=1}^{n} \frac{1}{r(k)} \epsilon_i(k)$$

The grey relational degree (GRD) is a representation of the results of MOR, MOE, TSS, and TSPS as a single value. By using these values, Taguchi analysis was performed again to determine optimum process conditions. The dLVL for the confirmation test was produced in these optimum conditions. Finally, the mechanical properties of this dLVL and the control LVL produced under the standard conditions applied in industry were compared.

3 RESULTS AND DISCUSSION

The air-dry density of the I-77/51 American poplar clone wood measured as 0.49 g/cm³. The air-dry density, DR, SB, MOR, MOE, TSS, and TSPS of dLVLs and control group LVL are given in Table 2.

The densities of the dLVLs increased by 31 % to 43 % compared to American poplar wood and 17 % to 28 % compared to the control group LVL. When the response table for the S/N (Table 3a) is examined, it is seen that the most effective production parameter on density is the CR (45 %), as expected. However, it was observed that the increase in CR did not cause a significant increase in the densities of dLVLs (Figure 2a). This can be attributed to the increase in the SB of dLVLs, as the CR increases, which has the greatest effect on SB (Table 3b and Figure 2b). The higher CR increases internal stresses and causes an increase in the SB (Blomberg et al., 2006; Kutnar et al., 2009; Laine et al., 2016; Unsal et al., 2011). Additionally, the water in the adhesive evaporates due to the high temperature applied in pressing of dLVLs. As a result of the increased press pressure required to increase the density, this water vapor may be trapped in dLVL, which causes increased steam pressure. Therefore, the dLVLs may have tended to return to their original thickness and increased the SB when the press was opened. On the other hand, as the SR increased, an increase was observed in the density of dLVLs, because the used adhesive filled the cell lumens (Figure 2a).
As seen in the response tables for the S/N, the most effective production parameters on MOR and MOE are CR and press time, respectively. While the contribution rates of CR and press time on MOR were 66% and 28%, those on MOE were 79% and 16%, respectively (Table 3c and 3d). The MOR and MOE values unexpectedly decreased due to the increase in CR (Figure 2c and 2d), although an increase in mechanical properties was expected (Kutnar and Sernek, 2007; Pelit et al., 2018; Yu et al., 2017). As a result, it is predicted that the highest MOR and MOE values will be obtained in dLVLs that are compressed at 38% and pressed for (10±3) minutes.

As seen in Table 3e, the most effective production parameter on TSS was press time (51%), followed by CR (24%), press temperature (21%), and SR (4%). As known, it is possible to use lower press temperature, pressure, shorter pressing time, and less adhesive,
as well as to increase mechanical properties by using densified veneer in the production of laminated materials (Bekhta and Marutzky, 2007; Bekhta et al., 2012; Bekhta and Salca, 2018). When the main effect plot for the $S/N$ was examined, it was found that the highest TSS was obtained by dLVL densified by the highest compression rate of 54 % and at a temperature of 170 °C for (10±5) minutes (Figure 2e).

When the response table for the $S/N$ (Table 3f) is examined, it can be seen that the most effective production parameters on the TSPS were the SR (55 %) and compression ratio (25 %), which made a statistically significant difference in TSPS. During the peeling process, cracks on the loose side of the veneer in the direction parallel to the fibers (lathe check) are inevitable (Huang, 2010). Furthermore, depending on the conditions, plastic deformation occurs during the densification, the cell lumens collapse, and the cell fractures develop (Bao et al., 2017; Blomberg and Persson, 2004). For these reasons, a decrease in TSPS can be expected. However, the adhesive used may have penetrated between these cracks and collapsed cell lumens, allowing them to repair. So, the highest TSPS was obtained at high SRs of 150 and 180 g/m², CR of 47 %, press temperature of 130 °C, and press time of (10±3) minutes (Figure 2f).

### 3.1 Multi-response optimization

#### 3.1. Višestruka optimizacija mehaničkih svojstava

In this study, GRA, as a multi-response optimization method, was used to determine the optimum production conditions for MOR, MOE, TSS, and TSPS si-
multaneously. The grey relational degrees (GRD) and the orders are shown in Table 4.

\[ \text{MOR, MOE, TSS, and TSPS were converted into a single response (GRD), and the effect of the production parameters on multiple performance was ordered by applying Taguchi method again. According to these results, the CR (48%) and press time (38%) had the highest effect on multiple performance of dLVLs (Table 5). The mechanical properties decreased with increasing compression ratio and pressing time (Figure 3).} \]

### 3.2 Confirmation tests

3.2. Potvrđni testovi

At first, dLVL panels for confirmation were produced using optimum production conditions of 38% compression, 170 °C press temperature, 10+3 minutes press time, and 150 g/m² SR, and their MOR, MOE, TSS, and TSPS were determined. It was found that the MOR, MOE, TSS, and TSPS of dLVLs produced under optimum conditions were 123.41, 11059, 9.40, and 1.42 N/mm², which is 49, 8, 71, and 23% higher than control samples manufactured under standard conditions used in industry, respectively. The mechanical properties of dLVLs produced under optimum conditions were also compared with those of laminated materials produced with veneers of higher density, as published in literature (Table 6). As it can be seen, the dLVL may substitute LVL produced from high-value wood species and Taguchi-based GRA allows dLVL production parameters to be optimized safely and efficiently.

### 4 CONCLUSIONS

4. ZAKLJUČAK

The objective of this study is to determine the most suitable production conditions of compression ratio, press temperature, press time, and adhesive spread rate to maximize the mechanical properties of dLVL. The effects of the production parameters on the mechanical properties of MOR, MOE, TSS, and TSPS were also determined by using Taguchi and grey rela-

### Table 4 Calculated grey relational degree

<table>
<thead>
<tr>
<th>Exp. Gr.</th>
<th>GRD</th>
<th>Orders</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.722</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>0.662</td>
<td>3</td>
</tr>
<tr>
<td>3</td>
<td>0.544</td>
<td>5</td>
</tr>
<tr>
<td>4</td>
<td>0.587</td>
<td>4</td>
</tr>
<tr>
<td>5</td>
<td>0.446</td>
<td>8</td>
</tr>
<tr>
<td>6</td>
<td>0.711</td>
<td>2</td>
</tr>
<tr>
<td>7</td>
<td>0.429</td>
<td>9</td>
</tr>
<tr>
<td>8</td>
<td>0.459</td>
<td>7</td>
</tr>
<tr>
<td>9</td>
<td>0.500</td>
<td>6</td>
</tr>
</tbody>
</table>

### Table 5 Response tables for S/N of GRD

<table>
<thead>
<tr>
<th>Level</th>
<th>CR</th>
<th>PT</th>
<th>Pt</th>
<th>SR</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-3.91</td>
<td>-4.93</td>
<td>-4.19</td>
<td>-5.29</td>
</tr>
<tr>
<td>2</td>
<td>-4.87</td>
<td>-5.78</td>
<td>-4.74</td>
<td>-4.63</td>
</tr>
<tr>
<td>3</td>
<td>-6.71</td>
<td>-4.76</td>
<td>-6.55</td>
<td>-5.56</td>
</tr>
<tr>
<td>Delta</td>
<td>2.80</td>
<td>1.02</td>
<td>2.37</td>
<td>0.93</td>
</tr>
<tr>
<td>Rank</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>4</td>
</tr>
</tbody>
</table>

*Signal to noise: larger is better / Omjer signala i šuma: veći je bolji*

### Table 6 Comparison of confirmation test results with control group and literature

<table>
<thead>
<tr>
<th>Comparison groups / Grupe za usporedbu</th>
<th>MOR</th>
<th>MOE</th>
<th>TSS</th>
<th>TSPS</th>
</tr>
</thead>
<tbody>
<tr>
<td>dLVL produced in optimum production conditions / dLVL proizveden u optimalnim proizvodnim uvjetima</td>
<td>123.41</td>
<td>11059</td>
<td>9.40</td>
<td>1.42</td>
</tr>
<tr>
<td>Non-densified LVL (control group) / neugušćeni LVL (kontrolna skupina)</td>
<td>82.77</td>
<td>10222</td>
<td>5.50</td>
<td>1.15</td>
</tr>
<tr>
<td>Literature review / pregled literature</td>
<td>Poplar LVL / LVL od topolovine</td>
<td>68.14⁺</td>
<td>6690⁵</td>
<td>4.24⁺</td>
</tr>
<tr>
<td>Beech LVL / LVL od bukovine</td>
<td>118.30ᵃ 95.41ᵇ</td>
<td>1951⁺ 8773ᵇ</td>
<td>10.90⁺</td>
<td></td>
</tr>
<tr>
<td>Beech plywood / furnirska ploča od bukovine</td>
<td>-</td>
<td>-</td>
<td>1.86ᵇ</td>
<td></td>
</tr>
<tr>
<td>Eucalyptus LVL / LVL od drve eukaliptusa</td>
<td>94.90⁺ 89.30ᵇ</td>
<td>9411⁺ 9131ᵇ</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Oak LVL / LVL od hrastovine</td>
<td>-</td>
<td>-</td>
<td>8.94⁺</td>
<td></td>
</tr>
</tbody>
</table>

⁺AyGen et al., 2014;ᵇBal and Bektas, 2012;ᶜUysal, 2006;ᵈRéh et al., 2019
tionship analysis methods to optimize single- and multi-responses.

As CR increased, the density of dLVLs unexpectedly decreased due to the increase in SB. In addition, it caused an increase in density due to the fact that the adhesive used filled the cell spaces.

It was found that CR had the most significant impact on MOR and MOE, and contrary to expectations, dLVLs with 38% compression showed the highest values. The most effective production parameters on TSS and TSPS were found to be press time and SR, respectively.

Multi-response optimization using grey relational analysis showed that the CR (48%) and press time (38%) had the most significant impact on the mechanical properties of dLVL. It has also been determined that the highest results will be obtained when the lowest CR of 38% and the shortest pressing time of (10±3) minutes are applied. This combination may also reduce production costs.

Confirmation tests showed that the mechanical properties of dLVLs produced in optimum production conditions improved by 49% (MOR), 8% (MOE), 71% (TSS), and 23% (TSPS) compared to control group of LVL produced by traditional production method applied in wood product industry. So, it can be said that poplar dLVLs can be used as structural elements and the production parameters of dLVLs can be optimized safely and effectively using Taguchi-based GRA.

5 REFERENCES

5. LITERATURA


41. ***TS EN 319:1999 Particleboards and fibreboards- Determination of tensile strength perpendicular to the plane of the board.

42. ***TS EN 322:1999 Wood-based panels- Determination of moisture content.

43. ***TS EN 323:1999 Wood- Based panels- Determination of density.