Drewno 2019, Vol. 62, No. 204
DOI: 10.12841/wood.1644-3985.292.13

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EFFECT OF PARTICLEBOARD DENSITY AND CORE LAYER PARTICLE THICKNESS ON SURFACE ROUGHNESS

Surface roughness is an important quality criterion for the finishing and utilization of particleboards, irrespective of whether they are of conventional density or lightweight design. In an investigation of the influence of a particleboard's density (650 kg/m^3 or 500 kg/m^3) on surface quality, all roughness and waviness parameters were found to increase with decreasing density. Particle thickness was measured by manually gauging the thickness of 45 particles from each particle type (Thin, Normal, Thick, Reference). The particles were taken from image analysis samples, with 15 particles for each replicate measurement. Further, the influence of increasing core layer particle thickness on surface roughness was investigated, using a large set of roughness parameters and statistical analysis. No significant correlation was found between particle thickness in the core layer and the particleboards' surface quality.

Keywords: particle thickness, particleboard density, surface roughness, robust Gaussian regression filter

Introduction

Surface roughness is a quality criterion for particleboards, especially if a decorative surface coating is to be applied [Nemli et al. 2007; Fuczek et al. 2010]. This applies to lightweight panels in particular, as lower wood material input results in reduced particle compaction and, presumably, rougher surfaces. Fine irregularities on the board surface resulting from sanding or calibration will show through the overlays, affecting product grade and quality [Hiziroglu 1996]. Studies on the surface quality of particleboards underline the importance of measuring the surface roughness prior to coating or covering with overlays [Nemli et al. 2005; Hiziroglu and Suzuki 2007; Nemli et al. 2007; Rolleri and Roffael 2010]. However, the lack of a dedicated standard metrology is

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a limitation in the evaluation of the surface roughness of wood-based panels, such as particleboards [Gurau and Irle 2017]. Previous researchers have based their interpretation of surface roughness on general standards, which apply well to homogeneous materials, but have been shown to produce distortions and misinterpretation of surface data if applied to wood and wood-based panels [Krish and Csiha 1999; Gurau et al. 2002; Fujiwara et al. 2004; Gurau 2004; Gurau et al. 2006; Coelho et al. 2008].

Dedicated research has shown that wood and wood composites require a special metrology protocol (measuring instrument, measuring length, filter type and associated cut-off value, lateral resolution, and a larger range of roughness parameters) in comparison with more homogeneous materials. The approach in this study takes into consideration recent findings and recommendations related to wood and wood-based metrology, to obtain a more reliable response for surface roughness [Gurau et al. 2012; Gurau and Irle 2017].

The aim of this work was to investigate the effect of particle thickness in the core layer (Thin, Normal, Thick), and of the particleboard density (650 or 500 kg/m^3), on the surface roughness of particleboard.

Materials and methods

Materials

Core layer particles of different thickness (Thin, Normal, Thick) were prepared primarily from softwood chips (*Pinus sylvestris*), using an industrial-scale knife ring flaker, at the Pallmann Research and Technology Center (PRTC) (Pallmann Maschinenfabrik GmbH & Co. KG, Zweibrücken, Germany). The three different thicknesses were obtained by varying the cutting blade projection. After manufacture, the particles were manually dried in a wood-drying kiln (fresh air/exhaust air) with a target moisture content of below 20%, and were further sieve fractionated for each core layer particle type (Thin, Normal, Thick) into the 'good fraction' (1.5-8 mm) and the rejected 'fines' (< 1.5 mm) and 'oversize' (> 8 mm) fractions. The thicknesses of the three types of lab-made core layer particles were 0.6 (±0.2) mm (Thin), 1.0 (± 0.3) mm (Normal), and 1.4 mm (±0.4) (Thick). Further results of the dimensional characterization of particles were determined in a study by Benthien et al. [2019], which was a part of this research project.

The wood chips, face and reference core layer material, liquid urea-formaldehyde (UF) adhesive (solid content 67%), and paraffin emulsion (solid content 50%) were provided by an industry partner (Swiss Krono Sp. z o.o., Żary, Poland). Ammonium nitrate (NH_4NO_3) solution with 40% solid content was used as a hardener.

Measurement of wood particle thickness

Particle thickness was measured by manually gauging the thickness of 45 particles from each particle type (Thin, Normal, Thick, Reference). The particles were taken from image analysis samples, with 15 particles for each replicate measurement. The selection of particles was based on their manageability by hand and not according to a target with the aim of obtaining a representative sample.

Manufacture of particleboards

Three-layer panels with a nominal thickness of 16 mm and target densities of 500 and 650 kg/m^3 were produced on a computer-controlled laboratory single-daylight hot press (Siempelkamp GmbH & Co. KG, Krefeld, Germany). Adhesive was applied on the particles in a drum blender equipped with an air-atomizing spray system. Face layer additives were 1% hardener, 1% urea (both based on the resin solid content) and 0.5% paraffin emulsion (based on the dry wood mass). For the core layer material, only 3% hardener was added. The amount of additional water was calculated according to the particle moisture content and added to the aqueous adhesive solution. The target moisture content was 11% for the face layers and 8% for the core layer. The adhesive content was 1% (based on dry wood mass) in the face layers and 8% in the core layer. Having regard to the target panel density and the resulting face-to-core layer ratio (35/65 at 650 kg/m^3 and 46/54 at 500 kg/m^3), particles were weighed and formed into mats on an aluminium caul plate using a 695 mm × 595 mm forming box. The face-to-core layer ratio differed for dense and light panels, as only the mass of the core layer particles was reduced to reduce panel density. After the forming box was removed, a second aluminium caul plate was laid on top of the mat, and both were covered with siliconized paper to prevent adherence between the panel and the caul plates.

At a press plate temperature of 200°C, the mats were compressed with a pressing time factor of 8 s/mm (effective press time: 128 s). The closing time of the press was 6 s. Within the first 20 s after closure, a thickness of 15.5 mm was sought at a maximum specific pressure of 4 N/mm^2. During the following 100 s, the maximum specific pressure was reduced from 1.5 to 1 N/mm^2 while the thickness was increased to a nominal panel thickness (16 mm). Plate positions were kept constant for 8 s while the specific pressure was further decreased stepwise (0.5 N/mm^2 per step). After hot-pressing, the panels were cooled under ambient conditions, and were then stored at 20°C and 65% relative humidity for at least one day before samples were cut.

Experimental setup and sample preparation

A total of 24 experimental particleboards were made, three for each of the eight panel types. Core layer particle thickness (Thin, Normal, Thick) and panel density (500 and 650 kg/m^3) were varied. Particleboards with 'Reference' core layer particles were made to benchmark the results obtained with lab-made particles in the core layer. Three specimens were cut from each panel. The total number of test specimens for each core layer particle type and target density was nine. Prior to testing, specimens were conditioned in a climatic chamber at 20°C and 65% relative humidity.

Measurement of surface roughness

For the measurement and evaluation of surface data, the surface roughness methodology proposed by Gurau et al. [2012] was used in this research. Compared with a laser instrument, a stylus with a standard scanning tip is more repeatable and more accurate [Gurau et al. 2012]. Therefore, measurements were performed on the particleboard surfaces using a MarSurf XT20 instrument (Mahr GmbH, Göttingen, Germany), equipped with an MFW 250 scanning head with a tracing arm in the range ±750 μm and a stylus with 2 μm tip radius and 90° tip angle, which measured the specimens at a speed of 0.5 mm/s and at a low scanning force of 0.7 mN. The instrument had MARWIN XR20 software installed to process the measureddata. The specimens were scanned on tracing lengths of 40 mm (a longer tracing length gives more accurate results). This selection was based on the former experience with wood surfaces that variation in wood anatomy gives unstable roughness parameters for shorter evaluation lengths [Gurau et al. 2012]. It is assumed that a similar evaluation length on particleboard surfaces can give more reliable results. Six profiles were recorded for each specimen, three on the face surface and three on the back surface, spaced at 15 mm from each other, so that a total of 54 profiles were available for further evaluation of parameters for each core layer particle type and target density. The lateral measuring resolution was set at 5 μm (8000 data points), as recommended in the methodology [Gurau et al. 2012]. The instrument provided a vertical resolution of 7 nm. The software first removed the form error, and then the waviness. Roughness profiles were obtained by filtering each profile using a Robust Gaussian Regression Filter (RGRF) as defined in the ISO 16610-31 standard [2016]. The cut-off used was 2.5 mm, as recommended in previous research [Gurau 2004].

To detect any difference in surface roughness caused by the two variables proposed in this study (particleboard density and size of chips in the core layer), a large range of roughness parameters were calculated and thoroughly analysed. These included *Ra*, *Rq, Rz*, *Rt, Rv, Rsk, RSm* from the ISO 4287 standard [1997] and *Rk*, *Rpk*, *Rvk, A1, A2* from 13565-2:1996 [1996], described in detail below. The mean parameters *Ra* and *Rq* are common roughness indicators, but alone they do not provide sufficient information about wood surface topography. Very different surfaces can have similar *Ra*. The height parameters *Rt*, *Rv*, *Rz* and the shape parameter *Rsk* are very sensitive to isolated extreme irregularities, which are not clearly detected by *Ra* or *Rq*. *Rt* and *Rz* quantify the highest amplitude of irregularities, giving a useful point of comparison between various surfaces. Surfaces with a negative skewness, *Rsk*, have fairly deep valleys below a smoother plateau. The greater the negative *Rsk* value, the more occurrences of deep features are detected in the profile. *RSm* is a measure of the width of irregularities: the larger the irregularities, the higher the *RSm* value. This parameter is useful because, in contrast to the majority of roughness parameters which give a vertical measure, it measures the surface gap (irregularities) in a horizontal direction.

A standard description of the aforementioned roughness parameters is given below, based on the ISO 4287 standard. A profile is represented by a vector of length *n* of ordinate values *Zi*.

$Ra = \frac{1}{n}\sum_{i=1}^{n} \lvert Z_i \rvert$	The arithmetic mean deviation of the assessed profile is the arithmetic mean of the absolute ordinate values Z(*x*) within a sampling length.
$Rq = \sqrt{\frac{1}{n}\sum_{i=1}^{n} Z_i^2}$	The root mean square deviation of the profile is the root mean square value of the ordinate values Z(*x*) within a sampling length.
$Rz = \lvert \max Zp \rvert + \lvert \max Zv \rvert$	The maximum height of the profile is the sum of the largest peak height *Zp* and the largest valley depth *Zv* within a sampling length.
$Rt = \lvert \max Zp \rvert + \lvert \max Zv \rvert$	The total height of the profile is the sum of the maximum profile peak height *Zp* and the largest absolute value profile valley depth *Zv* within the evaluation length.
$Rv = \lvert \max Zv \rvert$	The maximum profile valley depth *Rv* is the largest absolute value profile valley depth *Zv* within a sampling length.
$Rsk = \frac{1}{Rq^3}\left[\frac{1}{n}\sum_{i=1}^{n} Z_i^3\right]$	The skewness of the profile is the quotient of the mean cubed value of the ordinate values *Z(x)* and the cube of *Rq*, within a sampling length.
$RSm = \frac{1}{m}\sum_{i=1}^{m} Xs_i$	The mean width of the profile elements represents the mean value of the profile element widths *Xs* within a sampling length. A profile element comprises a profile peak and the adjacent profile valley.

In determining the parameter *RSm*, specific requirements apply to the height and spacing of the profile elements. The default minimum profile height within a profile element is 10% of *Rz*, and the default minimum spacing of profile elements is 1% of the sampling length. Both conditions must be met.

The material ratio curve (Abbot curve) parameters *Rpk*, *Rk* and *Rvk* describe the increase of the material portion of the surface with increasing depth of the roughness profile. *Rk* is the depth of the roughness core profile, and is chosen because it should be a measure mainly of manufacturing variables [Westkämper and Riegel 1993; Gurau et al. 2005]. *Rpk* is the average height of the protruding peaks above the roughness core profile, which together with *Rvk*, the average depth of the profile valleys projecting through the roughness core profile, gives an indication of irregularities outside the core roughness (above and below respectively). *Rvk* may be especially sensitive to species' anatomical valleys or to various gaps caused by the pressing process. *Rpk* is a measure of fuzziness protruding above the core roughness. The sum *Rk*+*Rpk*+*Rvk* was also determined for comparisons, because of the cumulative effect on surface roughness.

Other parameters described in the 13565-2 standard and calculated in this study quantify the peak area (*A1*) and the valley area (*A2*), which can also provide important information about the distribution of the irregularities in a profile. An *A2* value greater than *A1* means that valleys are predominant in the profile. The sum *A1*+*A2* was also calculated, to compare the magnitude of peak and valley areas between particleboards manufactured with different core layer particle types and densities.

Some parameters describing the waviness in the profile were calculated according to ISO 4287: *Wa* and *Wq*. Their meanings are similar to the equivalent roughness parameters, but they apply to the waviness profile. The waviness profile is the primary profile from which roughness has been subtracted. These parameters are interesting because they evaluate a surface in terms of its longer-wavelength characteristics. Waviness in the profile can be sensitive to species elasticity, but can also reflect surface unevenness caused by the manufacturing process.

Mean values and standard deviations were calculated for all of the waviness and roughness parameters described above. To visualize the effect of core particle size and particleboard density, individual profiles were computed in MathCAD Professional 2000. Their selection was based on the mean values of roughness parameters, such that they were representative for a given type of chip size or panel density (their roughness parameters were closest to the mean values). For statistical analysis the Duncan multiple range test was applied. The level of significance was taken as $p < 0.05$.

Results and discussion

The mean values of the roughness and waviness parameters, with their standard deviations in brackets, are given in Table 1. The letter symbols were determined using the Duncan multiple range test to compare the mean values of all groups.

Table 1. Surface roughness parameters and waviness parameters for particleboards

Parameter	Particleboard density: 500 kg/m^3				Particleboard density: 650 kg/m^3			
	Reference	Thin	Normal	Thick	Reference	Thin	Normal	Thick
Ra	20.4 (3.7) a	19.0 (2.8) b	19.4 (3.1) ab	18.7 (3.0) b	13.8 (1.9) a	13.7 (1.9) a	13.3 (1.2) a	14.0 (1.7) a
Rq	32.1 (6.3) a	29.6 (5.0) b	30.1 (5.1) b	29.0 (5.0) b	21.9 (3.4) a	21.5 (3.3) a	20.7 (2.3) a	21.6 (3.0) a
Rz	164.7 (29.3) a	154.9 (23.4) a	156.4 (24.5) a	155.6 (20.8) a	122.3 (17.0) a	121.7 (16.7) a	116.7 (13.0) a	121.8 (13.5) a
Rt	228.9 (55.9) a	218.4 (43.8) a	219.7 (52.5) a	219.3 (42.7) a	171.5 (33.7) a	175.8 (32.2) a	161.5 (27.4) a	174.2 (33.1) a
Rv	128.2 (24.5) a	118.6 (19.3) b	119.7 (18.1) b	118.6 (18.2) b	94.0 (14.5) a	91.9 (15.7) a	88.5 (12.2) a	92.2 (12.2) a
Rsk	-2.5 (0.4) a	-2.4 (0.3) a	-2.3 (0.4) a	-2.3 (0.5) a	-2.5 (0.5) a	-2.4 (0.6) a	-2.4 (0.4) a	-2.4 (0.4) a
Rk	41.0 (7.1) a	39.5 (5.0) a	40.5 (5.4) a	39.3 (5.8) a	29.2 (4.2) a	30.5 (3.8) ab	29.6 (2.7) a	31.3 (3.4) b
Rpk	13.8 (7.1) a	15.6 (8.8) a	15.4 (10.8) a	15.9 (7.9) a	11.0 (5.4) a	12.9 (6.4) a	11.3 (4.7) a	11.7 (3.7) a
Rvk	64.2 (13.6) a	58.6 (11.8) b	59.5 (10.9) b	56.8 (10.7) b	44.6 (7.6) a	43.3 (8.3) a	41.9 (6.2) a	43.8 (7.2) a
Rk+Rpk+Rvk	118.9 (21.8) a	113.7 (20.) a	115.5 (21.4) a	112.0 (17.2) a	84.8 (12.2) a	86.6 (12.1) a	82.8 (8.9) a	86.8 (9.7) a
A1	462.5 (331.4) a	551.8 (359.8) a	518.4 (415.2) a	571.3 (316.8) a	407.8 (237.6) a	494.9 (320.7) a	430.9 (208.1) a	447.0 (167.3) a
A2	7504 (2053) a	6571 (1704) b	6682 (1553) b	6341 (1693) b	4697 (1107) b	4280 (1033) b	4217 (811) b	4347 (1062) ab
A1+A2	7966 (2152) a	7123 (1824) b	7200 (1696) b	6912 (1743) b	5105 (1140) a	477 (1006) ab	4648 (814) b	4794 (1056) ab
Rsm	701.4 (91.4) a	700.5 (97.4) a	720.0 (96.0) a	706.5 (87.5) a	641.2 (69.1) a	656.5 (83.8) a	662.2 (72.6) a	654.5 (70.6) a
Wa	14.3 (3.34) a	13.6 (3.6) a	14.7 (4.3) a	13.9 (3.2) a	10.2 (2.0) ac	10.2 (2.0) ac	10.8 (2.3) bc	11.3 (2.3) b
Wq	17.2 (3.8) a	16.7 (4.7) a	17.9 (6.1) a	17.1 (3.8) a	12.7 (2.5) ac	12.7 (2.4) ac	13.2 (2.6) bc	14.1 (2.7) b

Different letters in each row indicate statistical differences ($p < 0.05$) in the roughness parameters.

When groups have the same letter in a given row (treated separately for the two particleboard densities), this indicates lack of statistical difference ($p < 0.05$) between the samples.

Instead of presenting the representative roughness profiles separately for each group of panels, it was decided that a single graph including the characteristic roughness profiles for all four groups at one particleboard density might provide a better visual comparison of the results. In this way, one can visually compare the amplitude of irregularities for all four chip size groups. Also, this representation can help the reader appreciate qualitatively the difference in the maximum amplitudes given by the two particleboard densities (comparing Figures 2 and 3). It is clearly visible that the higher-density particleboards have smoother surfaces. Figures on the x-axis indicate the length of the measured profiles, which was up to 40,000 µm. The y-axis gives the amplitude of irregularities in µm. It should be noted that the roughness profiles for the four chip groups are offset from one another to allow all of them to be presented on a single graph.

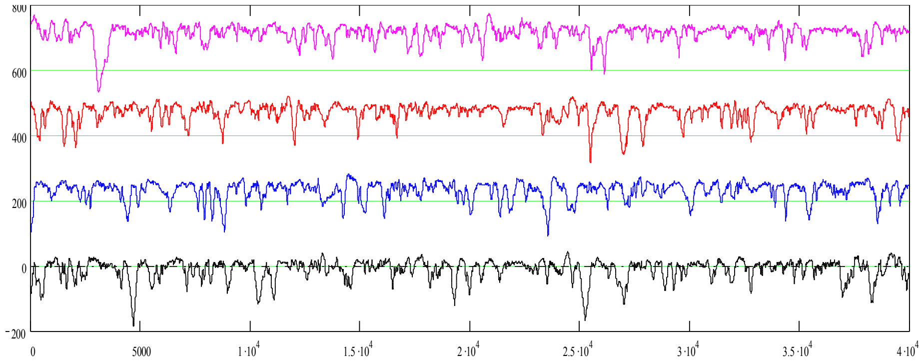

Fig. 2. Representative roughness profiles for all particleboard groups with density 500 kg/m^3. Black – Reference; blue –Thin; red – Normal; magenta – Thick. Values on both axes are in µm.

Analysis of roughness and waviness parameters for particleboard groups with density 500 kg/m^3

Looking at the representative profiles and irregularity amplitudes for each group of particleboards with density 500 kg/m^3 (Figure 2), it is hard to ascertain which is rougher or smoother. For this purpose, a detailed evaluation can be made only by comparing certain roughness parameters with known meaning and interpretation (Table 1).

From Table 1 it can be seen that the highest mean values of *Ra* occurred for the Reference particleboard, and this result is statistically significant. However,

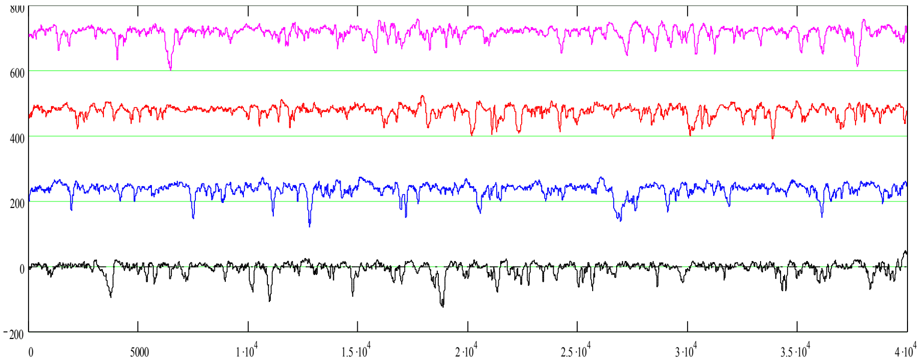

Fig 3. Representative roughness profiles for all particleboard groups with density 650 kg/m^3. Black – Reference; blue – Thin; red – Normal; magenta – Thick. Values on both axes are in µm

no significant differences were found for the lab-made particleboards (Thin, Normal, Thick). *Rq* is also a mean parameter, indicating the same trend as *Ra*, with 6–10% higher values for Reference than for the other groups. *Rz* is the maximum peak-to-valley distance within a sampling length. Although the mean *Rz* value was highest for Reference, this result was not validated by the statistical analysis (Table 1). The reason was the fluctuation in values within each group, which may be due to local variation in anatomical gaps in wood, and gaps caused by the pressing process, combined with raised fibres (peaks).

Rt has a similar meaning as *Rz*, but it is calculated over the entire evaluation length, representing the highest peak plus the deepest valley. As in the case of *Rz*, although the mean *Rt* was higher for Reference, no statistical difference was found between the four groups of panels (Table 1).

Rv is a component of *Rz*, and measures the means of the deepest valleys of the profiles, calculated from five sampling lengths of each profile. *Rv* was approximately 8% higher for the Reference panels than for the lab-made types. Also, the higher value of standard deviation for the commercial particleboard shows that these particleboards were less homogeneous than those made in the laboratory (Table 1).

All skewness values, *Rsk*, were negative, which indicates the prevalence of deeper valleys in the profiles. This means that profile gaps extending below the core datapoints, probably anatomical valleys and gaps between chips, were higher in magnitude than the size of peaks (raised fibres) for all groups tested. Although *Rsk* for Reference was slightly higher than the mean values for the other groups, the difference was not significant (Table 1). *Rk* measures the magnitude of the region with the highest density of datapoints (core roughness), taken separately from isolated peaks and valleys in the profile. *Rk* is expected to best characterize the differences between groups, because it relates to the location of the majority of datapoints in a profile, disregarding the extremes. For particleboards with density 500 kg/m^3, the mean values of *Rk* did not differ between the groups (Table 1). As with the majority of parameters, the standard deviation of *Rk* calculated for the Reference group was higher, indicating the lower homogeneity of the commercial particleboards in comparison with the lab-made samples.

Rpk measures the magnitude of isolated peaks protruding above the core roughness. The peaks of the Reference boards seem slightly lower than for the other groups, but with no statistically significant difference. However, *Rvk*, which is a measure of the deeper valleys going below the core roughness, was 7-12% higher in Reference samples than for Thin, Normal and Thick, and this trend was confirmed by the Duncan test (Table 1).

Rk+Rpk+Rvk is a cumulative parameter containing information about the size of the core roughness, plus the isolated peaks, plus the isolated valleys. The ordering of the groups by mean values of this parameter begins with Reference, followed by Normal, Thin and Thick. It appears, according to this cumulative parameter, that the particleboards with the roughest chip size had the smoothest surfaces. However, the differences between the groups were negligible and statistically insignificant (Table 1).

A1 is the area of protruding peaks above the core profile, from which *Rpk* derives. Both *A1* and *Rpk* indicate Thick as being slightly fuzzier than the other groups, but with no statistical significance. *A2* is the area of valleys going below the core data, from which *Rvk* derives. The valley area was approximately 11-16% greater than the peak area. Like *Rvk*, *A2* indicates more isolated valleys (12-18%) for Reference than for the other groups, but differences between the lab-made particleboards were not significant. *A1+A2* is a cumulative parameter indicating the total area of features going beyond the core roughness. This parameter showed the same trend as *A2*, due to the prevalence of valleys.

RSm is a width parameter which measures surface features in a horizontal direction. It may provide information about how wide the features in the profile are (the distance from one peak to a consecutive valley). *RSm* showed no significant difference between groups. *Wa* is a replica of *Ra*, and *Wq* is a replica of *Rq*, but applied to the waviness profile. They give indications regarding lower-frequency (higher-wavelength) irregularities, which look like “waves” on the surface, caused by pressing deflections or material elastic response. The Thin group had slightly lower waviness than the other groups (Table 1), but without statistical significance.

Analysis of roughness and waviness parameters for particleboard groups with density 650 kg/m^3

From Table 1 it can be seen that values for all roughness and waviness parameters were smaller for the denser particleboards, which means that a higher particleboard density improves the surface quality. The same trend was found in the values of standard deviation, which indicated that when the density of the particleboard is increased, its surface became more homogeneous.

The higher-density particleboards do not exhibit, in general, significant differences between the surface quality of different groups (Table 1). An exception is *Rk*, which took slightly higher values for particleboards in the Thick category than for the other groups. Also, the surface waviness (*Wa*, *Wq*) was greater for particleboards with a coarser core (Table 1).

A trend towards slightly deeper valleys was observed for Reference particleboards, judged by *A2* (Table 1), but it was not statistically supported by *Rvk* and *Rv*, in spite of their higher values. In spite of the fact that the Thin group had the smallest core particle size, the surface roughness analysed in terms of mean parameters was not smaller than that of the other groups.

Conclusions

Investigation of the surface quality of particleboards of different density and with varying particle thickness in the core layer did not reveal (with some exceptions: *Rk*, *Wa*, *Wq* for particleboards with a target density of 650 kg/m^3) any significant effect of particle thickness on the surface quality. For particleboards with the higher target density, generally no differences in quality between the panels with lab-made particles and industrial-made particles (Reference) were found. In the case of low-density particleboards, some of the roughness parameters (*Ra*, *Rq*, *Rv*, *Rvk*, *A2*, *A1+A2*) of the panels with industrial-made particles in the core layer were found to be significantly higher than for the panels with lab-made particles (Thin, Normal, Thick). The surface waviness of the low-density particleboards was not influenced by the thickness of the core layer particles. Comparing the particleboards' surface roughness and waviness parameters at the two density levels, the surface quality of the low-density particleboards was found to be below that of the particleboards of conventional density.

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Acknowledgements

The authors thank the Federal Ministry of Food and Agriculture (BMEL), Bonn/Berlin, Germany, for supporting the ‘LeiHoWe’ research project, under which the present study was carried out. They further thank the industry partners Kronopol Sp. z o.o. (Żary, Poland) for providing the test materials, and Pallmann Maschinenfabrik GmbH & Co. KG (Zweibrücken, Germany), especially Dr. Helmut Roll, for the production of the wood particles. We hereby acknowledge the structural funds project PRO-DD (POS-CCE, O.2.2.1., ID 123, SMIS 2637, ctr. No 11/2009) for providing the infrastructure used for surface quality measurements in this work.

Submission date: 28.06.2018

Online publication date: 12.11.2019