Int J Adv Manuf Technol (2006) 28: 775–780
DOI 10.1007/s00170-004-2414-y

ORIGINAL ARTICLE

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Analysis of roughness of a sanded wood surface

Received: 13 April 2004 / Accepted: 11 September 2004 / Published online: 27 July 2005
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Abstract Due to the non-homogeneity of timber material, the roughness profile of a board is affected by the wood anatomy, thus making the analysis of timber surface quality quite complicated. Currently, there is no reliable method to analyse timber surface quality independent of the timber species or timber properties. The current standard filtering methods used to determine the surface roughness profile from a measured profile or a primary profile fail to produce reliable results in timber surface analysis.

This paper proposes a new approach to overcome this shortcoming and to provide more accurate and reliable timber roughness analysis methods. The proposed methods are compared with the current standard methods using data from 35 samples of Messmate (*Eucalyptus obliqua*) sanded with seven different grit sizes of abrasive (P60, P80, P100, P120, P150, P180 and P240). The results suggest that the proposed methods are more consistent and accurate in describing sanded timber surface quality.

Keywords Abbott curve · Filter · Gaussian · Surface roughness · Valley removal

1 Introduction

The surface quality of wood products is a combination of the textures due to multiple processes [1] such as sawing, planing and sanding. The sanding process, to a large extent, determines the quality of the finished piece and consequently affects the overall perceived quality of the products [2].

The quality of the surface of wood products is often characterised by surface irregularities or surface roughness [3]. Traditional methods to measure surface roughness and quality include visual and tactile approaches. However, with these methods, only gross comparison is possible, and specific information about the surface is not quantifiable. There is a variety of different surface texture instruments available to measure surface roughness including the stylus profilometer, optical profilometer, ultrasonic optical light sectioning and image analysis using video camera. Those machines are mainly developed to measure engineered materials such as plastic and metal. Unfortunately, there is no device commercially available to be used specifically for timber surface measurement.

The lack of wood surface evaluation methods is mostly caused by the fact that wood roughness also depends on factors related to wood property or wood anatomy caused by its non-homogeneous structure. Species of wood vary considerably in their structure; even timber from different locations in the same tree can have different cellular structure. Moreover, an effective method to analyse the timber roughness is limited by the fact that the effect of wood structure on surface roughness has so far not been fully investigated [4]. The main reason is that it is difficult to distinguish the surface irregularities caused by timber processing from the roughness due to wood anatomy variations.

An ideally smooth timber surface never exists in reality. Usually, a smooth surface refers to one free of deviations due to machining or other surface treatment [5]. Profile data from a nominally flat surface contains form error, waviness and roughness. Form error is the long-wavelength deviations of a surface from the corresponding nominal surface, which usually result from large-scale manufacturing problems such as inaccurate alignment of the workpiece or uneven wear in machining equipment [6]. Waviness errors are intermediate in wavelength between roughness and form error [6]. Therefore, any quantitative evaluation of a sanded surface requires that the data be filtered to remove form error and waviness [7]. Unfortunately no such stan-

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dard has been developed for wood surfaces, and existing general standards currently used such as the Gaussian filter [8] and double Gaussian filters [9] are not suitable [10]. These two filtering methods contain end effects, which cause some part of the data on each end to be unusable, and it also introduces distortion in a profile with deep valleys, which cause 'pushed up' valleys or artificial peaks when compared to an unfiltered profile [7, 10].

A new filtering method needs to be developed to accommodate a reliable filtering procedure for timber profiles. Fortunately, recently proposed standards based on robust Gaussian regression filters (RGRF) defined in ISO/DTS 16610–31: 2002 (E) [11] provide a more accurate method of filtering the roughness profile for timber. However, the form error in the original profile needs to be removed before this filter can be applied. RGRF also allows all data to be usable without introducing the 'pushed up' problem introduced by current standards.

In timber – especially timber with large vessel size (porous timber) – the definition of surface roughness becomes difficult. Wood surfaces contain irregularities due to both the processing and the anatomy. Therefore, anatomical roughness must be excluded from any measurement of the surface if the processing roughness is to be properly evaluated [3, 6, 12, 13]. It means that the filtering method by itself is still insufficient. One way of separating the roughness due to wood anatomy is by removing deep valleys from the roughness profile and considering the deep valleys as outliers or roughness caused by wood anatomy.

Fujiwara et al. [3] introduced a method of identifying a threshold value for wood anatomy determined by observations of the profiles. Complications arise due to the need to set a threshold for different timber species based on different processes applied and different grit sizes used. The method also requires preliminary knowledge about the timber species to identify typical valleys in the roughness profile, leading to subjectivity in the threshold value determination.

The method of the deep valley elimination that was investigated in this work is based on the Abbott curve method according to the lower valley limit defined in ISO 13565-3:2000 [14]. This method allows the valley to be calculated statistically in order to eliminate the subjectivity of the identification of the valley limit.

The proposed method combines RGRF with the lower valley limit defined in ISO 13565-3:2000 to remove deep valleys due to wood anatomy. The combination of both methods allows more accurate evaluation of the timber roughness due to the sanding process and thus is independent of the wood anatomy. The desired outcome from the proposed method is to allow more precise measurement of the effect of different timber processes such as planing and sanding on the timber surface roughness or texture.

2 Experiment

Thirty-five samples of Australian hardwood, i.e. Messmate (*Eucalyptus obliqua*), were sanded with seven different grits of abrasive (P60, P80, P100, P120, P150, P180 and P240). The abrasive used was the 1919 SIA wood abrasive: open-coat aluminium oxide abrasive with F-weight paper back. Five samples were used for each grit size, and three primary profiles were measured from each sample with the Surtronic 3+ stylus-type profilometer manufactured by Taylor-Hobson. This profilometer measures a 25 mm trace length with a 5 μm radius, 90-degree angle stylus tip. It recorded roughness profile data with 1 μm horizontal reso-

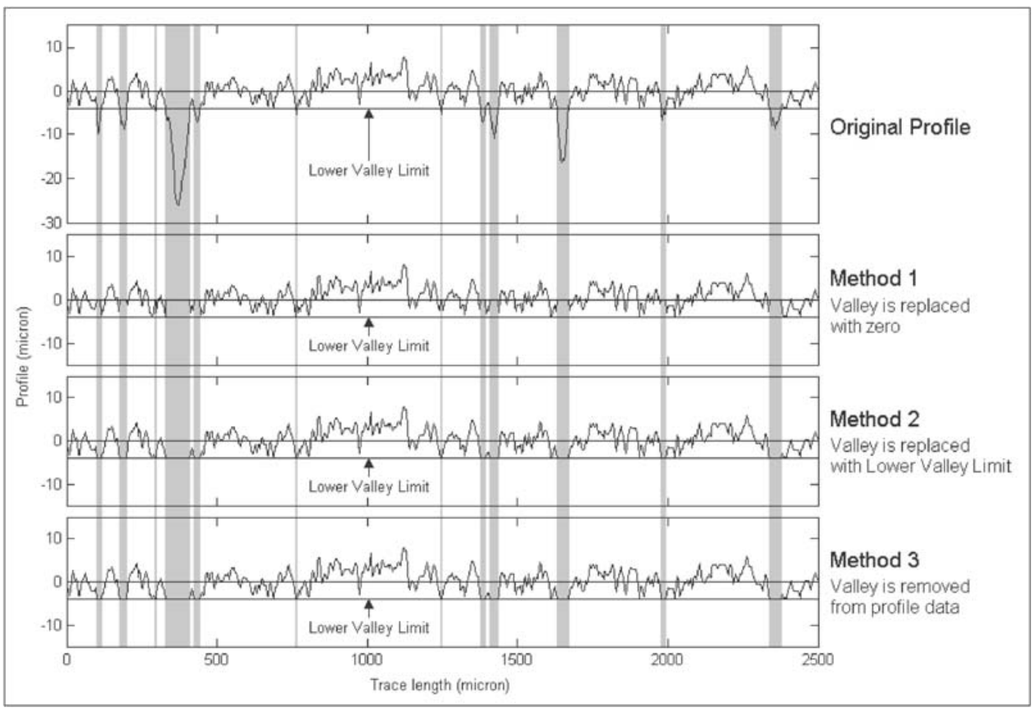

Fig. 1. Three proposed methods for deep valley removal. The shadowed profiles are the outlier data, as they are less than the lower valley limit

lution and 0.5 μm vertical resolution. The recorded data was then transferred to a PC to be analysed with the proposed method.

Due to the fact that RGRF requires extensive computer time, the horizontal resolution was reduced from 1 μm to 5 μm (i.e. reduction from 25 001 to 5 001 data points) before the primary profile data were analysed, to reduce the computation time without severely compromising the accuracy of the result too much. This accuracy was verified by trials on over 300 different timber surface roughness profiles by comparing each profile with different data resolution. Reduction to 5 μm showed an identical result to the original data. Roughness profiles were filtered with a cut-off value of 2.5 mm. This value, a typical standard cut-off value [9], was selected because it allows the detection of surface trends while still including the characteristic irregularities caused by both wood anatomy and the machining process [3]. Before we present the result, the methods compared are reviewed.

The wood anatomy is then removed from the roughness profile with the lower valley limit in ISO 13565-3:2000 by three different methods as shown in Fig. 1. The roughness parameters, R_a, R_q, R_z and $R_{\max}$, were calculated for the three methods, and the results were compared to the conventional Gaussian filter method and RGRF method without valley removal.

3 Current profile filtering methods

Gaussian filter is the most-used filtering method for roughness profiles and is actually acceptable for most homogeneous material such as plastic and metal. However, it is not suitable for timber due to the non-homogeneous properties of wood. A filter is called robust when the outlying data points do not lead to a distorted surface roughness measurement. The outlying data points in timber surface roughness are usually caused by roughness due to wood anatomy or any accidental high-profile peak; thus, a robust filter is desired. The RGRF also uses zeroth-order Gaussian regression filters to enable the evaluation of the entire length of the profile without end effects [7].

The filter equation in a discrete form for the RGRF is defined by:

$$\sum_{l=1}^{n}\left(z_l - w_k^{(m+1)}\right)^2 \cdot \delta_l^{(m)} \cdot s_{l,k} \cdot \Delta x \to \min_{w_k^{(m+1)}} \tag{1}$$

where n is the number of data points in the profile, z_l denotes the profile data values before filtering, w_k denotes the profile values of the filter mean line to be calculated, m is the index marking the iteration step, δ_l is the robust weighting of profile values, $s_{l,k}$ is the weighting function of the filter, Δx is the sampling interval, l is the index of the profile points, and k is the index of the location of the weighting function in the whole profile with $s_{l,k}$ obtained from

$$s_{l,k} = \exp\left(-\frac{\pi^2}{\ln(2)} \cdot \frac{(k-l)^2 \cdot \Delta x^2}{\lambda^2}\right) \tag{2}$$

The first iteration, when $m = 0$, the additional weight $\delta^{(0)} = 1$ is applied to each data point. In the subsequent iterations, the value of δ is given by

$$\delta_l^{(m)} = \begin{cases} 1 & m = 0 \\ \left[1 - \left(\frac{z_l - w_l^{(m)}}{c_B^{(m)}}\right)^2\right]^2 & \text{for } \left|z_l - w_l^{(m)}\right| \le c_B^{(m)} \\ 0 & \text{otherwise} \end{cases} \tag{3}$$

with

$$c_B^{(m)} = 4.4478 \cdot \text{median}\left|z_l - w_l^{(m)}\right|, \quad l = 1, \ldots, n \tag{4}$$

Profile heights that deviate from the mean line by more than c_B, are multiplied by zero. The profile heights close to the mean line are multiplied by a weighting value close to one, and therefore, almost their full value is included in the averaging function.

$$w_k^{(m+1)} = \frac{\sum_{l=1}^{n} s_{l,k} \cdot z_l \cdot \delta_l^{(m)}}{\sum_{l=1}^{n} s_{l,k} \cdot \delta_l^{(m)}} \tag{5}$$

The iterations are repeated until the difference between two consecutive median values is smaller than a given tolerance. In this study, this tolerance is set to 0.1 μm. However, before applying the RGRF, the form error needs to be removed from the original profile.

Figure 2 shows that after form-error removal, the RGRF produces a more accurate result compared to current standard filtering methods. The RGRF method has several advantages: it eliminates the ‘pushed up’ problem, allowing all of the data points in the roughness profile to be retained without producing end effects and also works for different surface roughnesses of sanded samples. These are shown by observation of the profile graphs obtained from over 3600 samples of recorded profiles.

The drawback of this method is that it is unsuitable for use in online production with current PC technology due to its long computation time. To reduce the computation time for this study, some variables, such as s (weighting function of the filter), were saved into a file and loaded back when needed instead of being recalculated for each computation. Trials on different PC configurations showed that, using a 1.6 GHz Pentium 4 with 256 MB SDRAM, it takes over 30 minutes to calculate a roughness profile with 5001 data, while, using a 2.4 GHz Pentium 4 with 512 MB DDR RAM, it takes approximately one to two minutes. Furthermore, for online measurement, a fast and reliable method for data collection is required, and the stylus profilometer is definitely too slow. There are some faster devices available using lasers or optics; however, some of these types are too sensitive to the grain colour and moisture on the timber surface and some of them do not record the true profile like the contact measurement method.

3.1 Deep valley removal scheme

Figure 3 shows the result of using the lower valley limit defined in ISO 13565-3:2000 to identify the borders between roughness due to processing and roughness due to wood anatomy.

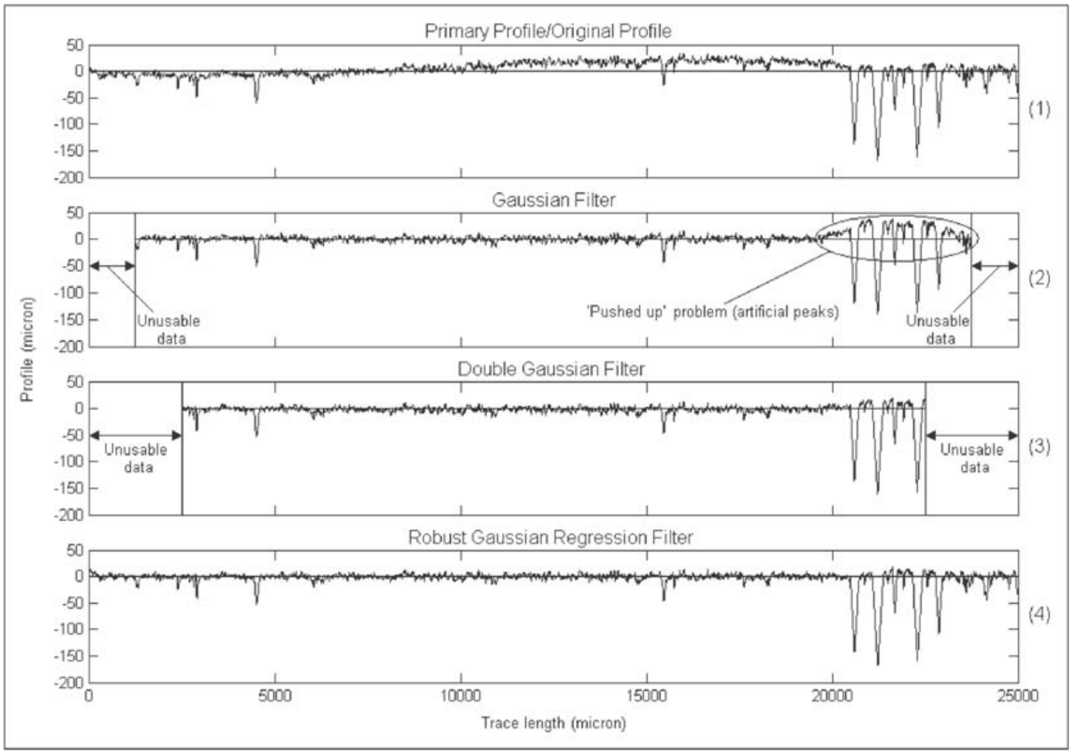

Fig. 2. Comparison of different existing filtering methods. Figure (1) shows the primary profile recorded by the profilometer; (2) to (4) show the result after filtering the primary profile with different filtering methods

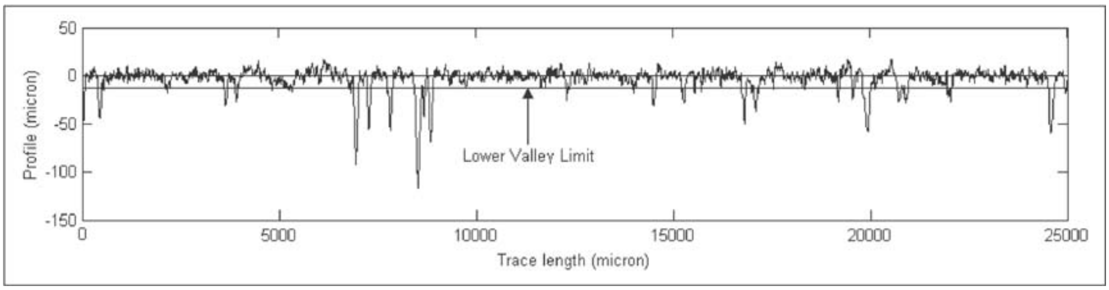

Fig. 3. Deep valley removal using the lower valley limit. The valleys below the lower valley limit are considered 'valleys due to wood anatomy' and therefore should be removed in the examination of the effect of sanding on timber surface quality

This is done by first calculating the Abbot curve or bearing-ratio curve of the roughness profile and then calculating its second derivative followed by identifying the first abrupt change in the value of the second derivative. The abrupt changes are determined by calculating the standard deviation of the second quarter of the derivative values, and then adding the data incrementally to the right. The index of the point where the ratio of the absolute value of the second derivative to the standard deviation of previous points exceeds a critical value is taken as the index of the inflexion point, and the corresponding value of the Abbott curve at this index point is the lower valley limit [7].

Any valleys that are deeper than the lower valley limit are assumed to be due to wood anatomy and are therefore considered as outliers and should not be included in the calculation of the wood roughness parameters resulting from a sanding operation. This method appears to work with different levels of roughness and is capable of producing a statistically more reliable result for timber surface analysis, due to the statistical method used for finding the first abrupt change in the second derivative of the Abbott curve. Moreover, it is a more reliable or more practical approach than subjectively identifying the limits manually by setting thresholds for different timber species and different sanding grit.

4 Method of deep valley removal

The proposed method combines the RGRF method with the valley removal method based on the lower valley limit calculated according to ISO 13565-3:2000. Different methods are proposed for deep valley removal once the lower valley limit is identified. The data values below the lower valley limit are modified in three different ways. These three methods are selected because they seem to be the most logical way to eliminate valleys due to wood anatomy. Method 1 is to replace such data with zeros, method 2 is to replace it with the lower valley limit value and method 3 is to remove the data from the roughness profile. Figure 1 shows the three different methods proposed.

4.1 Procedure to achieve the goal

1. Collect primary profile data using a profilometer (Fig. 2(1)).
2. Fit a polynomial into the data to calculate form error using a numerical method such as an iterative method or a least-squares polynomial fit (equivalent to the polyfit function in MATLAB). In this study, a polynomial of degree two was used.
3. Remove the form error by subtracting the polynomial estimation from the primary profile to get a roughness + waviness profile.
4. Apply the RGRF to produce a roughness profile (as shown in Eqs. 1 to 5).
5. Calculate the lower valley limit as explained in the deep valley removal scheme section.
6. Filter the data against the valley limit using the three methods:
   Method 1: if roughness data < valley limit, then roughness data = zero.
   Method 2: if roughness data < valley limit, then roughness data = valley limit.
   Method 3: if roughness data < valley limit, then roughness data removed, i.e. the number of profile data after valley removal will be reduced.
7. Calculate the roughness parameters, e.g. $R_a = \frac{1}{N} \sum_{n=1}^{N} z_n$, where z_n is the roughness profile due to processing or sanding.

5 Result and discussion

Figures 4 and 5 show the results achieved from application of the current method and the three proposed methods to samples as described in the experiment section. It can be seen that the roughness parameters obtained from the filtering methods without the deep valley removal do not always show good correlation with grit number. This is shown in Figures 4 and 5, where the timber surface roughness parameters do not show a smoother surface when sanded with finer grit abrasive, especially for the very fine abrasive (beyond P180). It is suggested that valleys caused by vessels in the timber affect the roughness parameters. When the average abrasive scratches are finer than the average valley size of the wood anatomy, the roughness parameter result will be dominated by the wood anatomy.

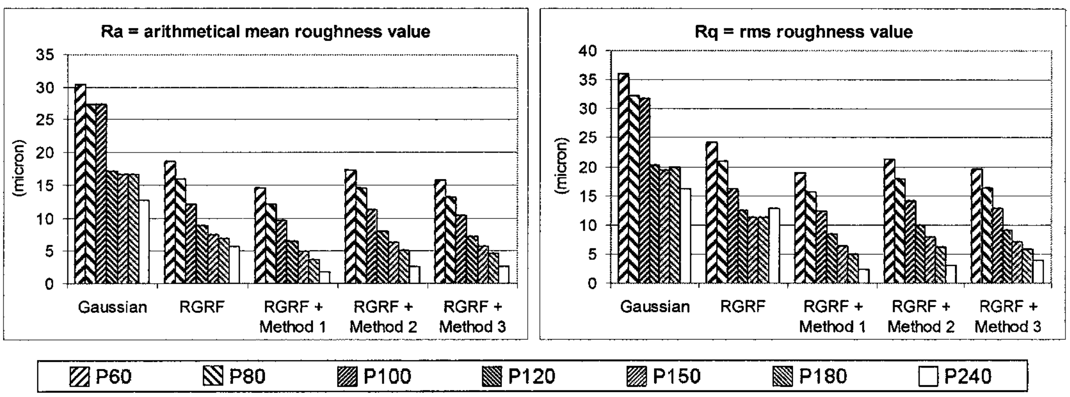

Fig. 4. R_a and R_q values of Messmate sanded with different abrasive grit sizes calculated using the conventional Gaussian method, RGRF and the three proposed methods. Smoother surface roughness is shown by shorter vertical bars

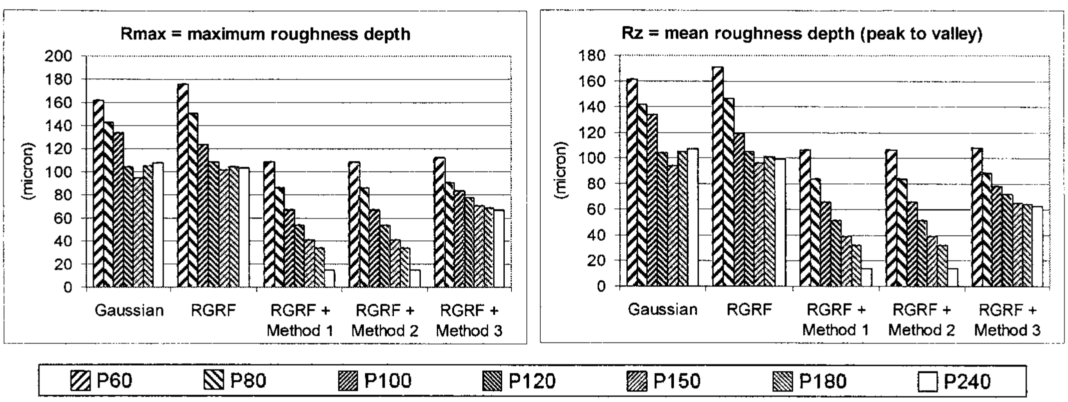

Fig. 5. R_{max} and R_z (ISO) values of Messmate sanded with different abrasive grit sizes calculated using the conventional Gaussian method, RGRF and the three proposed methods. Smoother surface roughness is shown by shorter vertical bars

On the other hand, the three proposed methods show a consistently good correlation with the grit number. All of the three methods seem to show very reliable and consistent results, which show that smoother grit size abrasive consistently produces less surface roughness. Therefore, the proposed method seems to be able to provide the answer. However, further studies will be necessary to compare the three methods to identify which is best.

6 Conclusion

To characterise timber surface roughness accurately, it is necessary to use a proper surface roughness measurement device and a proper method for surface roughness analysis. Timber surfaces contain irregularities due to both the processing and the wood anatomy. The anatomical roughness must be excluded if the processing roughness is to be properly evaluated, especially for timber with large vessel size, because the vessels in the wood anatomy might affect the roughness parameters calculated. Figure 4 shows that without the deep valley removal, the surface roughness parameters obtained do not always show a good correlation with the grit number.

The three methods of combining the RGRF method and the lower valley limit proposed in this study successfully show consistency and good correlation with the grit number, but further studies will be necessary in assessing the three proposed methods.

Acknowledgement The authors wish to express their gratitude to CRC Wood Innovations and Wentworth Furniture Manufacturer, who provided funding, facilities and support for this research. The authors would also like to thank all the staff at CRC Wood Innovations and the staff of Wentworth for their assistance and co-operation.

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