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General Regularities of Wood Surface Roughness

Endre MAGOSS*

Department of Wood Engineering, University of West Hungary, Sopron, Hungary

Abstract – The surface roughness of wood products is depending on many factors related both to wood properties and wood working operational parameters. Probably this is the reason why there are no generally valid correlation determining surface roughness parameters as a function of influencing factors. In particular, the account of wood structure in the surface roughness interpretation proved to be difficult.

In the last years an important progress was made in recognizing the role of the anatomical structure of wood species in the attainable surface roughness. The introduction of a structure number made it possible to express and characterize the different wood species numerically.

The aim of these studies was the separation of roughness components due to the anatomical structure and the woodworking operation. Using a special finishing technique, the roughness component due to woodworking operations was not significant and could be separated. The same specimens were also subjected to different woodworking operations using cutting velocities between 10 and 50 m/s. The processing of experimental data resulted in a chart showing the minimum roughness component due to different woodworking operations. Special experimental investigation was conducted to clear the influence of edge dullness on the surface roughness, especially on its Abbott-parameters. The measurements showed that the R_k-parameter is a good indicator to predict edge dullness.

structure number/ anatomical structure / woodworking / edge dullness / cutting speed / Abbott-parameters

Kivonat – Természetes faanyag felületi érdességének alapvető összefüggései. A faanyagok érdessége igen sok tényező együttes hatásaként jön létre, ezért az általános törvényszerűségek megtalálása sokáig váratott magára. Az utóbbi évtized új elgondolásai és a modern méréstechnika lehetővé tette az alapvető törvényszerűségek felismerését. A struktúra szám bevezetése lehetővé tette, hogy segítségével a fafajok számszerűsíthetők a felületi érdesség szempontjából, és lehetővé teszik általánosabb érvényű összefüggések felállítását.

A megmunkálás után kialakuló érdesség két fő összetevőre bontható: a megmunkálás okozta érdesség és a belső struktúra okozta érdesség. Speciális felületi megmunkálás alkalmazásával a megmunkálási érdesség részaránya minimalizálható és szétválasztható a belső struktúra okozta érdességtől. Megállapításra került továbbá a forgácsolási sebesség (10 m/s-50 m/s) és a szerszám él kopottságának hatása a felületi érdességre. Az R_k-paraméter változása jól mutatja szerszámkopás folyamatát.

* magoss@fmk.nyme.hu; H-9400 SOPRON, Bajcsy-Zs. u. 4.

1 INTRODUCTION

Roughness characterises the fine irregularities on a machined surface. These irregularities can be determined by measuring the height, width and shape of the peaks and valleys produced by woodworking operations or by anatomical structural properties. The surface quality is a complex definition and it is characterised today by different parameters such as the more common Ra, Rz and Rmax parameters. Further details can be established using the Abbott-curve and its related parameters Rpk, Rk and Rvk. These parameters are standardised (EN ISO 4287 and 13565-2) and for their determination modern measuring units are commercially available.

The surface quality is depending on many influencing factors and can be related both to wood properties and machining conditions. Among the wood properties the wood species, density, moisture content, the structural properties are to be mentioned. The structural properties include the specific number and distribution of inside diameter of tracheids and vessels.

The machining process has also a significant influence on the surface roughness. The most important factors are the cutting velocity and the dullness of knives, but the knife cutting angle, the cutting angle to the grains and the vibration amplitude of machine table and workpiece have also proved to be an influence on the surface roughness (Sitkei et al. 1990)

One of the main difficulties is the fact that the wood is not a true solid material having caves inside (vessels, cell lumens) and, furthermore, the wood as a brittle material is inclined to brittle fracture. As a consequence, the cutting mechanism is always associated with local fracture of the material giving uneven surface. The caves cut during the machining give also uneven surface. In this latter case, the surface irregularities depend on the local position of the cavities relatively to the surface. Wood species with large vessels in the early wood (ring porous wood) may locally cause large surface irregularities which have nothing to do with the machining process.

In the last decade an important progress was made recognizing the role of anatomical structure of wood species in the attainable surface roughness. The diameter of vessels, tracheids and other cell lumens cut during the machining process fundamentally determine the depth of irregularities in the surface. In order to characterize the effect of the anatomical structure on the surface roughness, a structure number is established and introduced (Magoss-Sitkei 2001) Another possible method is the removal of deep valleys (vessels) from the surface profile. Thus the surface roughness parameters will be more sensitive to the change of a given influencing factor (Fujiwara et al. 2003).

A further important progress could have been the separation of roughness components due to the anatomical structure and woodworking operations. Some researchers assumed that the parameters of Abbott-curve are suitable for separating the above components. In fact, these efforts were not fully successful and, therefore, further research works are still needed.

2 THEORETICAL CONSIDERATIONS

The diameter of vessels, tracheids and other cell lumens cut during the machining process fundamentally determine the depth of irregularities. The specific number of vessels related to the unit length in cutting direction is also an important factor. The diameter of vessels and tracheids always show a given distribution. However, if the distribution is generally normal, the use of the mean diameter will cause no greater errors.

The local position of vessels to the cutting plane is always random therefore, it may be treated as a probability variable. This means that the resultant effect of the vessels on the surface roughness will be given as a mean value with standard deviation.

It is assumed that in the cutting plane different vessels and tracheids will be cut (*Figure 1*) and these valleys contribute to the resultant roughness. The cross-section of valleys related to the unit length can be given as

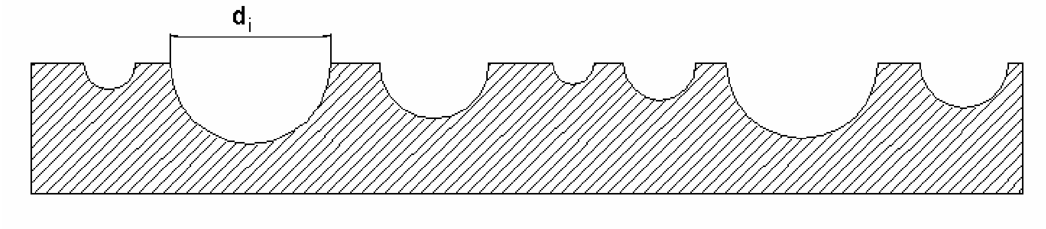

Figure 1. Definition of structure number

$$\Delta F = \frac{\Pi}{8}\left[a \cdot \left(\sqrt{n_1} \cdot d_1^2 + \sqrt{n_2} \cdot d_2^2\right) + b \cdot \left(\sqrt{n_3} \cdot d_3^2 + \sqrt{n_4} \cdot d_4^2\right)\right] \quad [\mathrm{cm}^2/\mathrm{cm}] \qquad (1)$$

where

- n_1, n_2 – are the number of vessels and tracheids in the early wood, in the unit cross-section,
- n_3, n_4 – are the number of vessels and tracheids in the late wood, in the unit cross-section,
- d_1-d_4 – are the mean diameter of vessels and tracheids in the early and late wood, respectively,
- a, b – are the portions of early and late wood.

The use of structure number makes it unnecessary to use the wood species as a variable, which can not be quantified. If the surface irregularities due to machining are small, then the surface roughness will mainly be determined by the anatomical structural properties and it can be regarded as the attainable optimum surface roughness.

The main problem of the roughness component separation is the overlapping of component sizes and, therefore, the filtering method can not give accurate results. One possible way to separate the above components seems to be the following method. Using a special finishing technique, the irregularities due to woodworking operation can be kept minimal and these irregularities are rising from an apparently flat surface (*Figure 2*). In this case, these irregularities are not higher than 10-15 μm and can be measured and evaluated.

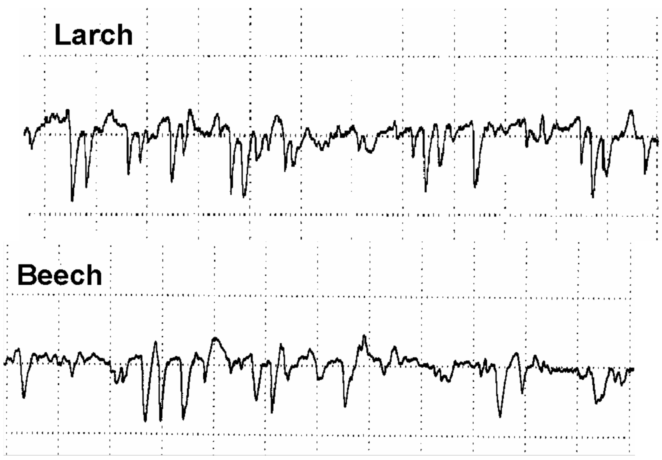

Figure 2. Roughness profiles for finished surfaces.

3 MATERIALS AND METHODS

In order to verify the usability of the new structure number, a wide variety of wood species were selected having different density and inside structure. Five broad leaved (cottonwood, ash, beech, black locust, oak) and five conifers (scotch pine, larch, fir, spruce, eastern white cedar) were selected and air dried at 50-60 % relative humidity.

Three 20- by 5-cm samples were tangentially cut from each wood species and were equally machined using sharp milling head on a CNC-controlled milling machine. On each specimen four measuring surfaces were machined and displaced by 0.3 mm to each other. This method should take into account the fact that the relative placing of cutting plane and vessels to each other is random. The cutting speed was generally 50 m/s, but special measurements were conducted to clear the effect of cutting speed on the different roughness parameters, especially on the Abbott-parameters. The cutting speed varied between 10 and 50 m/s.

The Mahr Company stylus unit (Model S3P MFW 250) was used in this study. The pick-up has a skid type diamond stylus with a tip radius of 5 µm. The active tracing length is 12.5 mm. Each measurement was represented by the surface profile, the Abbott-curve and by the calculated roughness parameters R_a, R_z, R_{max}, R_{pk}, R_k, R_{vk}, M_{r1} and M_{r2}. On each measuring surface a minimum of three tracing were made.

In order to calculate the structure number, the size and specific number of vessels and tracheids are needed. From each specimen used to roughness measurements additional small specimens were cut to determine the structural properties. While the structure number is sensitive to the accuracy of experimental data, a combined image processing method and light microscope method was used. The image processing method alone generally gave insufficiently accurate results. The measured data are summarized in Table1 (Magoss – Sitkei 1990).

Table1. Structural properties of specimens

wood species	early wood $\overline{d_i}$ [µm]	early wood $\overline{n_i}$ [piece/cm^2]	$\overline{a}$	late wood $\overline{d_i}$ [µm]	late wood $\overline{n_i}$ [piece/cm^2]	$\overline{b}$
thuja	26.5	142 800	0.8482	14.0	316 600	0.1518
spruce	30.0	111 335	0.8478	19.0	160 400	0.1522
pine	28.0	125 100	0.6694	20.0	135 840	0.3306
larch	38.0	65 490	0.6310	17.5	145 000	0.3690
beech (vessel)	66.0	15 740	0.7000	48.0	14 020	0.3000
beech (tracheid)	8.2	342 890		6.4	490 290	
oak (vessel)	260.0	400	0.5900	35.7	12 000	0.4100
oak (tracheid)	22.5	120 000		19.6	85 000	
b. locust (vessel)	230.0	546	0.5800	120.4	1 500	0.4200
b. locust (tracheid)	15.0	270 000		9.6	280 000	
cottonwood (vessel)	69.7	9 500	0.6666	44.0	12 700	0.3333
cottonwood (tracheid)	12.7	309 500		11.0	300 892	
ash (vessel)	177.0	670	0.6100	52.0	750	0.3900
ash (tracheid)	19.0	190 000		14.0	230 000	

In order to separate the roughness components three 20 by 5 cm samples were tangentially cut from each wood species and after machining they were subjected to finishing using a special finishing machine. The finishing was repeated until the measured profile was flat and thus suitable for evaluation.

Establishing the finished surfaces, the same samples were subjected to milling operation using various cutting speeds between 10 and 50 m/s. These surfaces were evaluated with the common surface measuring methods.

On the finished surfaces a hypothetical base line was first established and, taking only the positive amplitudes into consideration, the corresponding R_z'-value was calculated (*Figure 3*). This is the roughness component due to woodworking operation. Knowing the overall R_z-value and the latter subtracted from it, we get to an R_z-value due to the anatomical structure of wood.

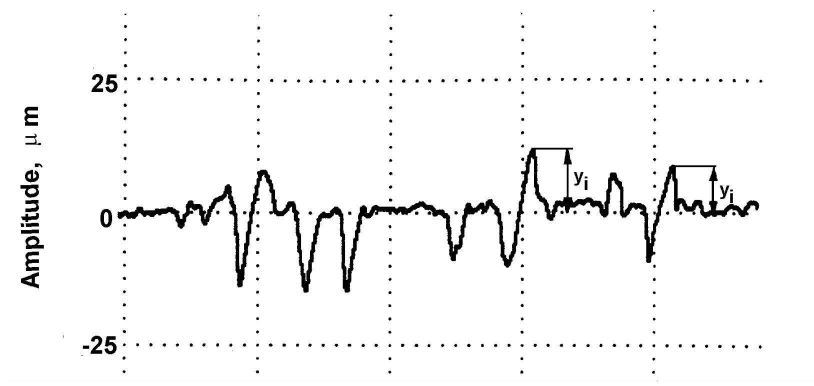

Figure 3. To the calculation of roughness component due to woodworking operation

For the evaluation of standard deviations large number of measurements was needed, approx. 60-100.

4 EXPERIMENTAL RESULTS

4.1 The effect of cutting speed

It is generally well-known that increasing cutting velocities will give better surface quality, using the common roughness parameters such as the average roughness R_a or mean peak-to-valley height R_z. At the same time, no experimental results were presented to clear the relationship between the overall roughness parameters (R_a and R_z) and their components in the Abbott distribution.

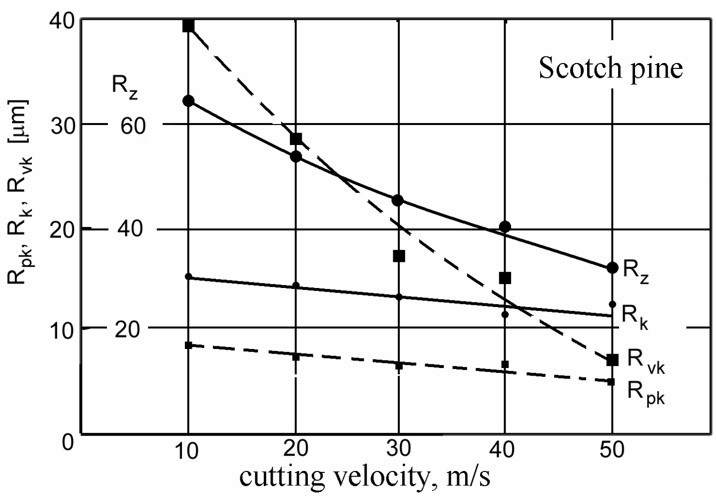

Figure 4. Surface roughness parameters as a function of cutting speed. Scotch pine.

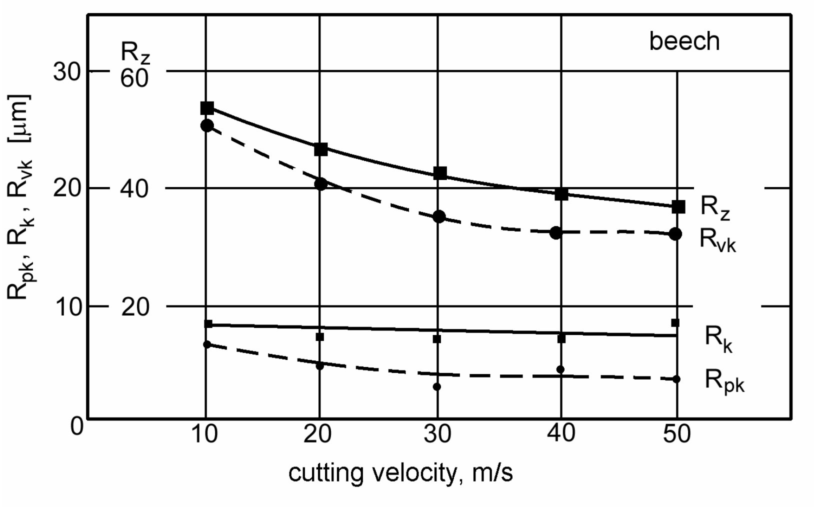

Figure 5. Surface roughness parameters as a function of cutting speed. Beech.

Figures 4 and *5* depict R_z-values and their components as a function of cutting speed using sharp knives. The beech had an average vessel diameter of 60 µm and the thick-walled fibres among the vessels had cavities of 10-15 µm diameters. The scotch pine in the early wood showed tracheid diameters of 25-30 µm and in the late wood 13-18 µm.

From *Figure 4* and *5* it can be concluded that in both cases the R_{pk} and R_k values remain nearly constant or slightly decrease as a function of cutting speed. On the other hand, R_{vk}-values fundamentally depend on cutting speed. It may also be seen that, in the case of pine, this dependence is stronger, especially at low cutting velocities. This result may be explained by the fact that the pine wood had smaller local stiffness around the cutting edge, therefore, inertia forces play a more important role to ensure a clear cutting surface. At the same time, beech had larger structural cavities giving greater R_{vk}-values even at high cutting velocities.

Further measurements were carried out at a cutting velocity of 50 m/s and the angle of tracing to grains was 90°. Observations have shown that this cutting speed can minimise the roughness component due to machining (see the upper curve in *Figure 14*).

4.2 The use of structure number

As outlined earlier, all wood species can be characterized by the structure number given by Eq.(1). Using the data summarized in Table1, the structure number can be calculated for each specimen used in these investigations and it can be interrelated to the measured roughness parameters.

The obtained results are depicted in *Figure 8* as a function of structure number. The smallest structure numbers are of the conifers and the biggest of the oak species. Some results obtained on African ebony specimens are also included. Curve No. 3 shows the roughness of specimens due to the anatomical structure and this is the ultimately attainable minimum surface roughness for a given anatomical structure.

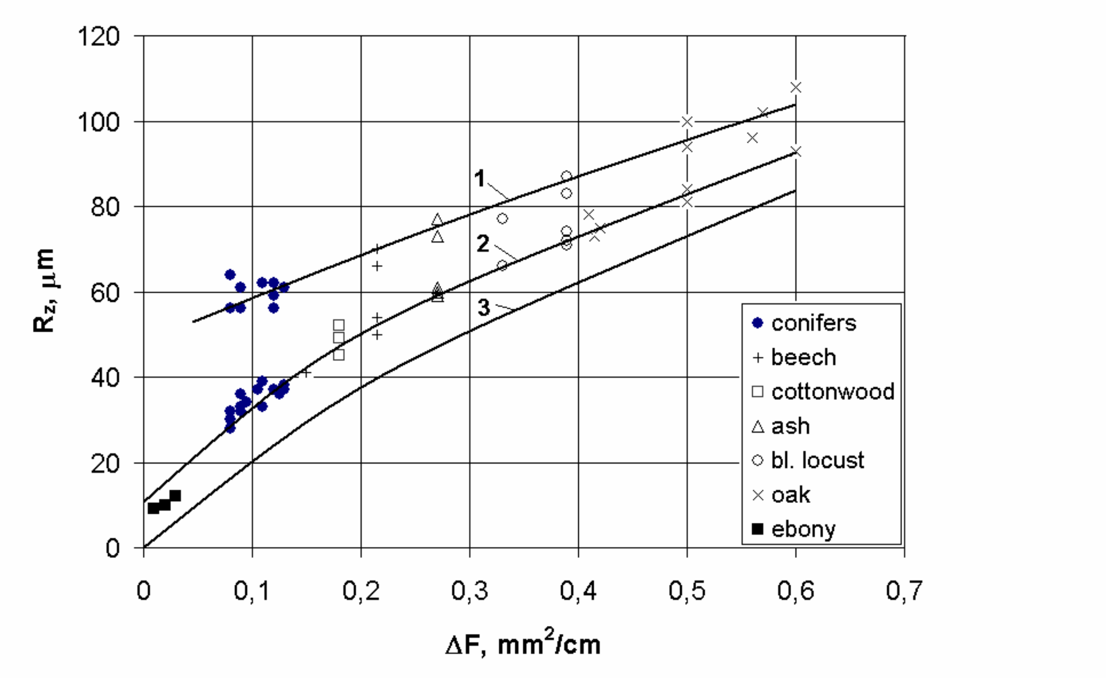

Figure 6. Peak-to-valley height as a function of structure number

1. - cutting velocity is 10 m/s,

2. - cutting velocity is 50 m/s,

3. - roughness component due to anatomical structure.

The effect of cutting speed on the surface roughness is given by the curves 1 and 2. It is noticable that the differences between curves 1 and 2 are higher for conifers in comparison to hard woods. This finding may explained by the higher rigidity (E modulus) of hard woods allowing smaller local deformations during the cutting process. It may generally be stated that conifers have higher roughness component due to woodworking operations in comparison to hard woods. It appeared that the surface roughness will probably be determined by the anatomical structure of wood, especially for hard woods with big vessels. The effect of main influencing factors on the surface roughness was also determined and the following general relationship was obtained (Magoss –Sitkei 2000):

$$R_z = \left(123\Delta F^{0,75} + 35e_z^{\;0,6}\right)\cdot\left(1+\frac{50-v_x}{50}\,\frac{0,1183}{\Delta F^{0,83}}\right) \qquad 10m/s \le v_x \le 50m/s \qquad (2)$$

Where

ΔF is the structure number, mm^2/cm

ez is the tooth feed, mm

vx is the cutting velocity, m/s

The use of the structure number allows finding further noteworthy relationships among the different surface roughness parameters.

Choosing the R_a/R_k ratio, a strong variation is obtained as a function of structure number (*Figure 7*). This means that different wood species can not be compared to one another using simply a given roughness parameter.

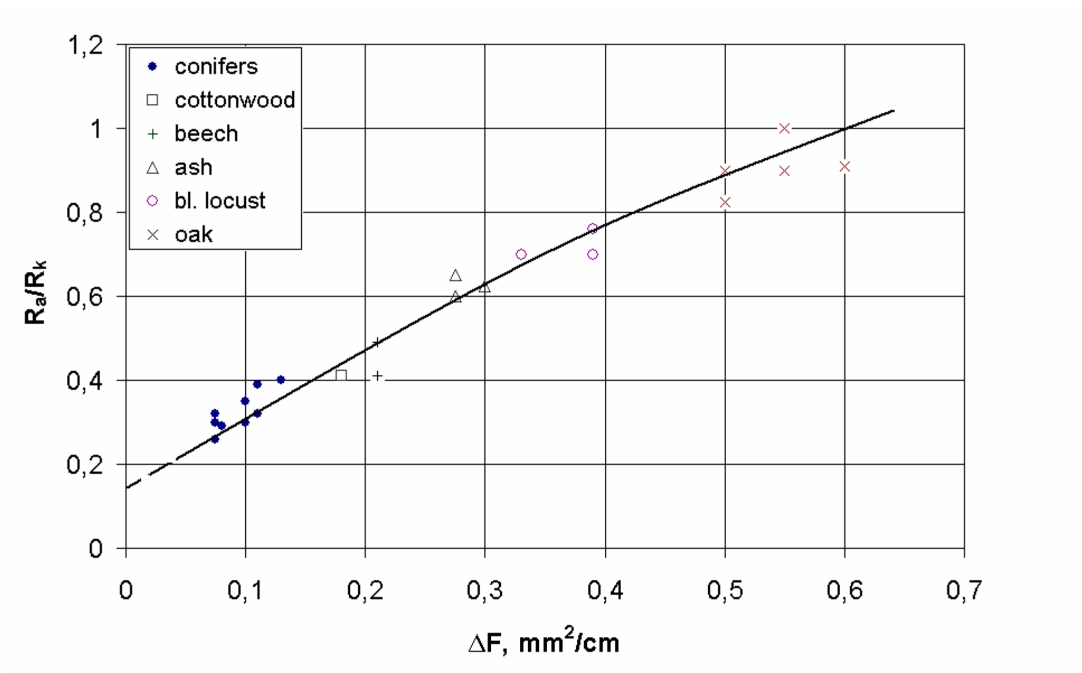

Figure 7. Variation of the R_a/R_k ratio as a function of structure number

The reduced valley height related to the peak-to-valley height (R_{vk}/R_z) shows also definite correlation with the structure number, which is given in *Figure 8*. The height ratio for hard woods means that most of the roughness is given by deep valleys due to the anatomical structure of wood.

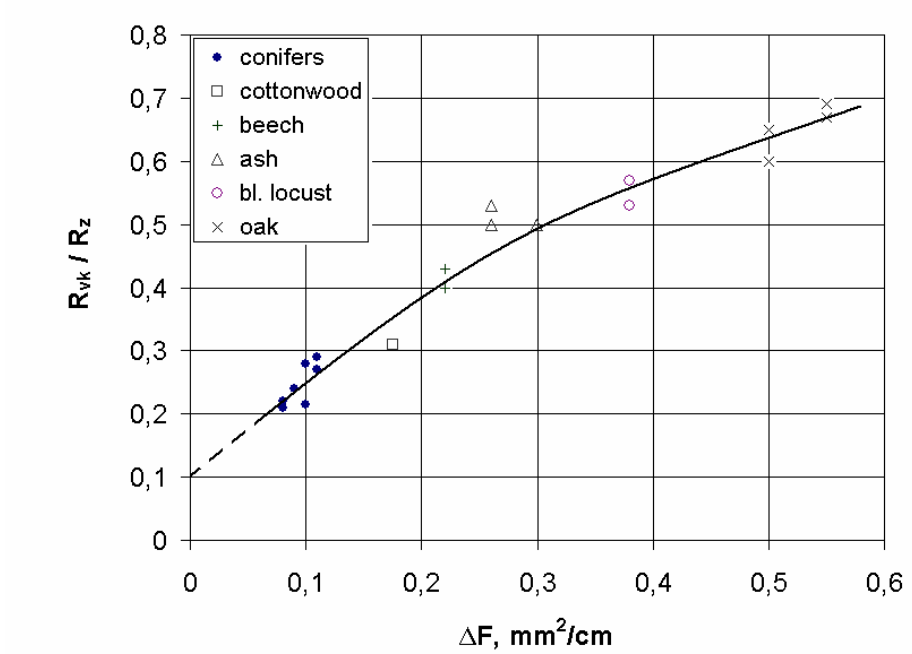

Figure 8. Variation of the R_{vk}/R_z ratio as a function of structure number

The R_k/R_z ratio versus structure number is shown in *Figure 9*. This relationship is also uniquely defined and shows that the reduced mid part of Abbott-curve plays an important role in the development of the resultant roughness in soft wood surfaces.

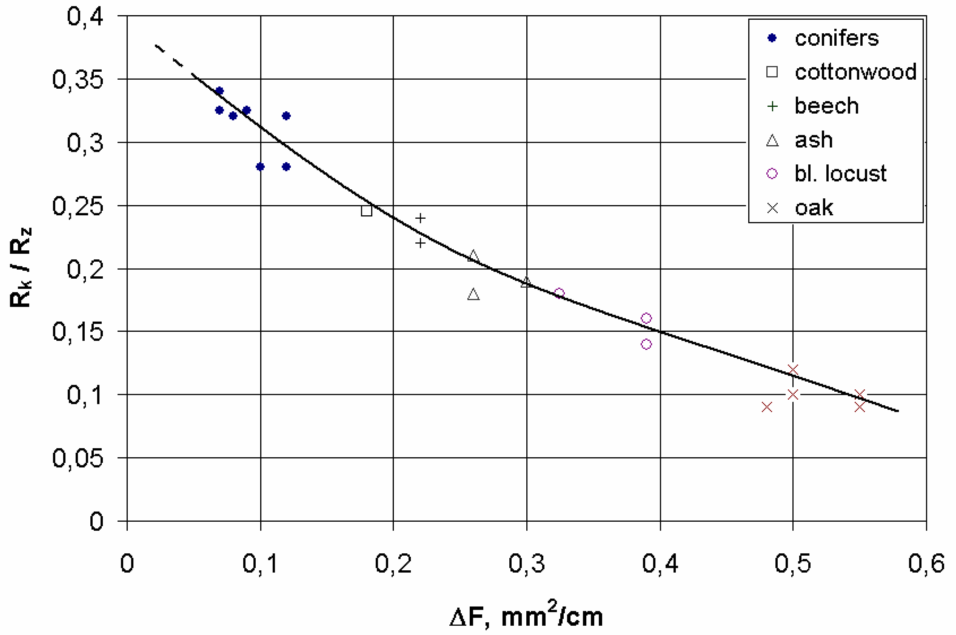

Figure 9. R_k/R_z ratio versus structure number

4.3 Interrelations among the roughness parameters

In the following the interrelation between the common roughness parameters (R_a and R_z) and Abbott-parameters was investigated. Strong relationship was observed between the average roughness and the sum of Abbott-parameters. Its graphical representation is given in *Figure 10.*

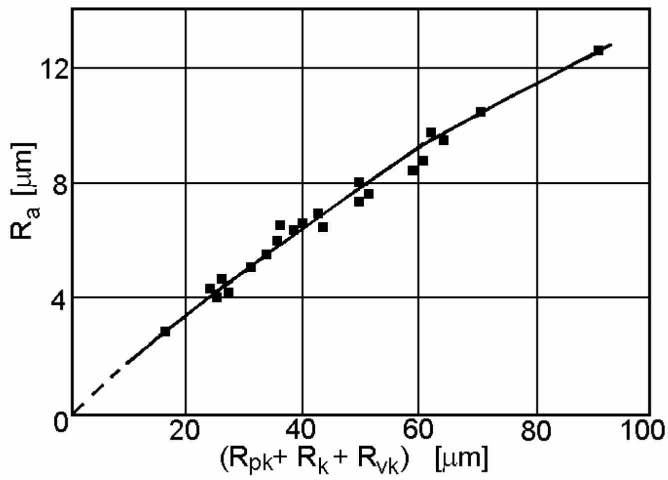

Figure 10. Relationship between average roughness and Abbott-parameters

It is well-known that between R_a and R_z only an insignificant interrelation exists (Sander 1993). As a consequence, no uniquely defined relationship between R_z and the sum of Abbott-parameters can be expected. Nevertheless, the experimental results depicted in *Figure 11* show an interesting picture.

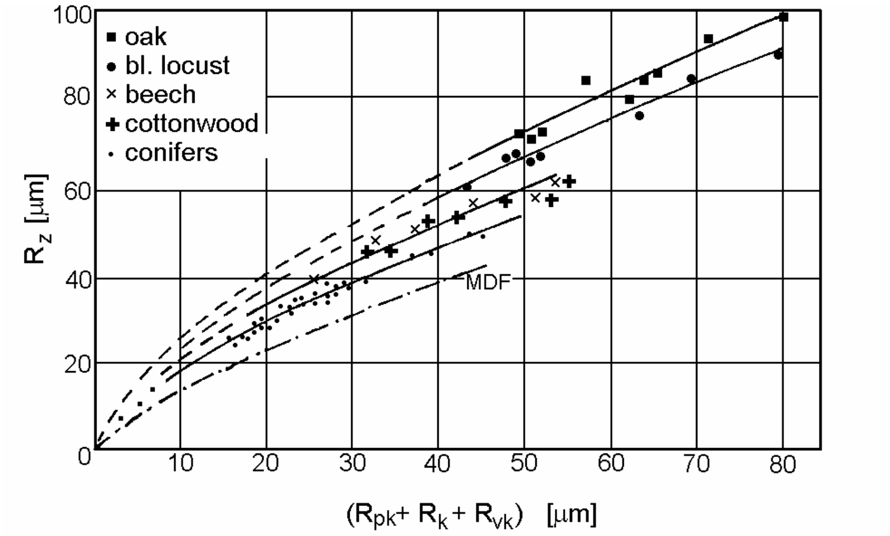

Figure 11. Peak-to-valley height versus Abbott-parameters

A large number of curves are obtained and, as an addition for a more accurate explanation, the measurement results on MDF-boards of different volume density are included (Devantier 1997). MDF has the most uniform anatomical structure which gives the lowest curve. The oak possesses large vessels and hereby a much less uniform structure and, therefore, gives the uppermost curve. The curves for other species are lying between the two extremes according to their inhomogeneities. The curves obeys the following general form

$$R_z = A \cdot \left(R_{pk} + R_k + R_{vk}\right)^{0.65} \tag{3}$$

The constant can be expressed as

$$A = 7.45 \cdot \left(R_k + R_{vk}\right) / R_z \tag{4}$$

Using the Abbott-curve, the lack of material in the uneven surface can be determined. An equivalent layer thickness may be calculated as follows

$$\Delta h_e = R_{pk} \cdot \left(1 - \frac{M_{r1}}{2}\right) + \frac{R_k}{2} + \frac{R_{vk} \cdot \left(1 - M_{r2}\right)}{2} \tag{5}$$

Where: M_{r1} and M_{r2} should be substituted as decimal values. The following rough estimation shows the weight of the parts in Eq. (5):

$$\Delta h_e = 0.95 \cdot R_{pk} + 0.5 \cdot R_k + 0.08 \cdot R_{vk} \tag{6}$$

In practical cases the R_{pk}-layer can eventually be neglected due to the fact that the few peaks rising out from the surface can easily be crushed by pressing.

The graphical representation of the lack of materials related to the unit surface is seen in *Figure 12*. The upper curve refers to the case including also the R_{pk}-layer. The deviation of measurement data is somewhat higher than in other cases.

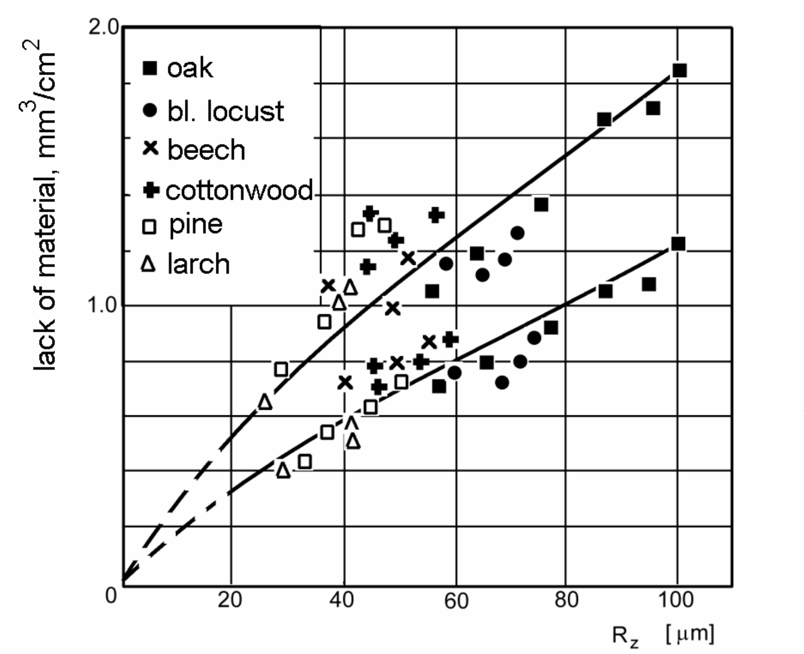

Figure 12. Lack of material as a function of surface roughness

4.4 Effect of blunt cutting edges

It is well-known that the use of blunt knives fundamentally increases the surface roughness. Our measurements have also shown that, in the case of pine and beech and using edge radius between 10 and 53 µm, the roughness with increasing dullness nearly linearly increased. A more detailed processing of experimental results showed that the R_k-value may be an important indicator characterising edge dullness. *Figure 13* shows experimental results for four wood species using sharp and blunt edges.

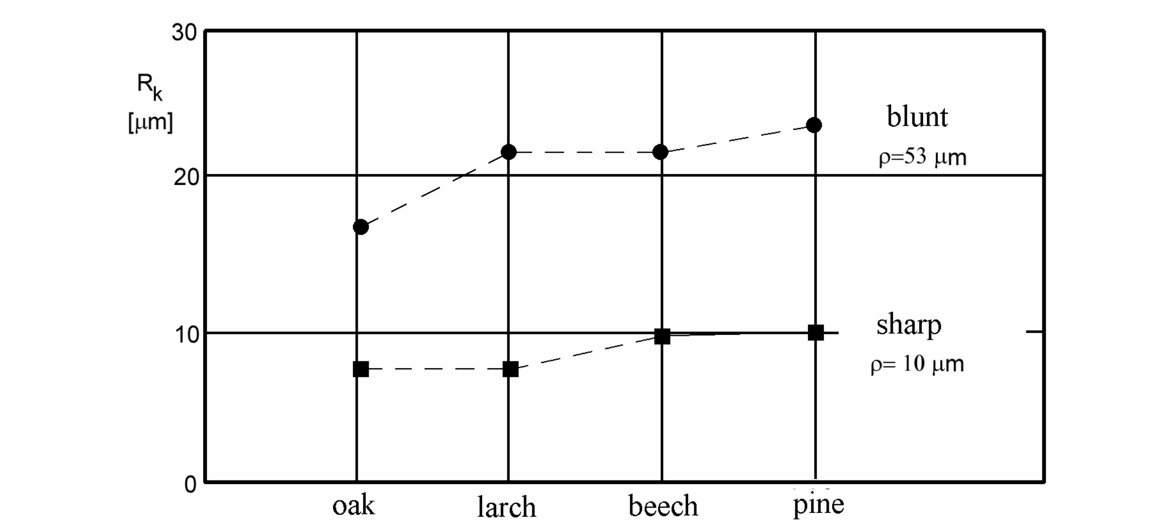

Figure 13. R_k-values for four wood species using sharp and blunt cutting edges

In this study, the oak has shown an unusual behaviour. Using increasingly blunt edges, the overall roughness R_z only slightly increased or remained constant. At the same time, the R_k-value doubled quite similarly to the other species. The surface machined with blunt edges showed a wavy character which did not correlate to the large vessels (*Figure 14*).

Furthermore, most of the vessels cut during the machining disappeared in the surface due to the deformation of upper layers (Magoss - Sitkei 2001). It may also be assumed that even the deep cavities in the surface contribute to the deforming action of the blunt edge.

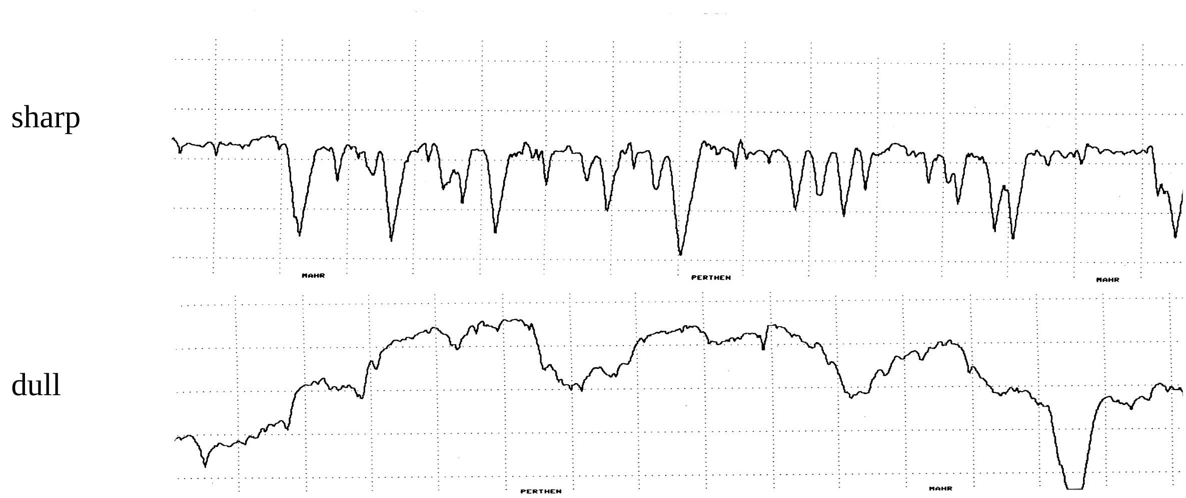

Figure 14. Surface profiles of oak wood using sharp and blunt cutting edges

The deformed and fractured layers make surfaces less stable and a subsequent surface treating may cause further waviness and local deformations. Consequently, the surface roughness alone is not always sufficient to characterise surface quality in every respect.

5 CONCLUSIONS

Based on theoretical considerations and experimental results, the following conclusions may be drawn:

- an increasing cutting speed reduces the surface roughness, primarily by diminishing the R_{vk}-values,
- the soft wood species are more sensitive to the change of cutting velocity concerning surface roughness,
- the proposed structure number shows strong correlation with the attainable surface roughness,
- different roughness parameter ratios show definite correlation with the structure number. This finding further stresses the beneficial use of the structure number uniquely characterizing the different wood species.
- among the different roughness parameters interrelations are found,
- the lack of material in the rough surface can be expressed as a function of surface roughness,
- the mid component of the total roughness R_k is a good indicator to predict edge dullness.
- using a special surface finishing technique, the separation of roughness components due to anatomical structure and woodworking operations has been carried out with reasonable accuracy.

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