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Eur. J. Wood Prod. (2009) 67: 257–263
DOI 10.1007/s00107-009-0323-3

ORIGINALS · ORIGINALARBEITEN

Up-milling and down-milling wood with different grain orientations – theoretical background and general appearance of the chips

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Received: 22 July 2008 / Published online: 25 March 2009

Abstract Peripheral milling with up-milling and down-milling techniques is very well known from a geometrical point of view. However, in processing anisotropic materials such as wood these geometrical aspects imply relevant differences when machining. In fact milling anisotropic materials leads to different cutting geometries when up-milling or down-milling and when changing the depth of cut. This results in a relative orientation of the grain depending on the process adopted. In this paper the geometrical interactions between tool and wood grain have been analysed theoretically and supported by experimental evidence. To achieve this result, Douglas fir has been processed with different depths of cut and grain orientations, the resulting chips have been collected and analysed. The experiments show how a shift of the cutting phenomenon and the chip type can be observed to support the theoretical background.

Gleichlauf- und Gegenlauffräsen von Holz bei unterschiedlichem Faserverlauf – theoretischer Hintergrund und erzeugte Spänegeometrien

Zusammenfassung Die geometrischen Aspekte beim Umfangfräsen mittels Gleichlauf- und Gegenlauffräsung sind sehr bekannt. Allerdings treten bei der Zerspanung von anisotropen Materialien wie z. B. Holz erhebliche Unterschiede auf. Tatsächlich führt das Fräsen von anisotropen Materialien beim Gleichlauf- und Gegenlauffräsen sowie bei einer Änderung der Frästiefe zu unterschiedlichen Schneidgeometrien. Die Ursache ist die jeweilige Orientierung des Faserverlaufs in Abhängigkeit des angewandten Verfahrens. In dieser Studie wurden die geometrischen Interaktionen zwischen Werkzeug und Faserverlauf theoretisch analysiert und mittels experimenteller Ergebnisse bestätigt. Dazu wurde Douglasienholz bei unterschiedlichem Faserverlauf und mit unterschiedlichen Frästiefen bearbeitet und die erzeugten Späne wurden analysiert. Die bei den jeweiligen Fräsverfahren experimentell ermittelten Spanformen bestätigen die theoretischen Annahmen.

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1 Introduction

When milling wood it is universally known that the material can be cut using up-milling or down-milling techniques according to the directions of the cutting velocity vector and the feeding velocity vector. When the two vectors (applied to the tool) have the same direction, the cutting is up-milling (herein after referred to as UM), when the vectors have an opposite direction, the cutting is down-milling (herein after referred to as DM). UM and DM techniques have a different influence on the cutting resulting in differences in the cutting geometry. The cutting geometry is a well known factor, as it is the same as the one found in metal cutting, which is well documented in cutting technology books. In general, the following is assumed for UM and DM: different shape of the chip, different cutting velocity (albeit often negligible), different wave depth of the surface marks, the beginning of the cut from the thickest (DM) or from the thinnest (UM) part of the chip, different vibro-acoustic behaviour and different relative angle in the cutting path between the grain and the rake face. This has many consequences on other factors such as: magnitude and direction of cutting force, tool wear, evolution of force along the cutting path. The grain orientation is a fundamental factor in order to understand the cutting of wood. Given that wood is an anisotropic material, it is well known that when stressed in different directions, it behaves differently. The result, when machining with different grain orientations, is a wide range of mechanisms of chip formation that require specific analysis in order to be understood. Essential work has already been carried out regarding cutting geometries and is well documented in text books (Zompì and Levi 2003, Juan 2000, Santochi and Giusti 2000), as well as on the fundamentals of wood cutting processes (Kivimaa 1950, Franz 1958, McKenzie 1961, McKenzie and Franz1964, McKenzie and Cowling 1971a, 1971b, Woodson and Koch 1970, Mori 1969, 1970, 1971a, 1971b, Piao and Fukui 1984), the basic properties of wood when stressed with different grain orientations (Yoshihara and Ohta 2000), and the surface quality after cutting. Some work has already been completed in the field of surface quality and grain orientation (Stewart 1969, 1971, Negri and Goli 2000, Goli et al. 2002, 2003, 2004a, 2004b), and certain scholarly articles analyse some of the above mentioned factors together (Cyra and Tanaka 2000). This paper is aimed at presenting a geometrical explanation of the general processes during milling of wood and in particular to understand the relations between the blade and the grain. First, a geometrical introduction is presented which is then supported by experimental evidence from the chip type. Douglas fir was machined with different grain orientations using a three axis CNC router and the resulting chips were collected and analysed after cutting.

2 Material and method

After some preliminary tests with different grain orientations, depths of cut (*doc*), feeding speeds and tool revolution per minute; samples such as shown in Table 1 were prepared and a machine set-up such as in Table 2 was chosen. The parameters are noted with their abbreviations and are thus reported in the text.

During machining, the chip suction system was disabled in order to collect the chips after cutting. The sample was fixed on a dynamometric platform in order to measure the cutting forces, which will be discussed elsewhere. The sample was fixed directly on the dynamometric platform by a compression plate, and the platform was firmly mounted on a steel plate which was surface ground on both sides to ensure a perfectly flat contact surface. The assembly was then fixed to the machine table by a conventional vacuum system (see Fig. 1). The specimens were routed by peripheral milling using a straight blade and the sample was prepared in order to achieve only a peripheral contact with the cutting tool. The machine was tested for repeatability of the positioning which was measured within ±0.05 mm. The reference surface was obtained by cutting 10 times with a depth of cut of 0.05 mm. Although very near the repeata-

Table 1 Description of the specimens used in the tests and relative abbreviations
Tabelle 1 Beschreibung der Versuchsparameter und jeweilige Abkürzungen

Species:	Douglas fir (*Pseudotsuga Menziesii* Fr. Var. Menziesii)
Moisture content (mc):	13% ∼
Average specific gravity (ρ_{12}):	0.43 g/cm^3
Depth of cut (doc):	0.5–1.5 mm
Cutting length (l):	80 mm
Cutting height (h):	30 mm

Table 2 Experimental set-up and relative abbreviations
Tabelle 2 Versuchsbedingungen und jeweilige Abkürzungen

Milling machine type:	3 axes CNC router
Milling machine model:	SCM Record 1
Rake angle (γ):	20°
Clearance angle (α):	15°
Inserts on the cutting head (z):	2
Inserts material:	tungsten carbide screwed inserts (WC)
Cutting technology:	up-milling (UM) and down milling (DM)
Feeding speed (F):	5 m/min
Cutting speed (Vc):	29 m/s
Tool revolutions: (S):	13 867 rev/min
Cutting head diameter (D):	40 mm

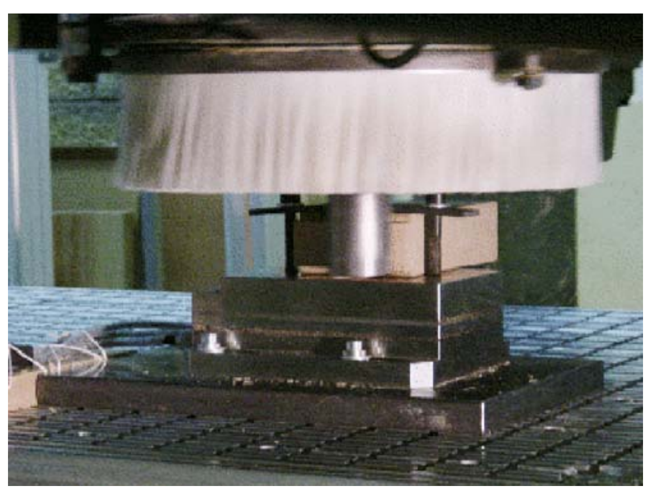

Fig. 1 The specimen hanging on the dynamometric platform during a cut
Abb. 1 Prüfkörper im eingebauten Zustand während des Fräsens

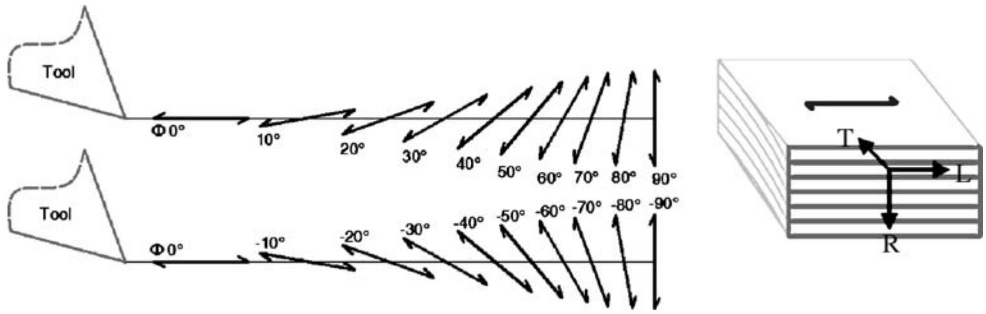

Fig. 2 Grain orientation and tangential specimens, the darker face is the face that has been machined
Abb. 2 Faserverlauf und tangentiale Proben. Die dunklere Fläche ist die bearbeitete Fläche

bility of the machine after 10 cuts of 0.05 mm, the absolute error can still be considered equal to 0.05 mm. This leads to very thin chips and a process very close to sanding instead of routing, and consequently a very clear reference surface. In fact, processing at 0.1 mm cut depth already results in surface defects, that when processing against the grain, propagate under the surface resulting in a bad reference surface. The final cut (0.5 mm or 1.5 mm) was made in the same working cycle in order to reduce positioning errors as much as possible and minimise the play of the machine.

The specimen was machined along and across the grain, and with and against the grain, varying the grain orientation in steps of 10° to 10°. To describe the grain orientation with respect to the blade, a system proposed by McKenzie (Ω–Φ) was used where Ω is the angle between the grain and the cutting edge and Φ the angle between the grain and the cutting velocity vector. The angle Ω was kept constant at 90° while Φ was varied. When $\Phi = 0°$ processing is along the grain, tilting the grain leads to processing with ($0 < \Phi < 90$) or against ($0 > \Phi > -90$) the grain (see Fig. 2). Finally, because the cutting geometry at 90° is the same at −90°, these values of Φ lead to processing across the grain. Tangential specimens were processed on their radial face in order to minimise the effects of the interactions between early- and late-wood (see Fig. 2). Specimens were cut as close to each other as possible in order to minimise the wood variability, and from a straight grain oriented board.

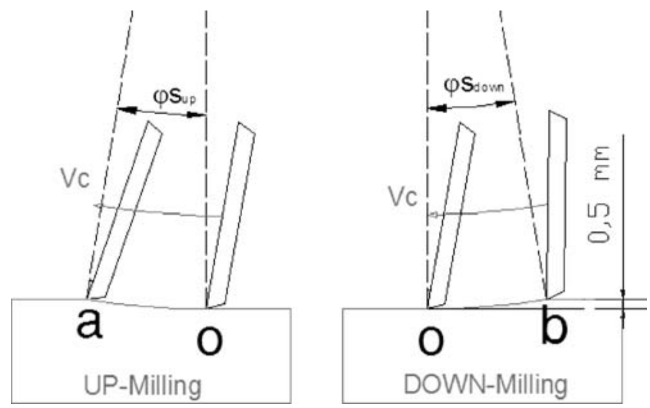

Fig. 3 Different impact point and coming out of the tool when up-milling or down-milling. Work angle ϕs_{up} for the up-milling technique and ϕs_{down} for the down-milling technique
Abb. 3 Verschiedene Auftreff- und Austrittstellen des Werkzeugs beim Gleichlauf- und Gegenlauffräsen. Fräswinkel ϕs_{up} beim Gleichlauffräsen und ϕs_{down} beim Gegenlauffräsen

3 Theoretical background

Solid wood is usually machined with the UM technique because of:

- the progressive increase of the chip thickness that leads to a lesser impact between tool and wood at the contact time,
- the limited wear of the tool when compared to down-milling,
- lesser safety concerns,
- very similar final surface status to the one achieved with the DM technique (the situation could be very different for wood derivates or for some specific processes).

When UM, although the chip is longer, the resulting lesser tool wear is due to the last part of the chip usually being torn away instead of being cut, and because of the progressive rather than abrupt beginning of the cut.

These differences between the two techniques are mainly ascribed to the different cutting geometries. When UM, the cut begins at the thinnest part of the chip (point *o* in Fig. 3), while DM begins at the thickest part (point *b* in Fig. 3). Moreover, in UM and DM, the relative orientation of the blade, in relation to the grain, changes. In fact in UM the tool cutting path is along the arc *oa* while in DM it is along the arc *bo* (see Fig. 3). In UM the maximum chip thickness is obtained very close to point (*a*), whereas it is close to point (*b*) when DM. Given that the rotation of the tool during cutting is the *work angle* (ϕs) it can be said that (see Fig. 4):

- during a cut, either in UM or DM, between the minimal chip thickness and the maximum chip thickness the tool has a rotation of ϕs,

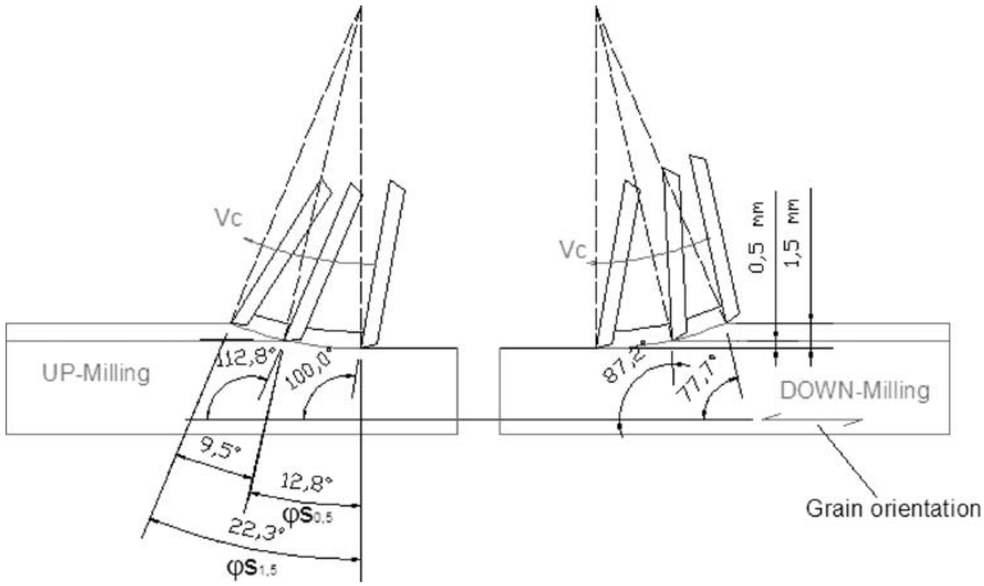

Fig. 4 Relative angles between the rake face and the grain at the maximum chip thickness level when up-milling or down-milling with 0.5 mm and 1.5 mm of depth of cut and a tool diameter of 40 mm

Abb. 4 Winkel zwischen Fräswerkzeug und Faserverlauf bei maximaler Spandicke beim Gleichlauf- und Gegenlauffräsen mit einer Frästiefe von 0,5 mm und 1,5 mm und einem Werkzeugdurchmesser von 40 mm

- this rotation, referred as to the grain orientation, corresponds to $+\phi s$ (*oa* arc) when UM and $-\phi s$ (*ob* arc) when DM,
- between the maximum chip thicknesses UM and the maximum chip thickness DM, the tool undergoes a rotation of $2\phi s$ (*ab* arc).

These are very important factors because the cutting forces and the cutting mechanisms are largely influenced by the chip thickness, and it is then expected that the magnitude and direction of the cutting forces will be mainly dependent on the processes acting at the maximum chip thickness levels. Given that the grain orientation (Φ) changes continuously with the cutting velocity vector direction, it is necessary to introduce two other factors in order to describe the processes: the *absolute grain orientation* (Φa), that is the grain orientation taking the new formed surface in machining as reference, and the *relative grain orientation* (Φr), that is the grain orientation value at the maximum chip thickness. Thus a specified *work angle*, that can be computed using Eq. 1,

$$\phi s = \arccos((R - p)/R) \tag{1}$$

from any Φa the relative grain orientation can be easily determined for the UM and DM processes using Eqs. 2 and 3.

$$\Phi r_{up} = \Phi a - \phi s \tag{2}$$

$$\Phi r_{down} = \Phi a + \phi s \tag{3}$$

Moreover, since between UM and DM with the same absolute grain orientation results in a shift of $2\phi s$, it means that to obtain the same relative grain orientation at the maximum chip thickness point (the same Φr) when UM or DM, different Φa must be chosen. Table 3 shows for a given value of Φa the resulting value of Φr when UM or DM with 0.5 or 1.5 mm of *doc*. For example processing with 0° of Φa with 0.5 mm of *doc*, UM will give a Φr of 12.8° while DM will give a Φr of −12.8°. A the same time it is clear that UM with Φr 12.8° and DM with Φr −12.8° will result in the same Φa of 0°.

From a geometrical point of view the greater the depth of cut, the greater ϕs and the greater the effect of the *rela-*

Table 3 Absolute grain orientations (Φa) and the corresponding relative grain orientations (Φr) for different depths of cut when up-milling and down-milling

Tabelle 3 Absoluter Faserverlauf (Φa) und entsprechender relativer Faserverlauf (Φr) für unterschiedliche Frästiefen beim Gleichlauf- und Gegenlauffräsen

Φa	$\Phi r_{0.5\ up}$	$\Phi r_{0.5\ down}$	$\Phi r_{1.5\ up}$	$\Phi r_{1.5\ down}$
−90	−77.2	77.2	−67.7	67.7
−80	−67.2	87.2	−57.7	77.7
−70	−57.2	−82.8	−47.7	87.7
−60	−47.2	−72.8	−37.7	−82.3
−50	−37.2	−62.8	−27.7	−72.3
−40	−27.2	−52.8	−17.7	−62.3
−30	−17.2	−42.8	−7.7	−52.3
−20	−7.2	−32.8	2.3	−42.3
−10	2.8	−22.8	12.3	−32.3
0	12.8	−12.8	22.3	−22.3
10	22.8	−2.8	32.3	−12.3
20	32.8	7.2	42.3	−2.3
30	42.8	17.2	52.3	7.7
40	52.8	27.2	62.3	17.7
50	62.8	37.2	72.3	27.7
60	72.8	47.2	82.3	37.7
70	82.8	57.2	−87.7	47.7
80	−87.2	67.2	−77.7	57.7
90	−77.2	77.2	−67.7	67.7

Table 4 Similar chips to be obtained when UM or DM processing with and against the grain with 0.5 mm depth of cut
Tabelle 4 Bedingungen zur Erzeugung ähnlicher Späne beim Gleichlauf- und Gegenlauffräsen in und gegen Faserrichtung mit einer Frästiefe von 0,5 mm

Against the grain										
$\Phi a_{0.5\ up}$	−90	−80	−70	−60	−50	−40	−30	−20	−10	00
$\Phi a_{0.5\ down}$	70	80	90	−80	−70	−60	−50	−40	−30	−20
With the grain										
$\Phi a_{0.5\ up}$	00	10	20	30	40	50	60	70	80	90
$\Phi a_{0.5\ down}$	−20	−10	00	10	20	30	40	50	60	70

Table 5 Similar chips to be obtained when UM or DM processing with and against the grain with 1.5 mm depth of cut
Tabelle 5 Bedingungen zur Erzeugung ähnlicher Späne beim Gleichlauf- und Gegenlauffräsen in und gegen Faserrichtung mit einer Frästiefe von 1,5 mm

Against the grain										
$\Phi a_{1.5\ up}$	−90	−80	−70	−60	−50	−40	−30	−20	−10	00
$\Phi a_{1.5\ down}$	50	60	70	80	90	−80	−70	−60	−50	−40
With the grain										
$\Phi a_{1.5\ up}$	00	10	20	30	40	50	60	70	80	90
$\Phi a_{1.5\ down}$	−40	−30	−20	−10	00	10	20	30	40	50

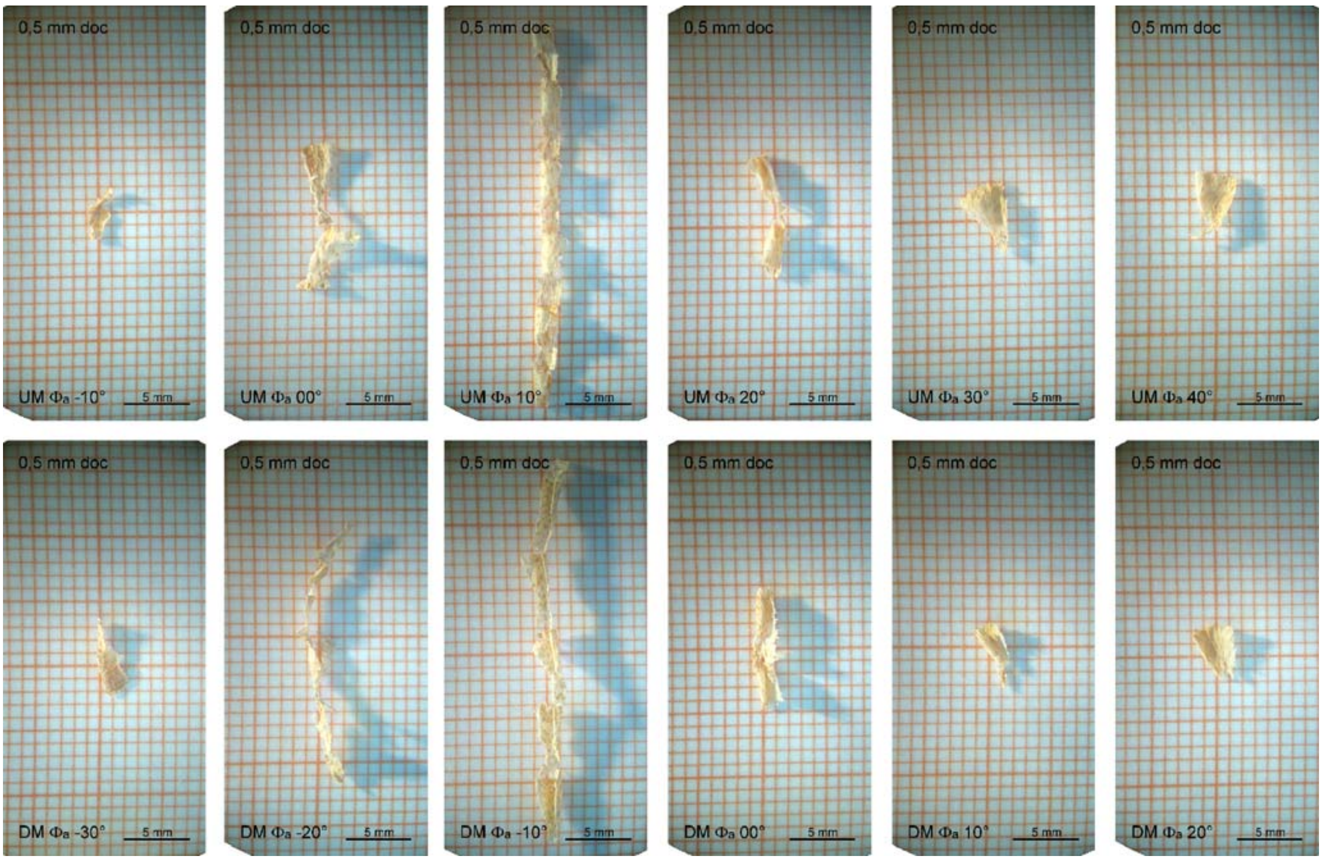

Fig. 5 Douglas fir chips obtained when up-milling and down-milling with different grain orientations with a 0.5 mm depth of cut
Abb. 5 Beim Gleichlauf- und Gegenlauffräsen und unterschiedlichem Faserverlauf mit einer Frästiefe von 0,5 mm erzeugte Douglasienspäne

tive grain orientation. In any case, relevant *work angles* do not necessarily result in a poor final surface status because the final surface quality mainly depends on mechanisms acting in a limited area near the surface (Koch 1972, Goli et al. 2004a, 2004b). Since the rotation of the tool inside this area does not usually lead to relevant shifts in the grain orientation, no relevant differences between the final quality within UM and DM processes were observed (Goli et al. 2002). The movement of the tool that, in UM, comes out from the surface tearing out the fibres, and in DM goes towards the surface, pressing fibres, appears to be a more significant influence on the final surface when UM and DM.

The result of these conditions is that rather than leading to relevant changes in the surface status, UM or DM lead to relevant changes in the cutting forces and chip types, and in particular the following is clear:

- the final quality will be strictly dependent on the *absolute grain orientation* (Φa) that determines the grain orientation near the forming surface,
- the chip types and the cutting forces will mainly depend on the *relative grain orientation* (Φr) because that will be the grain orientation at the maximum chip thickness level.

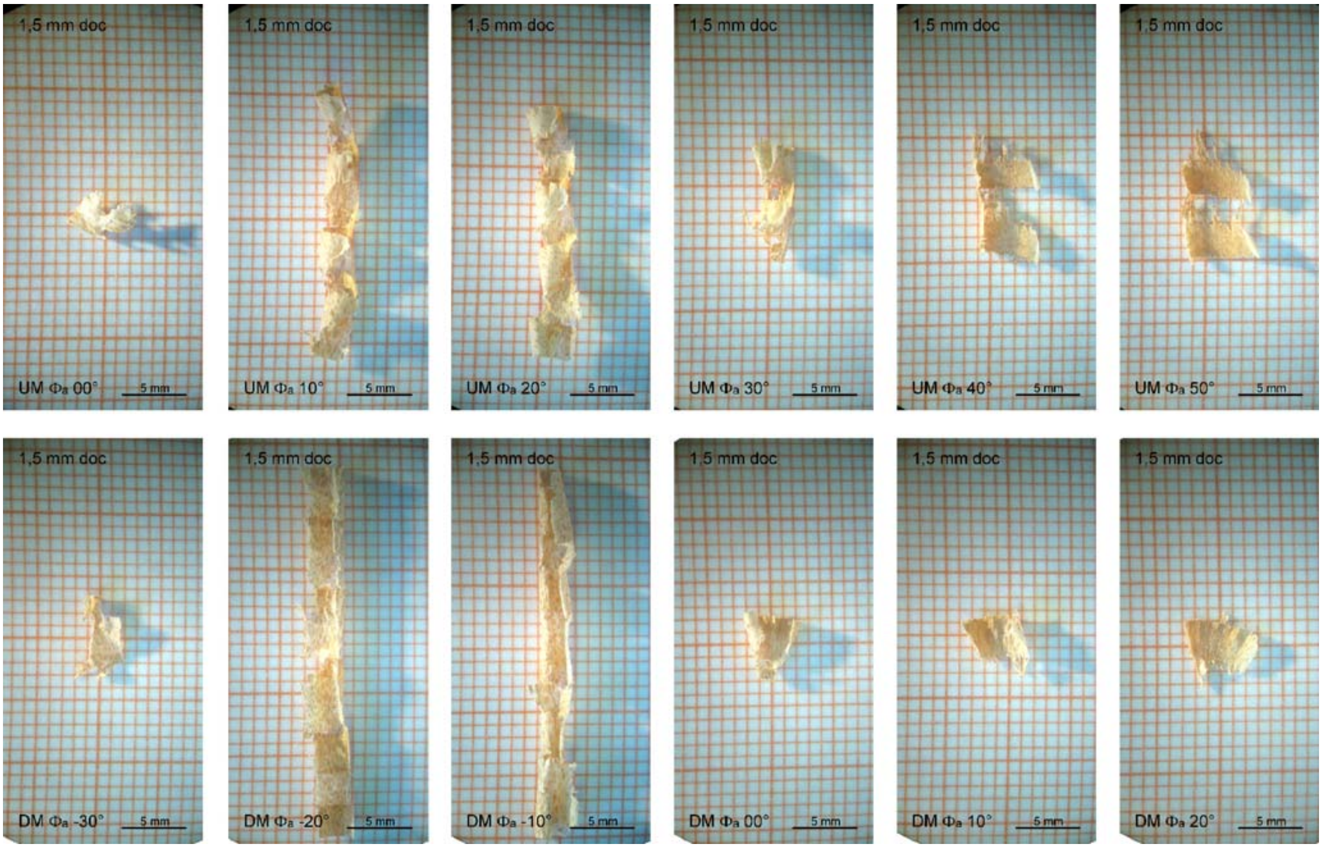

Fig. 6 Douglas fir chips obtained when up-milling and down milling with different grain orientations with a 1.5 mm depth of cut
Abb. 6 Beim Gleichlauf- und Gegenlauffräsen und unterschiedlichem Faserverlauf mit einer Frästiefe von 1,5 mm erzeugte Douglasienspäne

The practical effect of these considerations when UM and DM with the same Φa and the same *doc* will thus be:

- a shift of approximately $2\phi s$ in the Φa of the same chip type in the collected chips when ordered according to the absolute grain orientation,
- a shift of approximately $2\phi s$ in the Φa of the cutting forces when plotted vs. the absolute grain orientation.

4 Experimental results

Since in the experiments the samples are processed with increments of 10° of grain, the work angles computed in the theoretical part will need to be rounded off to the nearest 10° step. As ϕs processing with a 0.5 mm depth of cut is about 12.8°, it can reasonably be rounded off to 10°. And as ϕs is 22.3° when processing with a 1.5 mm depth of cut it can be reasonably rounded off to 20°. The practical effect of the theoretical background discussed previously should be that processing along the grain with $\Phi a = 0°$ results in similar chips when UM with $\Phi a = 10°$ or DM with $\Phi a = -10°$. This is because at their thickest parts, the chips have a very close relative grain orientation. The values reported in Tables 4 and 5 should help to compare similar chips and to interpret Figs. 5 and 6. The case previously discussed for a *doc* of 1.5 mm should result in the same type of chips when UM with $\Phi a = 20°$ and DM with $\Phi a = -20°$.

In a photographic comparison of the chips obtained when processing with 0.5 mm *doc* (see Fig. 5) this behaviour can be clearly observed and a shift is visible in the chip type of about 20° as discussed before. The chip obtained when UM with a Φa of 00° is similar to those obtained when DM with Φa −20°, and the same for the other orientations investigated. Even when processing with 1.5 mm *doc* a shift can be clearly observed. In this case the shift is bigger than for 0.5 mm *doc* but not as big as expected. In fact for 0.5 mm *doc* the expected shift is 20°, the same value observed in the chip type, for 1.5 mm *doc* the expected shift is 40° while the real shift was found to be 30° (see Fig. 6). This is probably because when increasing the *doc* the chip in the last part is not cut but torn away. Because of this the cut happens at an angle $\phi i < \phi s$ that results in a lower value than the one computed theoretically. The theoretical background previously discussed is then completely supported by this experimental part concerning the chip examination.

5 Conclusion

Cutting wood with different grain orientation offers a wide range of phenomenon. The geometric basics have been discussed in this paper and some relevant connections have been found between grain orientation and depth of cut. Absolute and relative grain orientations have been defined and discussed. The experimental part presents evidence totally supporting the theoretical assumptions advanced. The differences in the relative grain orientation analysed in the theoretical part have been shown to have significant consequences on the chip type when up-milling and down-milling with different grain orientations and depths of cut. For chip types the resulting processes shifted according to the rotation of the tool during the process. In particular, the resultant chip type was found to be identical when processing with the same relative grain orientation.

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