

Article

Influence of Process Parameters and Rake Angle on Modeling of Cutting Forces in Wood-Based Materials

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Abstract

The environmental impact of technical systems is becoming increasingly important. Particularly in mechanical engineering, with its high demands on process stability and product quality, environmentally beneficial materials such as wood, with its heterogeneous and anisotropic structure, present challenges. Therefore, understanding the cutting process and the cutting forces is of great importance. This publication builds upon an established cutting force model and presents experiments to determine the specific cutting force ($k_{c0.5}$) and normal cutting force ($k_{cn0.5}$) for birch plywood. Furthermore, the influence of the rake angle ($K_{\gamma c}$ and $K_{\gamma cn}$) and the cutting speed (K_{vc} and K_{vcn}) on the cutting forces is investigated. These correction factors are integrated into the established cutting model and verified under the assumption of no relevant directional dependence of the cutting forces due to the fibers of the plywood under investigation at the macroscopic level. The correction factors were determined based on the experiments and show a high degree of agreement with experimentally measured values. The correction factors lead to an increase in accuracy of predicting cutting forces during the peripheral milling of birch plywood. The model enables the prediction of cutting force with an average 30% increase in accuracy compared to the reference model. The results thus allow for a more accurate description of the cutting forces, from which important insights can be derived in the future for optimizing the cutting process and the tool, as well as for addressing tool wear and process quality.

Keywords: modeling; machining force model; cutting forces; sustainable manufacturing; plywood; wood veneer composite



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1. Introduction

1.1. Motivation and State of the Art

When assessing products, the environmental impact of systems is becoming increasingly important alongside technical specifications [1,2]. This trend is leading to global initiatives to develop and implement new process technologies aimed at improving and optimizing manufacturing systems [3], and has also boosted demand for sustainable and environmentally friendly construction materials in mechanical engineering [4].

Selected woods and wood-based materials represent a promising option for such environmentally beneficial materials [1,2]. Wood is a natural material with a complex cellular structure that is optimally adapted to the tree's living conditions [5]. Different cell types perform various functions, such as providing strength and facilitating the transport

and storage of nutrients and water. Due to the growth process, anisotropic and inhomogeneous mechanical material properties arise. Particularly in the longitudinal direction, wood exhibits high strength combined with low weight, making it a high-performance, natural lightweight construction material. Its anisotropic and inhomogeneous structure also means that wood's cutting behavior varies significantly depending on the direction [6]. Consequently, wood properties relevant to machining can vary by several hundred percent depending on the direction of the fiber within the wood, making the precise design and calculation of machining processes challenging [5]. Natural variations in cell structures and uneven distributions of chemical substances further contribute to influencing machining properties.

By rearranging the structural elements through processes that involve cutting and subsequently joining the wood, the direction-dependent properties of the resulting composite materials can be specifically influenced. This reduces the anisotropic behavior of the wood and improves its suitability for the intended application. Dunky and Niemz [7] provide an overview of the classification of wood-based materials. A classification of the components of wood-based materials is also provided.

For applications in mechanical engineering, there are requirements on the dimensional accuracy of components and the homogeneity and reproducibility of workpiece properties. These must be achievable using suitable processes, whilst taking into account the anisotropic properties of wood as a material [8]. Consequently, knowledge of the cutting process during manufacture, particularly the cutting force and its effect on the component, becomes increasingly relevant [9]. Many studies focus on the investigation of manufacturing parameters, their effect on the overall process, and the resulting product properties. In these studies, however, extensive empirical investigations focus only on specific tool, machine, and workpiece parameters and do not allow for a comprehensive examination of the cutting process. For instance, Hlášková et al. determine the cutting force and specific cutting resistance of modified beech wood, attempt to calculate the fracture parameters for cuts in the axial-perpendicular direction based on experimental results, and compare the results with untreated beech wood using sawing processes as an example [10]. Rawangwong et al. investigated the influence of various factors on surface roughness during the turning of coconut and palmyra palm wood for the manufacture of furniture components using carbide cutting tools, focusing on the factors of cutting speed, feed rate and depth of cut to achieve optimal surface roughness [11]. Similarly, the study by De Deus et al. demonstrated the relationship between cutting speed, feed rate and depth of cut on the surface quality of medium-density fiberboard (MDF) [12]. Atanasov et al. also conducted an experimental investigation into the influence of key process parameters in the solid wood milling process of tropical meranti wood (feed rate and chip thickness) on surface roughness [13]. Demir et al. also investigated the effects of machining parameters (spindle speed, feed rate and cutting tool diameter) on CNC milling machines on the surface quality of plywood, chipboard and medium-density fiberboard (MDF) [14]. Adamčík et al. also investigate the influence of feed rate and spindle speed during CNC milling on the surface quality of plywood for industrial applications and likewise establish a correlation with surface roughness parameters [15].

Cutting force, as one of the most important process variables, is a combination of factors arising from tool geometry parameters, machine tool precision and rigidity, process parameters (such as cutting speed and feed rate, etc.) and material properties. Due to these multidimensional, mutually influencing parameters, the development of mathematical models to describe cutting force is a critical task.

One approach to obtaining more accurate predictions regarding the cutting process is the development of cutting force models [5]. These serve to precisely describe the

forces acting between the tool and the workpiece during the cutting process [16]. Cutting force models thus aim to optimize manufacturing processes, improve manufacturing quality and extend the service life of tools. The two main approaches are empirical and analytical descriptive models, with the latter forming the basis for the first numerical cutting force models [17]. Empirical cutting force models are widely used in practice. They are based on previously conducted practical experiments and mathematically describe the relationship between the machining parameters and the cutting forces, without a detailed analysis of physical processes. Analytical models use explicit physical laws to model the behavior of a system and can usually only be formulated for simple systems. Other modelling approaches and combinations also exist. The literature indicates that the analytical approach to calculating the cutting force is not applicable, or is applicable only to a limited extent, due to its mathematical complexity and missing parameters [18].

1.2. Research Objective and Questions

The Kienzle model is well-established in mechanical engineering for calculating cutting forces during the machining of isotropic metallic materials. This model is based on the observation that an empirically determined, material-dependent specific cutting force exhibits a double-logarithmic relationship with chip thickness [19]. Gottlöber [5] has adapted and validated this model for the anisotropic properties of wood-based materials. However, this model does not take into account any process- or tool-related correction factors, as found in the Kienzle model, which limits the predictive accuracy of the model.

This paper therefore focuses on describing the determination of the specific cutting force ($k_{c0.5}$) using birch plywood as an example. Furthermore, a model extension based on experimental results is implemented, and it is examined whether the extended cutting force model for this wood-based composite material can be described on a macroscopic level based on no relevant directional dependence of the cutting forces. The model adjustments also focus on the influence of the rake angle and the cutting speed. This work therefore aims to answer the following research questions (RQ):

- RQ1: Are established cutting force models for isotropic materials also valid for peripheral milling in the plane of 0/90° plywood?
- RQ2: How do the rake angle and cutting speed influence the cutting force and normal cutting force?
- RQ3: Does the proposed model improve the prediction accuracy compared with the established Gottlöber model?

By investigating the influence of these parameters, the model extension for cutting force determination leads to improved predictions of cutting forces in the machining of wood-based materials. The results enable a more differentiated and quantitatively more accurate characterization of the expected cutting force components.

2. Methods

In the cutting force models developed by Kienzle and Gottlöber, the cutting force corresponds to the vector sum of the individual component forces. These components consist of the cutting force F_c , which represents the force acting orthogonally to the tool edge in the working plane. The second component is the normal cutting force F_{cn} , which represents the force acting orthogonally to F_c in the working plane. The third force component is the passive force F_p , which is orthogonal to both F_c and F_{cn} . By vectorially adding these three cutting force components, the resulting cutting force F_z can be calculated with Equation (1).

$$F_z^2 = F_c^2 + F_{cn}^2 + F_p^2 \quad (1)$$

Studies have shown a proportional relationship between the chip cross-sectional area A and a proportionality factor, referred to as the specific cutting force k_c , which describes the material-dependent resistance to chipping per mm^2 of area. This area, the stress cross-section A , is calculated, as shown in Equation (2), as the product of the cutting width b and the cutting thickness h .

$$A = b \cdot h \quad (2)$$

The specific cutting force k_c is calculated, as shown in Equation (3), from the material-dependent principal value of the specific cutting force $k_{c1.1}$ and the depth of cut h , taking into account the increase in cutting resistance m_c .

$$k_c = h^{-m_c} \cdot k_{c1.1} \quad (3)$$

In the case of peripheral milling, due to the interrupted cut and the resulting changing chip thickness, the depth of cut h shown above is determined by the average chip thickness h_m [5] over the cutting edge contact time, which can be calculated using Equation (4). Here, a_e is the depth of cut in mm; D is the diameter of the tool in mm; f_z is the feed per cutting edge in mm; v_f is the feed speed in mm/min; i is the number of cutting edges on the milling tool; n is the rotational speed of the tool in rpm; and [5] provides the entering angle κ in $^\circ$ (see Figure 1).

$$h_m = \frac{a_e \cdot 360^\circ \cdot \sin \kappa}{D \cdot \pi \cdot \arccos\left(1 - \frac{2 \cdot a_e}{D}\right)} \cdot f_z = \frac{a_e \cdot 360^\circ \cdot \sin \kappa}{D \cdot \pi \cdot \arccos\left(1 - \frac{2 \cdot a_e}{D}\right)} \cdot \frac{v_f}{i \cdot n} \quad (4)$$

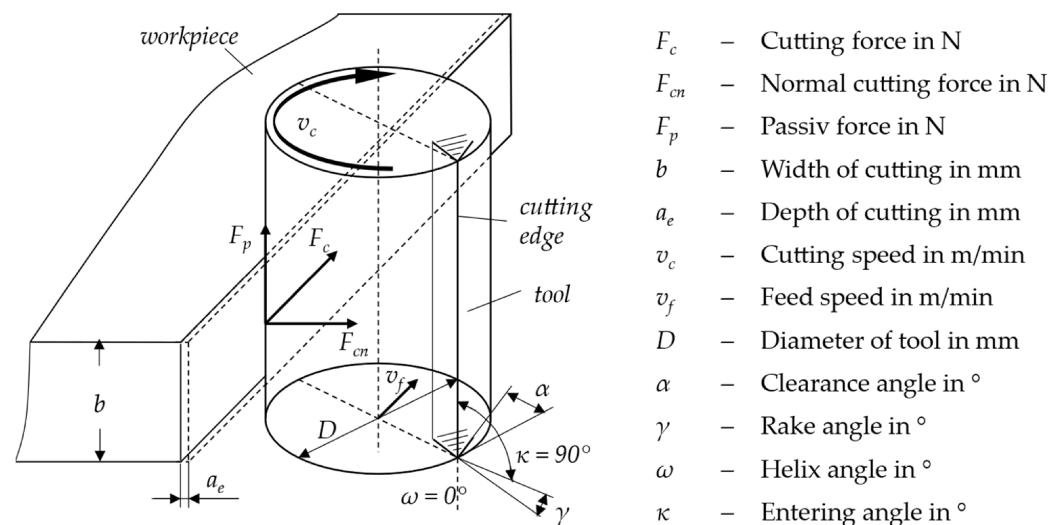


Figure 1. Schematic illustration of the tool's cutting path starting from the edge of the plywood (up-cut milling).

A key difference in the calculation of the cutting force components according to Kienzle and Gottlöber lies in the fact that, in Kienzle's model, the increase in cutting resistance has a variable value, whereas in Gottlöber's model m_c is a constant ($m_c = 0.5$), which also results in an adjustment of the variable cutting value to $k_{c0.5}$. In the standard processing of wood products, such a simplification of the non-linearity is often acceptable [5]. A further difference is that, in contrast to the Gottlöber model, the Kienzle model employs correction factors K_i , such as for cutting material, rake angle, cutting speed, cooling lubrication strategy or tool wear. The individual cutting force components can be calculated using the following formulas, where Formulas (5)–(7) represent the calculation according to Kienzle and Formulas (8)–(10) represent the calculation according to Gottlöber.

Machining force components according to Kienzle [19]:

$$F_c = A \cdot k_c \cdot \prod K_i = b \cdot h_m^{1-m_c} \cdot k_{c1.1} \cdot \prod K_i \quad (5)$$

$$F_{cn} = A \cdot k_{cn} \cdot \prod K_i = b \cdot h_m^{1-m_{cn}} \cdot k_{cn1.1} \cdot \prod K_i \quad (6)$$

$$F_p = A \cdot k_p \cdot \prod K_i = b \cdot h_m^{1-m_p} \cdot k_{p1.1} \cdot \prod K_i \quad (7)$$

Machining force components according to Gottlöber [5]:

$$F_c = b \cdot h_m^{0.5} \cdot k_{c0.5} \quad (8)$$

$$F_{cn} = b \cdot h_m^{0.5} \cdot k_{cn0.5} \quad (9)$$

$$F_p = b \cdot h_m^{0.5} \cdot k_{p0.5} \quad (10)$$

For the investigated birch plywood, the cutting force components can be calculated using Gottlöber's cutting force model. Due to the bidirectional structure of the plywood layers, in which the fibers in each layer are rotated by 90° , this study makes the simplified assumption that, at the macroscopic level, the fiber orientation of the individual plywood layers has no significant directional influence on the cutting forces in the x- and y-directions. This assumption is based on the parameters in Gottlöber's cutting force model for the composite materials chipboard and MDF, which also exhibit a superimposed fiber orientation across their thickness. For these materials, a single $k_{c0.5}$ value is specified, rather than a specific cutting force for each of the three main cutting directions, as is the case with all other wood-based materials. However, this assumption must be verified in the experiments to be conducted. This simplification makes it possible to introduce direction-independent correction values for the rake angle and cutting speed within the described directions. In order to maintain the assumption of the absence of a directional dependence of the cutting forces of the plywood in the longitudinal and transverse directions, it is necessary to avoid the occurrence of forces in the direction of the board thickness in the tests to be carried out. This can be achieved by performing peripheral milling on the chipboard whilst ensuring that the helix angle of the milling cutter is $\omega = 0^\circ$, meaning that, in theory, no passive forces occur. All relevant variables, forces and angles for the peripheral milling carried out in the tests, in the form of a finishing process of the plywood edge, are summarized schematically in Figure 1.

In order to calculate the cutting force components for this process, the following parameters must be taken into account in addition to the variably adjustable process parameters, according to [6]: cutting speed v_c , tool geometry (rake angle γ , helix angle ω , entering angle κ).

It is therefore necessary to include correction factors for this speed and these angles in the calculation. Due to the absence of a helix ($F_p = 0$) and the entering angle of 90° , with the tool positioned orthogonally to the side surface of the chipboard, these correction factors are neglected in this study. The relevant correction factors are therefore the cutting speed correction K_{v_c} and the correction factor for the rake angle K_γ . The Gottlöber model is extended in accordance with Equations (11) and (12).

$$F_c = b \cdot h_m^{0.5} \cdot k_{c0.5} \cdot K_{v_c} \cdot K_\gamma \quad (11)$$

$$F_{cn} = b \cdot h_m^{0.5} \cdot k_{cn0.5} \cdot K_{v_{cn}} \cdot K_{\gamma_{cn}} \quad (12)$$

Based on the assumption of the absence of a relevant directional dependence of the cutting forces of the birch plywood material in the x-y plane, the function types of the established correction factors from the Kienzle model are adopted for the Gottlöber model. The

applicability of these approaches is tested and verified through the experiments conducted. A successful application of the correction functions can also be interpreted as an indication of the absence of a relevant directional dependence of the cutting forces. The correction factors in the Kienzle cutting force model are calculated according to Equations (13)–(16). Here, K_{v_c} and $K_{v_{cn}}$ are correction factors for the cutting velocity of the cutting force and normal cutting force, whilst K_{γ_c} and $K_{\gamma_{cn}}$ are correction factors for the influence of the rake angle on the cutting force and normal cutting force. In turn, Formulas (13) and (14) demonstrate a linear model of correction factors K_{γ_c} and $K_{\gamma_{cn}}$ depend from rake angle γ . The parameters a_{γ_c} and $a_{\gamma_{cn}}$ indicate a linear decrease in process forces as the rake angle increases, while the parameters γ_{0_c} and γ_{0_cn} are constants for the material being machined. Formulas (15) and (16) employ a power function representing the dependence of the correction factor on the cutting speed v_c . The parameters in these models are the initial cutting speed v_{c0} and the exponents x_c x_{cn} .

$$K_{\gamma_c} = 1 - a_{\gamma_c} \cdot (\gamma - \gamma_{0_c}) \quad (13)$$

$$K_{\gamma_{cn}} = 1 - a_{\gamma_{cn}} \cdot (\gamma - \gamma_{0_cn}) \quad (14)$$

$$K_{v_c} = \left(\frac{v_c}{v_{c0}} \right)^{x_c} \quad (15)$$

$$K_{v_{cn}} = \left(\frac{v_c}{v_{c0}} \right)^{x_{cn}} \quad (16)$$

3. Experimental Setup and Procedure

To analyze the specific cutting forces and to determine the influence of the rake angle and cutting speed on the cutting force, all experimental investigations were carried out on a DMC V850 CNC machine from DMG MORI (Bielefeld, Germany). The forces acting on the workpiece were recorded by a Kistler 9255B 3-component dynamometer and pre-processed by a Kistler 5070A charge amplifier (measurement frequency 19.2 kHz). The material used is bidirectional 0/90° fabric birch plywood with a thickness of 21 mm and 15 layers. The material is machined using eight-fluted carbide end mills with a tool diameter of 20 mm. The cutters have a clearance angle of 20° and rake angles between 6° and 41°.

Table 1 provides a summary of the machines, equipment, materials and process parameters used.

Table 1. Equipment and process parameters used for modelling.

Equipment & Process	Parameter	
Machine tool	DMC V850 by DMG MORI	
	Max. rotational speed	18,000 rpm
	Maximum axis speed	42 m/min
Force gauge	Kistler 3-Component-Dynamometer 9255B	
	Measuring range	−20 kN to +40 kN
	Measurement accuracy	<0.01 N
Tool	Material	K-40UF (Carbide)
	Diameter (d)	20 mm
	Number of cutting edges	8
	Helix angle (ω)	0°
	Entering angle (κ)	90°
	Clearance angle (α)	20°
	Rake angle (γ)	6°, 11°, 16°, 21°, 26°, 31°, 36°, 41°

Table 1. Cont.

Equipment & Process	Parameter	
Workpiece	Material	birch plywood
	Width of cut (b)	21 mm
	Number of veneer layers	15 Layers, symmetrical, bidirectional $0^\circ/90^\circ$
Process	Cutting speed (v_c)	125 to 1125 m/min
	Feed speed (v_f)	2000 and 8000 mm/min
	Depth of cut (a_e)	0.6 mm

For the experiments, a peripheral milling process was designed for birch plywood in such a way that as many overlapping, direction-dependent effects as possible were eliminated by the experimental setup itself. To avoid passive forces, a tool with a helix angle of 0° was used and the tool was guided parallel to the workpiece ($\kappa = 90^\circ$). A finishing process with a cutting depth of 0.6 mm was selected as the machining strategy to evaluate the cutting forces of each cutting edge separately, since only one cutting edge is in contact at a time. The parameters varied in the investigations were the rake angle and the cutting speed, in order to determine the correction factors K_γ and K_{vc} . Furthermore, the feed speed v_f was varied, since the feed changes the chip cross-section and thus alters the cutting force. This enables the determination of the specific cutting force of birch plywood. The parameters measured during the experiment and subsequently analyzed in further detail are the cutting force components during machining. All tests were conducted with a constant tool setting and the corresponding process parameters (feed speed and cutting speed) in up-cut milling (see Table 1). For the analysis, the mean values of the measured values from 20 cutting-edge engagements were used for each parameter variant. The left-hand side of Figure 2 shows the experimental setup described above. The right-hand side schematically depicts the force vectors measured by the measuring platform (orange) and those required for calculating the cutting force (blue). The conversion of the measurement data from the workpiece coordinate system (orange) to the tool coordinate system (blue) is performed using Equations (17)–(19), where φ_0 denotes the cutting arc angle within which a cutting edge is in contact with the workpiece.

$$F_{c_test} = F_x \cdot \cos\varphi - F_y \cdot \sin\varphi \quad (17)$$

$$F_{cn_test} = F_y \cdot \cos\varphi + F_x \cdot \sin\varphi \quad (18)$$

$$\varphi = \arccos(1 - 2 \cdot a_e / D) \quad (19)$$

To enable a comparison of the experimental data based on the average chip thickness for the various cutting edge geometries, the arithmetic mean of the cutting force F_{cm} for the engagement of a cutting edge was calculated. A correlation was found between the maximum measured cutting force per cutting edge engagement ($F_{c_test_peak}$) and the arithmetic mean of the cutting force, taking into account the contact time of a cutting edge with the workpiece. A measurement curve of the cutting force over time for a single cutting edge contact is shown as an example in Figure 3. The force values for modeling are calculated from the integral under the measurement curve. The integral value can be estimated using the simplified Formulas (20) and (21). This simplification results in a maximum deviation in cutting force of 6%, which is acceptable for most practical applications. In this way, data sets for the cutting force and normal cutting force were generated for each experiment.

$$F_{c,m} = \frac{1}{T} \int_0^T F_{c_test} dt \approx 0.61 \cdot F_{c_test_peak} \quad (20)$$

$$F_{cn,m} = \frac{1}{T} \int_0^T F_{cn_test} dt \approx 0.7 \cdot F_{cn_test_peak} \quad (21)$$

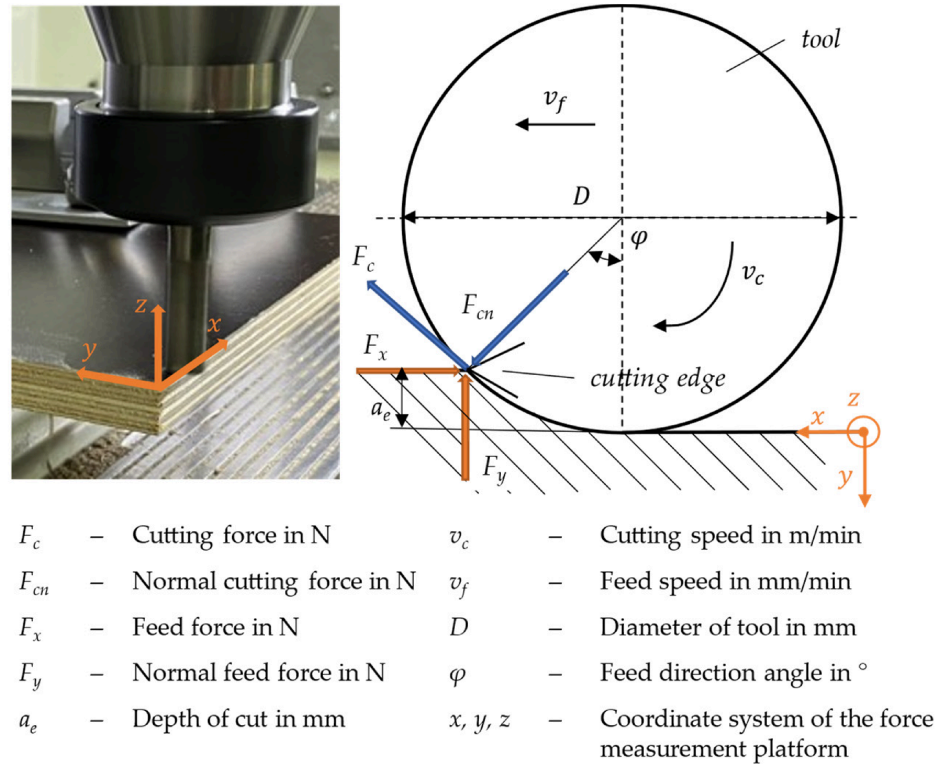


Figure 2. Workpiece- and tool-related force systems in peripheral milling of plywood (up-cut milling).

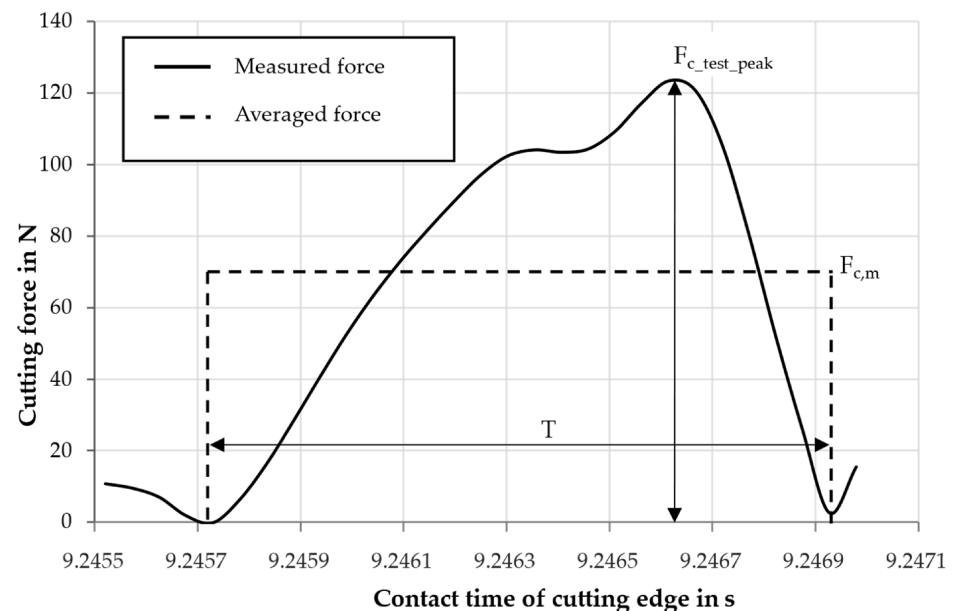


Figure 3. Force with dependence on time during the engagement of a cutting edge and the simplification of this to the average force for the model.

4. Results

Initially, a series of tests was conducted at a constant cutting speed to determine the specific cutting force, the specific normal cutting force, and the influence of the rake

angle. In these tests, the feed speed (2000 mm/min and 8000 mm/min) and the rake angle were varied according to the methodology described above. The correction factor v_{c0} in Equations (15) and (16) was set to 125 m/min, since lower cutting speeds are uncommon in wood machining. To determine the specific cutting force k_c later, the influence of the correction factors must be eliminated as much as possible. For this reason, a cutting speed of 125 m/min was selected for these experiments. Furthermore, to ensure that only one cutting edge is in contact, a cutting depth of 0.6 mm was selected, as described in Table 1.

Figure 4 shows a comparison of the cutting force, the normal cutting force and the passive force over the contact time of the individual cutting edge. The force curve in the diagram shows an increasing cutting force, which can be attributed to the increase in the depths of cut caused by up-cut milling and, consequently, a steady increase in the cross-sectional area until the cutting edge exits the workpiece material. The normal cutting force and the passive force are lower than the cutting force. The passive force amounts to approximately 5–7% of the cutting force. The average normal cutting force is approximately half the average cutting force. Furthermore, the normal cutting force and the passive force are superimposed with a coherent oscillation. This was observed across all measurements. The oscillations occur particularly in the direction of the normal cutting force and in the direction of the passive force. One possible explanation is a periodic fluctuation in the cutting or engagement conditions. Such fluctuations may be attributable either to the inhomogeneity of the fiber-reinforced composite or to relative movements between the tool and the workpiece, which lead to variations in the cutting depth. Due to the way the workpiece is clamped, it has a cantilevered length and can be regarded as a bending beam that can be set into vibration by external loads. Several factors contribute to such vibrations: the low bending stiffness in the thickness direction resulting from the plate geometry, the absence of fiber reinforcement in this direction, as well as the shallow cutting depth and the resulting low cutting forces. Particularly at shallow cutting depths, even slight deflections can lead to comparatively large relative changes in the cutting conditions and thus to clearly visible fluctuations in force. One possible excitation mechanism is the interrupted cut in milling processes, as each contact of the cutting edge induces a pulse into the workpiece. Additional excitation may result from the breaking or tearing out of individual fibers. However, it seems unlikely that individual fiber breakage events are directly reflected in the force signal, since the observed force oscillation has a frequency of approximately 2 kHz, whereas individual fiber breakage events occur at a significantly higher frequency. Based on the available results, it is therefore assumed that the observed vibrations are primarily related to the cantilevered length of the workpiece and are attributable to a natural frequency of the workpiece. However, this argumentation should be verified in further investigations, for example, through impact hammer tests, structure-borne sound measurements, or high-speed recordings.

The results presented do not show any directional dependence of the forces under different contact conditions and fiber separation angles. Therefore, it is assumed that, for a macroscopic cutting force model, the cutting forces in the X-Y plane can be considered direction-independent.

Figure 5 shows the effect of the rake angle and feed speed on the cutting force. It can be seen that the cutting force decreases as the rake angle increases. The relationship between the rake angle and the cutting force can be described by a monotonically decreasing, concave curve. The average cutting force can be reduced by half by using a highly positive rake angle ($\gamma = 41^\circ$) compared to an almost neutral rake angle ($\gamma = 6^\circ$). This can be explained, in part, by the reduced amount of chip deformation required, but also by the orientation of the fiber layers, with the fiber direction aligned with the feed direction. Under the selected cutting conditions, these layers do not necessarily have to be cut through at large positive

rake angles. Furthermore, similar to conventional machining processes for homogeneous materials, it is evident that cutting forces increase as the feed rate increases. For example, the cutting force nearly doubles when the feed rate increases from $v_f = 2000$ mm/min to $v_f = 8000$ mm/min.

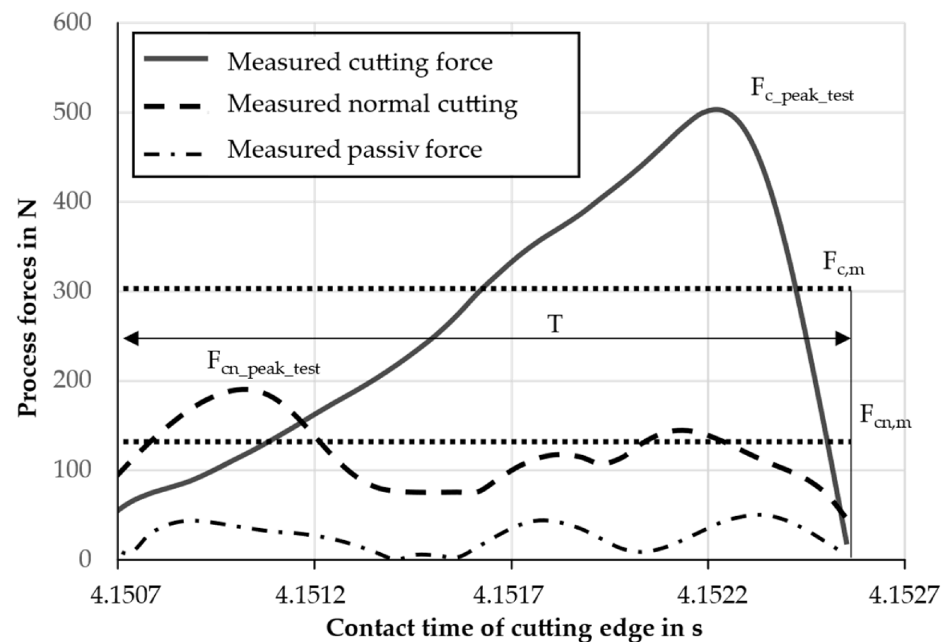


Figure 4. Comparison of measurement data for the cutting force components during the engagement of a cutting edge.

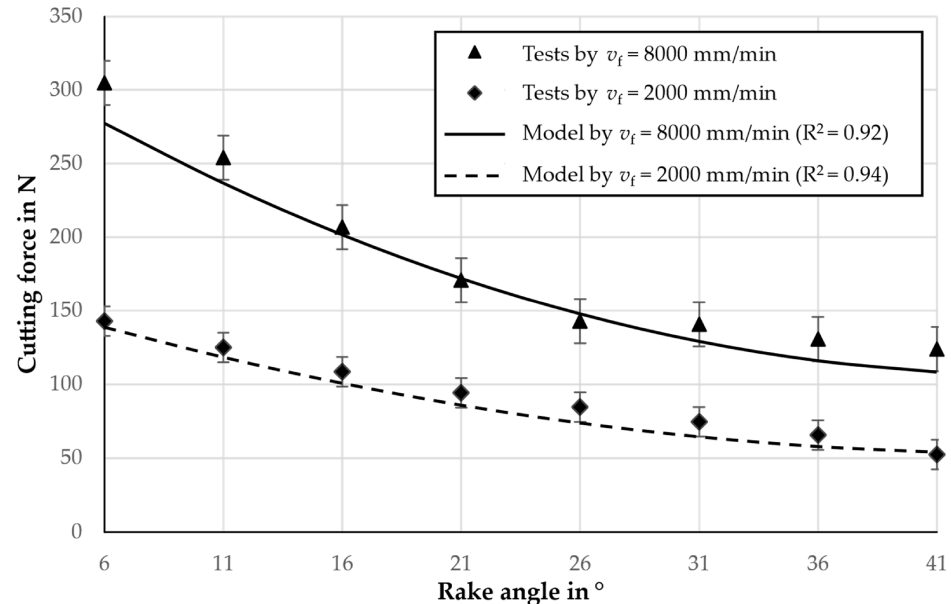


Figure 5. Effect of the rake angle and feed speed on the measured cutting force at a cutting speed $v_c = 125$ m/min.

Figure 6 illustrates the influence of the rake angle and feed speed on the normal cutting force. In general, it is evident that, due to the superimposed vibration described above and the simultaneously low cutting normal forces, the accuracy of a model to be developed later is reduced. The error caused by the vibration is so large compared to the cutting normal force that the standard deviations (error bars) increase significantly. The effect of the rake angle on the normal cutting force is analogous to that on the cutting force. Only the effect

of a change in feed speed has a smaller impact on the normal cutting force. Qualitatively, the normal cutting force exhibits the same dependence on the rake angle correction as the cutting force.

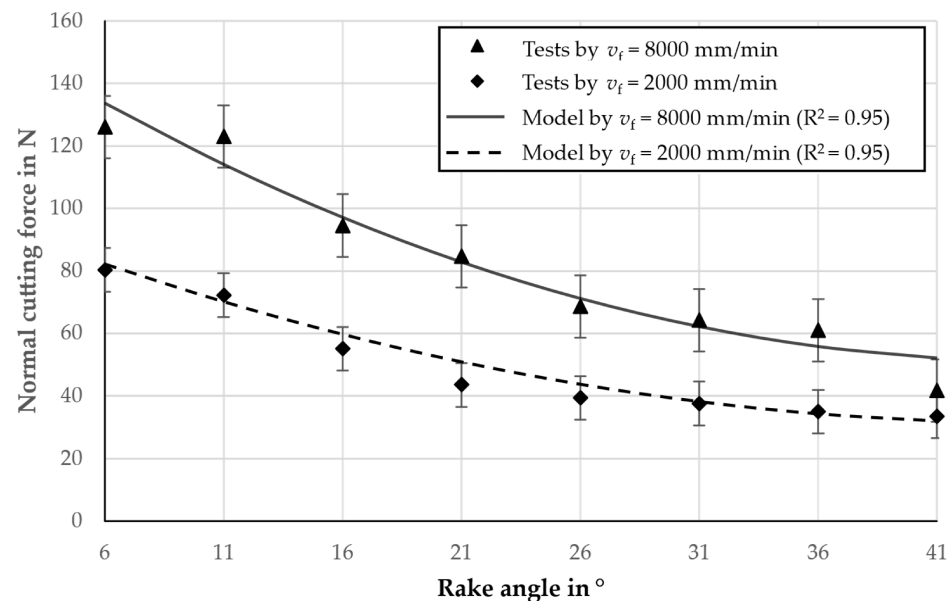


Figure 6. Effect of the rake angle and feed speed on the measured cutting normal force at a cutting speed $v_c = 125$ m/min.

4.1. Determination of Specific Cutting Force $k_{c0.5}$ $k_{cn0.5}$ and Rake Angle Correction Factor K_{γ_c} and $K_{\gamma_{cn}}$

After processing the measurement data, the model parameters suitable for the cutting force model and the normal cutting force model were determined. First, the specific cutting forces $k_{c0.5}$ and $k_{cn0.5}$ as a product with the correction factors of rake angles K_{γ_c} and $K_{\gamma_{cn}}$ on cutting and normal cutting forces are determined using Equations (22) and (23). The data for this are taken from the test series described above. The influence of the cutting speed can again be eliminated by using a cutting speed of 125 m/min.

$$k_{c0.5} = \frac{F_{c,m_test}}{b \cdot h_m^{0.5} \cdot K_{\gamma_c}} \quad (22)$$

$$k_{cn0.5} = \frac{F_{cn,m_test}}{b \cdot h_m^{0.5} \cdot K_{\gamma_{cn}}} \quad (23)$$

In the next step, the specific cutting forces $k_{c0.5}$ and $k_{cn0.5}$, as well as the correction factors of rake angles K_{γ_c} and $K_{\gamma_{cn}}$, were determined using the least-squares method. Equation (24) describes the rake angle correction factors for the cutting force, and Equation (25) describes the same correction for the normal cutting force. These equations are plotted in Figures 5 and 6.

$$K_{\gamma_c} = 1 - 0.03 \cdot \gamma + 0.00035 \cdot \gamma^2 \quad (24)$$

$$K_{\gamma_{cn}} = 1 - 0.03 \cdot \gamma + 0.00033 \cdot \gamma^2 \quad (25)$$

A quadratic function was chosen to correct for the influence of the rake angle in wood machining, as it more accurately describes the relationship between the rake angle and the cutting force over a wider range of angles. In conventional metal machining, tools with rake angles of $\gamma \leq 25^\circ$ are predominantly used. Accordingly, there is only limited knowledge regarding the influence of larger rake angles on the cutting force. Within the range of 6° to 25° , the relationship can also be approximately described by a linear function in wood

machining, analogous to the rake angle correction for steel according to Equation (26). However, when the range of rake angles under consideration is expanded, it becomes apparent that this linear function no longer adequately represents the actual relationship, making a quadratic description necessary.

$$K_{\gamma_{c, \text{steel}}} = 1 - 0.015 \cdot (\gamma^\circ - 2^\circ) \quad (26)$$

Thus, the full range of values for the specific cutting force $k_{c0.5}$ was determined to be 52–62 N/mm^{1.5}. However, the range 52–54 N/mm^{1.5} was adopted, as it yields an R² value of 0.92–0.94, see Figure 5. The full range of values for the specific normal cutting force $k_{cn0.5}$ was determined to be 21–33 N/mm^{1.5}. The range 24–32 N/mm^{1.5} was adopted, as it yields an R² value of 0.95; see Figure 6. These values, determined from the experiments, and the tabulated values for solid birch wood are summarized in Table 2.

Table 2. Specific cutting force constant for birch wood-based materials.

Model		Value in $\frac{N}{mm^{1.5}}$
specific cutting force for birch plywood	$k_{c0.5}$	52 ... 54
specific normal cutting force for birch plywood	$k_{cn0.5}$	24 ... 32

The measured values of the specific cutting force $k_{c0.5}$ for birch plywood are nearly twice as high as the comparable parameters $k_{c0.5}$ and $k_{cn0.5}$ for solid birch wood. The elevated values can be explained by the addition of the binder used to bond the individual veneer layers and the subsequent pressing and consolidation during the manufacturing process of birch plywood panels.

4.2. Determination of the Correction Factor K_{vc} and $K_{v_{cn}}$

For the birch plywood used, the correction factors for cutting speed K_{vc} and $K_{v_{cn}}$ can be described using Equations (27) and (28). Figures 7 and 8 show a comparison of the model results with the actual measurement data. The same basic function for cutting speed correction was used here as in the Kienzle model. A cutting speed of 125 m/min was chosen as the base value at which the correction factor yields a value of $K_{vc} = 1$. Lower cutting speeds are not effective for wood machining.

$$K_{vc} = \left(\frac{v_c}{125} \right)^{-0.14} \quad (27)$$

$$K_{v_{cn}} = \left(\frac{v_c}{125} \right)^{0.16} \quad (28)$$

The diagrams show that as cutting speeds increase, the average cutting forces decrease. Compared to the cutting speed correction factor for metals, the correction factor for wood behaves similarly. The greatest reduction in cutting force occurs at low cutting speeds between 125 m/min and 375 m/min. After that, the decrease in cutting force as a function of cutting speed becomes degressive. The curve in Figure 7, fit using the selected basis function, works very well for the cutting force, as evidenced by the coefficient of determination ($R^2 > 0.95$). For the normal cutting forces, however, a larger deviation is observed at the measurement point $v_c = 375$ m/min. This is evident because the model's graph overestimates all measured values, while only this one deviating measured value is underestimated. In subsequent experiments, it must be investigated whether this is due to a measurement error or a deviation caused by material inhomogeneity, such as a knot or an anomaly in the machining process.

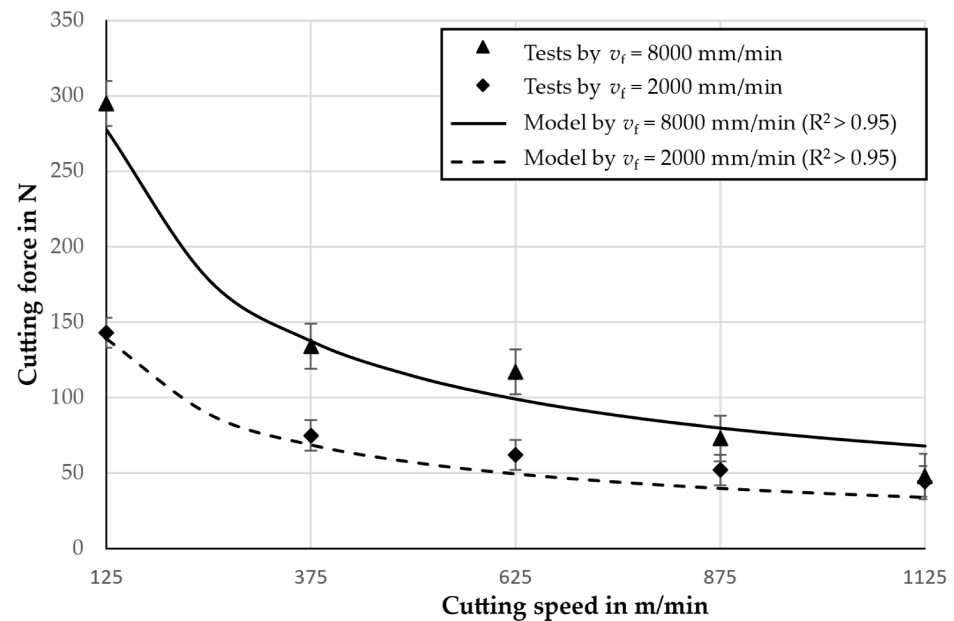


Figure 7. Effect of cutting speed on cutting force during the milling of birch plywood.

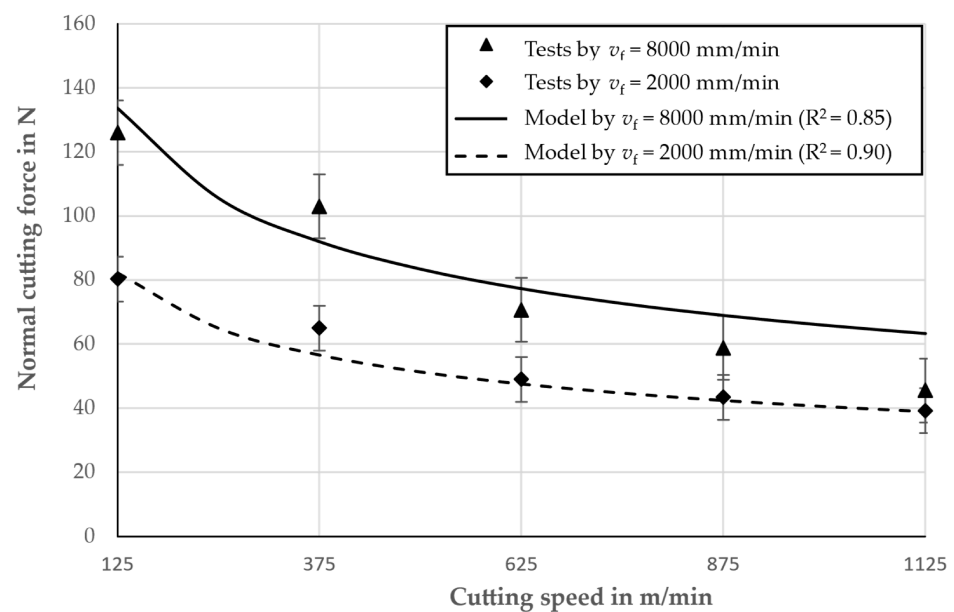


Figure 8. Effect of cutting speed on normal cutting force during the milling of birch plywood.

4.3. Consolidation of the Cutting Force Model

In summary, the specific cutting force and determined correction factors yield an extended model for determining the cutting force during the milling of birch plywood, which is described in Equations (29) and (30) for the cutting force and normal force, respectively. The coefficient of determination R^2 ranges from 0.85 to 0.95 (see Figures 5–8), indicating that the model is accurate.

$$F_c = b \cdot h_m^{0.5} \cdot (52 \dots 54) \frac{N}{mm^{1.5}} \cdot \left(\frac{v_c}{125}\right)^{-0.14} \cdot (1 - 0.03 \cdot \gamma + 0.00035 \cdot \gamma^2) \quad (29)$$

$$F_{cn} = b \cdot h_m^{0.5} \cdot (24 \dots 32) \frac{N}{mm^{1.5}} \cdot \left(\frac{v_c}{125}\right)^{0.16} \cdot (1 - 0.03 \cdot \gamma + 0.00033 \cdot \gamma^2) \quad (30)$$

The model presented here makes it possible to predict the cutting forces for birch plywood as a function of the rake angle and the cutting force. However, the investigations

showed that the feed speed also has a direct influence on the chip forces. This influence needs to be quantified and described mathematically in future studies. In the modeling of this wood material presented here, however, as described in Chapter 1, it is important to note that it is an inhomogeneous and anisotropic material whose properties are not only direction-dependent but also subject to natural fluctuations.

4.4. Validation of the New Correction Factors

To validate the extended model, see Equations (29) and (30), a series of experiments was conducted using birch plywood of various thicknesses. These experiments were carried out at a different feed speed (v_f) of 6000 mm/min (see Table 3). The data obtained regarding the influence of the rake angle on cutting force and normal cutting force are compared for the extended model and the experimental data in Figures 9 and 10.

Table 3. Overview of the equipment and process parameters used for model validation.

Equipment & Process		Parameter
Workpiece	Material	Birch plywood
	Width of cut (b)	12 mm
	Number of veneer layers	9 layers, symmetrical, bidirectional
	Material	Birch plywood
	Width of cut (b)	21 mm
	Number of veneer layers	15 layers, symmetrical, bidirectional
	Material	Birch plywood
	Width of cut (b)	40 mm
	Number of veneer layers	29 layers, symmetrical, bidirectional
Process	Cutting speed (v_c)	125 bis 1125 m/min
	Feed speed (v_f)	6000 mm/min
	Depth of cut (a_e)	0.6 mm

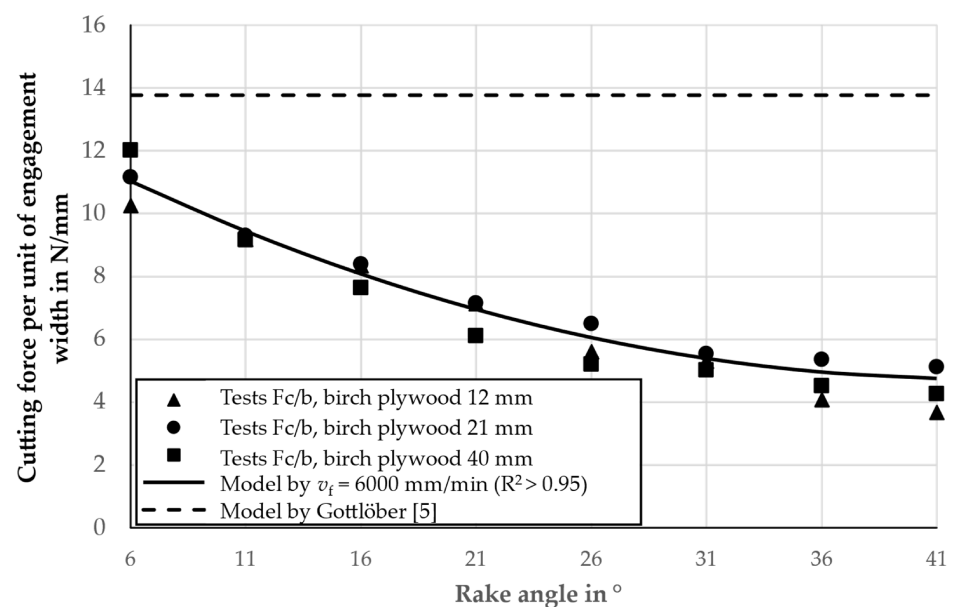


Figure 9. Comparison of the effect of the rake angle on the cutting force per unit of mm of width of the cut for the presented model, the Gottlöber model (based on $k_{c0.5} = 54 \text{ N/mm}^{1.5}$) and the experimental data (mean values) at $v_c = 125 \text{ m/min}$.

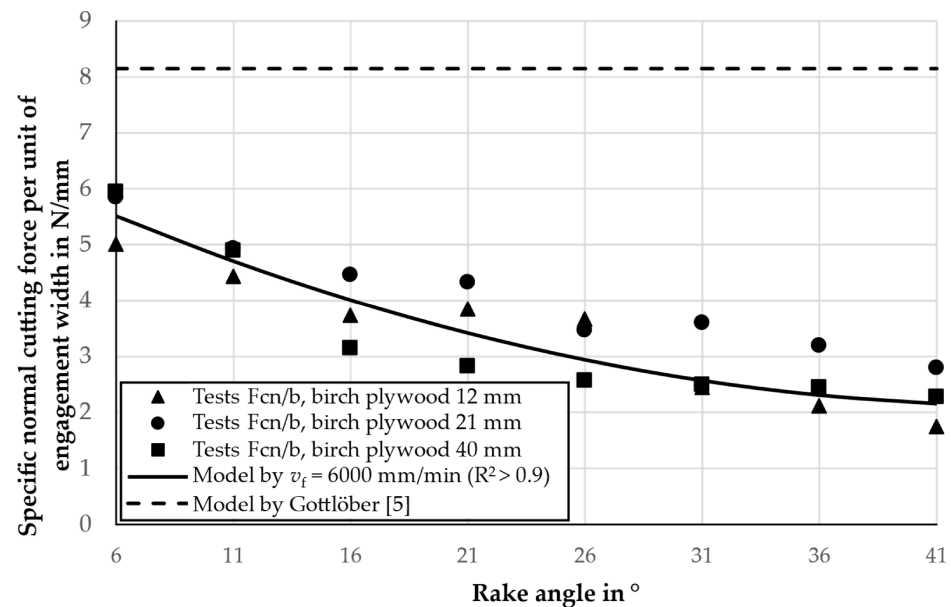


Figure 10. Comparison of the effect of the rake angle on the normal cutting force per unit of mm of width of the cut for the presented model, the Gottlöber model (based on $k_{cn0.5} = 32 \text{ N/mm}^{1.5}$) and the experimental data (mean values) at $v_c = 125 \text{ m/min}$.

Figures 9 and 10 compare cutting speed with cutting force and normal cutting force for various plywood thicknesses. In addition, these figures compare the extended model with the results calculated using the Gottlöber model. In order to make the results from the cutting force model comparable across different plywood thicknesses, the cutting force was divided by the thickness; as a result, the Y-axis of the graphs shows the cutting force per millimeter of engagement width. For the calculation of cutting and normal cutting forces according to the Gottlöber model, the specific cutting forces $k_{c0.5}$ and $k_{cn0.5}$ were used, which were obtained in this work; see Table 2.

The diagrams show that the predictive accuracy of the presented model is high, particularly for F_c/b . For F_{cn}/b , there are higher deviations; however, the coefficient of determination is still $R^2 > 0.9$. Furthermore, it can be seen that both cutting force components follow the same trend. F_c/b is approximately twice as large as F_{cn}/b . Both forces are halved by increasing the rake angle from 6° to 41° . To reduce the cutting forces and thus the stress on the workpiece and the tool, the largest possible rake angle should therefore be selected. In further investigations, it is desirable to increase the rake angle even further to enable a potential additional reduction in cutting forces.

As shown in Figures 11 and 12, the model presented here can predict the cutting force and the normal cutting force as a function of cutting speed. In this case as well, the prediction accuracy is higher for the cutting force ($R^2 = 0.95$) than for the normal cutting force ($R^2 = 0.85$). Furthermore, the diagrams show that the prediction of cutting forces by the extended cutting force model based on Gottlöber presented here is more precise than that of the existing cutting force model. The Gottlöber model yields higher values for the process forces, which is mainly attributable to the lack of an exact value for the material-specific constant in the cutting force equation in the literature, as well as to the somewhat simplified non-linearity of the cutting depth dependence in the Gottlöber model. The developed models enable the cutting force to be predicted with an average increase in accuracy of 30% compared to the Gottlöber model; for the normal cutting force, the accuracy is approximately 15% higher.

The verification of the cutting force model presented here reveals that, similar to metallic materials, cutting forces can be reduced by increasing cutting speeds. A weakness

of the model is evident in Figure 12. Currently, the presented model is unable to simulate the increased decline in cutting normal force at cutting speeds exceeding 625 m/min.

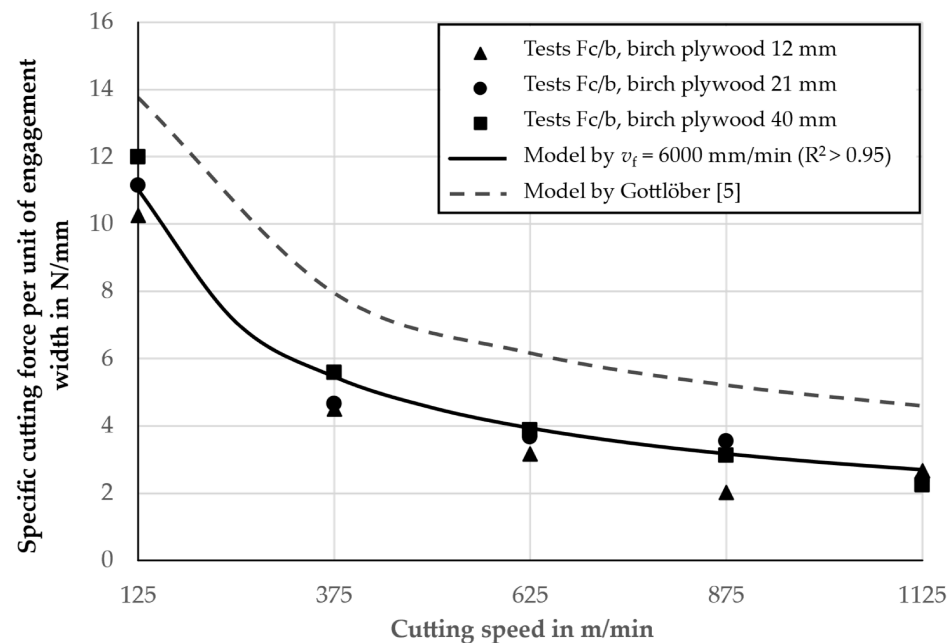


Figure 11. Comparison of the specific cutting force between the extended model, the Gottlöber model (based on $k_{c0.5} = 54 \text{ N/mm}^{1.5}$), and measurement results (mean values) with varying cutting speeds.

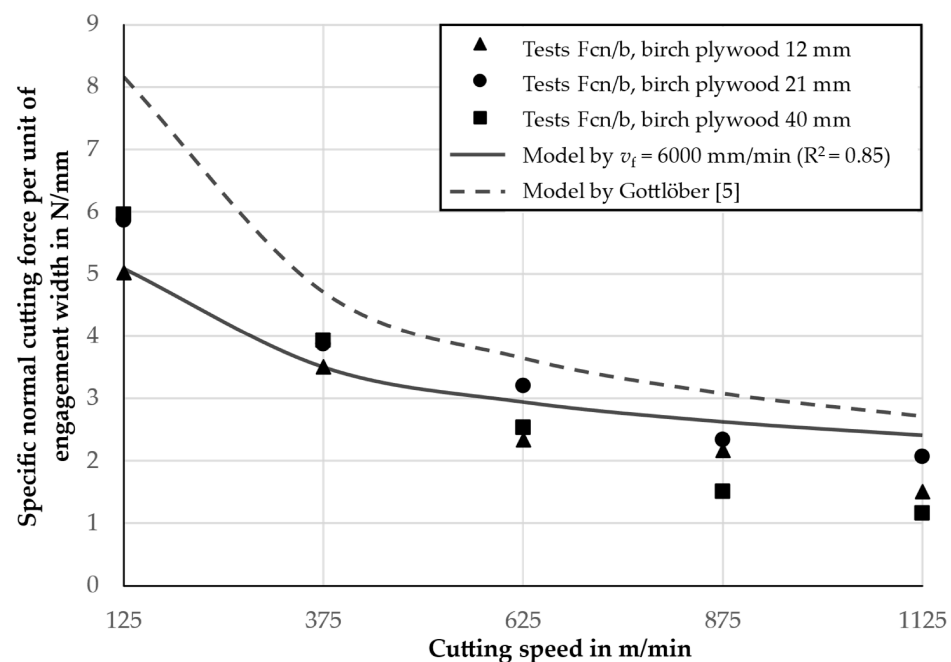


Figure 12. Comparison of the specific normal cutting force between the extended model, the Gottlöber model (based on $k_{cn0.5} = 32 \text{ N/mm}^{1.5}$), and measurement results (mean values) with varying cutting speeds.

5. Conclusions

The increasing economic and environmental demands placed on processes and products are driving the use of sustainable materials in mechanical engineering. However, this requires a thorough understanding of the materials and processes involved—particularly the machining process itself. Cutting forces play a crucial role in this context. Although established models have been used to predict these forces, they did not account for specific

process variables. The aim of this study is therefore to deepen this process knowledge by extending the established cutting force model, thereby enabling more accurate predictions of cutting forces.

As part of this study, tests were conducted on birch plywood panels to analyze the influence of cutting speed and rake angle on the cutting force. Regarding the research questions, the determined specific cutting force $k_{c0.5}$ consistently aligns with the values reported in the technical literature. In addition, a correction factor for the rake angle was determined; like the results for the correction factor for cutting speed, this factor showed a high degree of agreement with further experiments. The tests showed that increasing the rake angle to over 40° and increasing the cutting speed can reduce the cutting forces.

The results of the extended model were further validated through additional experiments. These involved varying the birch plywood sheet thickness and the feed speed, thereby differing from the experiments used to determine the correction factor. The extended model demonstrates high predictive accuracy, although it slightly overestimates the cutting force. However, compared to the established Gottlöber model, there is a significant improvement in the prediction of the cutting force. The extended model enables cutting force prediction with an average accuracy improvement of 30% over the Gottlöber model. For the normal cutting force, the accuracy is approximately 15% higher. In the studies conducted to develop the extended Gottlöber cutting force model for birch plywood, no relevant directional dependence of the cutting forces in the x-y plane could be demonstrated at the macroscopic level.

The results of this work make it possible to predict cutting forces more reliably and, based on this, to facilitate the optimal design of tools—regarding wear resistance, energy consumption, and vibration excitation—in future studies. This creates opportunities to substitute metallic materials with wood-based materials, as it is possible not only to predict cutting forces but also to anticipate positive effects on dimensional accuracy and surface quality.

Future work should focus on further characterizing wood and wood-based materials to broaden the knowledge base regarding their application, including in industrial sectors (e.g., mechanical engineering). Additionally, the influence of factors such as moisture and temperature on cutting force should be investigated.

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