



Fracture toughness and shear yield stress determination from quasi-linear cutting tests of Scots pine (*Pinus sylvestris* L.) with a normalisation process by local density aided by X-ray computed tomography

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Abstract

The Atkins model has been widely adopted for determining mechanical properties of wood, such as fracture toughness and shear yield stress, which are typically normalised by global density for cutting force and power predictions. This study explores the feasibility of determining these mechanical properties for knotty and clear Scots pine (*Pinus sylvestris* L.) using local densities revealed by X-ray computed tomography scanning. Six wood workpieces, three from Poland and three from Sweden, were scanned and subsequently cut on a custom single-tooth quasi-linear cutting machine. Cutting forces for both clear and knotty regions were recorded and normalised by local densities. Results indicate that clear Polish pine exhibits higher local-density-normalised fracture toughness and shear yield stress than Swedish pine, suggesting that wood origin influences mechanical properties beyond mere density differences. Knots display significantly lower local-density-normalised shear yield stress compared to clear wood, despite their higher density. The large variation in normalised fracture toughness observed in knots is attributed to differences in cutting direction relative to knot orientation. The study highlights the effectiveness of computed tomography scanning to provide detailed insights into wood density and structure, enabling more accurate normalization of cutting forces and enhancing the understanding of wood machinability across different origins and structural characteristics.

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1 Introduction

Fracture mechanics properties, such as fracture toughness and shear yield stress, are key parameters in the cutting force and cutting power model proposed by Atkins (2003, 2005). This model describes cutting forces in processes where the chip is formed by shearing, typically when the rake angle is less than 25° (Orlowski 2010). For rake angles greater than 25°, the chip forms through plastic bending, and the model developed by Williams (1998) is more appropriate for describing cutting forces. Williams' model also uses fracture toughness to describe the energy required to separate the chip from the bulk, with chip deformation occurring through bending.

Orlowski and Atkins (2007) adapted the original Atkins model to predict the cutting power in the wood sawing process and to determine the values of fracture toughness and shear yield stresses from experimental machinability tests. This approach of determining fracture toughness and shear yield stresses based on the cutting process has been widely applied in various analyses (Orlowski et al. 2013; Javorek et al. 2013; Hlaskova et al. 2015, 2018, 2019). These analyses focused mainly on different wood species and sawing processes with linear or rotational main movement. Beer et al. (2005) also used the Atkins model to determine values of fracture mechanics properties in linear cutting of particleboard. However, particleboard, considered isotropic, contrasts with solid wood, which exhibits strong anisotropy due to the directional properties of its fibres and varying density profiles. Density significantly impacts cutting forces and other mechanical properties (Chuchala et al. 2014; Machado et al. 2014; Caceres et al. 2018).

Linear cutting processes allow the determination of fracture toughness and shear yield stresses for a specific direction relative to wood fibres (Orlowski et al. 2013; Chuchala et al. 2020b, 2021). Knowledge of these directional mechanical properties is required when using the Atkins model to predict cutting power and cutting forces in sawing processes such as frame sawing and bandsawing (Chuchala et al. 2020a). A more complex process is circular sawing, where the cutting direction continuously changes its orientation relative to the wood fibres. After extensive analysis, Orlowski et al. (2017) introduced a method to determine the values of these mechanical properties and effectively predict the cutting power during circular sawing (Orlowski and Ochrymiuk 2017; Orlowski et al. 2020).

Variations in wood density within the same species, origin, and even within a single sample, significantly affect the cutting forces. In addition, the presence of knots, which have much higher density than the surrounding wood, also causes substantial increases in cutting forces (Caceres et al. 2018; Licow et al. 2020). However, wood from a given

species maintains a relatively consistent chemical composition (Sable et al. 2012; Lachowicz et al. 2019); apart from density variation, it is essentially the same material, which suggests its mechanical properties should be similar. Taking into account these assumptions and the fact that density significantly affects cutting forces (Chuchala et al. 2014; Caceres et al. 2018) and mechanical properties (Machado et al. 2014; Miyoshi et al. (2018; Sinn et al. (2020; Chuchala et al. (2020b) proposed normalising by density both the cutting forces and cutting power. This normalisation was then used to determine density-normalised values for fracture toughness and shear yield stresses. However, these normalisation processes were based on the global density of the wood specimens analysed.

Computed tomography (CT) scanning is currently the most effective method for assessing the internal structure of wood (Beaulieu and Dutilleul 2019). This method involves transmitting X-rays through one side of the log and measuring the X-ray attenuation on the opposite side. Since the attenuation is mainly decided by density when scanning wood (Lindgren 1991), CT scanning can be used to measure local density within a wooden object. The internal density structure of wood can be spatially reconstructed by integrating projections obtained from various angles around the log axis (Radon 2005). CT scanning allows for the identification of many internal wood features (Fredriksson 2012), including knot position (Longuetaud et al. 2012; Breinig et al. 2013; Fredriksson et al. 2019), grain orientation (Sepúlveda et al. 2003), annual ring width (Onoe et al. 1984), and wood density (Wang et al. 2019).

The aim of the present study was to determine the local-density-normalised values of fracture toughness, as well as shear yield stresses, for Polish and Swedish clear pine wood as well as knotty wood, based on CT scanning data.

2 Materials and methods

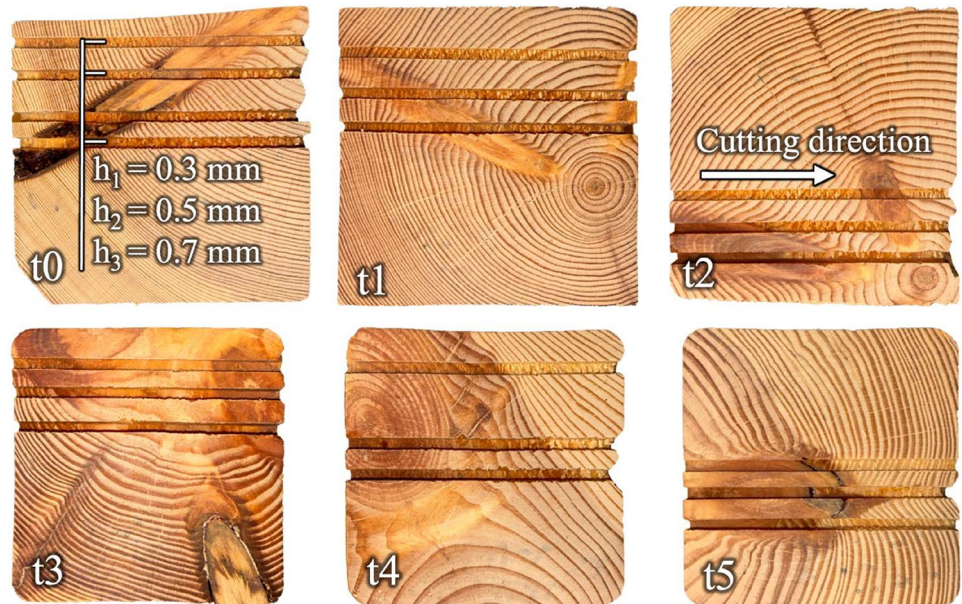
2.1 Materials

The study was carried out on six beams of Scots pine (*Pinus sylvestris* L.) collected from northern Sweden by Sävar sawmill and from northern Poland by Sylva Sp. z o.o. Each beam was prepared with a square cross-section and was obtained from a different log. The three Swedish beams measured 75 mm × 75 mm × 2500 mm (respectively width, height, and length), and the three Polish beams measured 70 mm × 70 mm × 2000 mm (respectively width, height, and length). The beams were chosen to include substantial structural differences, such as clear wood, different knot types and varying annual ring widths within a single beam. After kiln-drying under industrial conditions, the beams were stored in

Fig. 1 Cross sections of the clear wood with three grooves on each. Cutting directions are from left to right. The markings identify the workpieces (t0, t1, t2: Sweden; t3, t4, t5: Poland)



Fig. 2 Cross sections of the knotty wood side with three grooves on each. Cutting directions are from left to right. The markings identify the workpieces (t0, t1, t2: Sweden; t3, t4, t5: Poland)



a climatic chamber with given parameters at a temperature of $T=20\text{ }^{\circ}\text{C}$ and a relative humidity of $RH=65\%$, corresponding to a moisture content of $MC=12\%$.

The specimens underwent scanning using a laboratory CT scanner Mito (MiCROTEC, Bressanone, Italy) after the desired MC of 12% was reached. Scanning resolution was 0.3 mm in all three Cartesian directions, i.e., employing 0.3-millimetre voxels. CT data were imported to 3D Slicer, version 5.0.3 (The Slicer Community, Boston, MA, USA), which was used to visually assess knot locations inside the specimens. Based on the visual inspection in 3D Slicer, a segment of approximately 250 mm in length was chosen from each of the six beams. Each segment was chosen so that one end of the cross section contained only clear wood

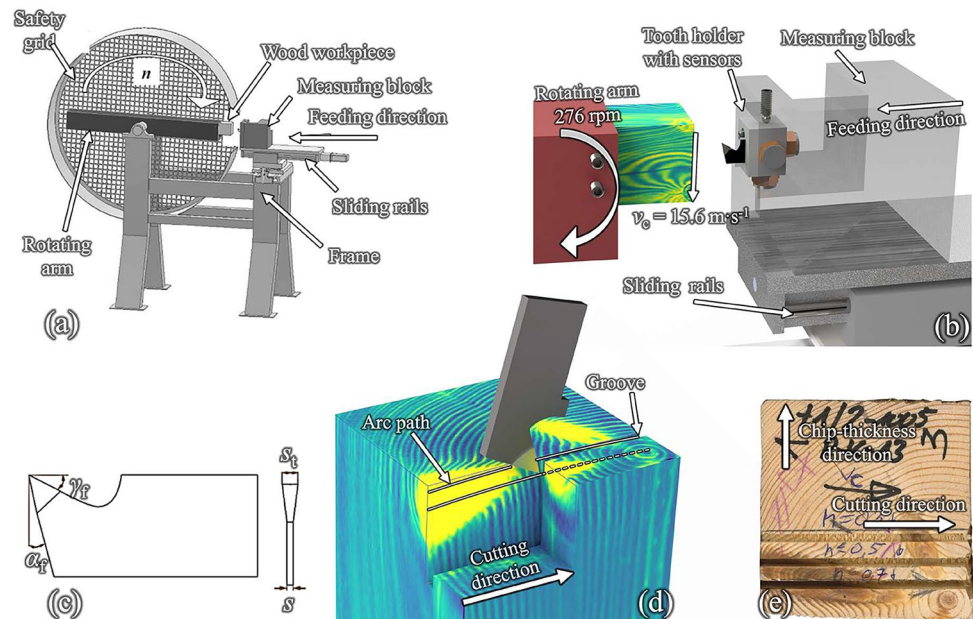
(Fig. 1), while the other end contained knotty wood (Fig. 2). These 250-millimetre segments are hereafter referred to as the workpieces.

2.2 Cutting machine, cutting parameters, and cutting tools

Figure 3 depicts the test machine setup that measures the forces during single-tooth cutting of wooden workpieces. Previous cutting force measurements have been performed on this machine (Meulenberg et al. 2021, 2022a, b).

The testing machine consists of three main parts. The first part includes the frame, safety grid, and drivetrain. The second part is a rotating arm that holds the workpiece. The

Fig. 3 Cutting station implementing quasi-linear cutting process: general view (a), detailed view of cutting zone (b), cutting tooth geometry (c), three-dimensional representation of the workpiece from CT data (d) and the scanned cross section (e). Note that images (d) and (e) represent the same workpiece as in Fig. 6



third part is the platform, which includes the stationary measuring block with a tooth holder, and sliding rails in both feed and lateral directions. The wood workpiece is securely affixed to the rotating arm using four bolts. The arm, with a radius of 540 mm including the clamped workpiece, undergoes clockwise rotation at a speed of $n = 276 \text{ min}^{-1}$, leading to a linear speed of $v_c = 15.6 \text{ m} \cdot \text{s}^{-1}$.

Three piezoelectric sensors are connected to the tooth holder, each aligned with one of the three orthogonal directions, namely, the primary, side, and feeding directions. These sensors are used to quantify the force components exerted on the tooth throughout the cutting procedure. The cutting tooth (Fig. 3a and b) is fixed in place by the tooth holder, and feeding movement is provided by a stepper motor and guided by the sliding rails.

The tip of the tooth was loaded statically with a known weight of 500 g in three orthogonal directions. A calibration matrix was derived based on the sensor readings and the known weight, and was used to convert measured amplitudes in the three sensors into cutting force in the main direction. The same principle was applied to cutting force in other directions, although they are not discussed in this paper.

Details of the cutting tooth are as follows: the tooth was tipped with Stellite™ 12 (Deloro Wear Solutions GmbH, Koblenz, Germany), side clearance angle $\alpha_f = 12^\circ$, side rake angle $\gamma_f = 27^\circ$, overall set (theoretical kerf) $S_t = 2.87 \text{ mm}$ and saw blade thickness $s = 1.47 \text{ mm}$ (Fig. 3c). After sharpening, the main cutting edge was rounded to a radius of about $r_o = 12 \mu\text{m}$. This is the same cutting tooth geometry that is currently applied in numerous Swedish sawmills (Meulenberg et al. 2022a, b). The single tooth was obtained by cutting it off from a typical band saw blade.

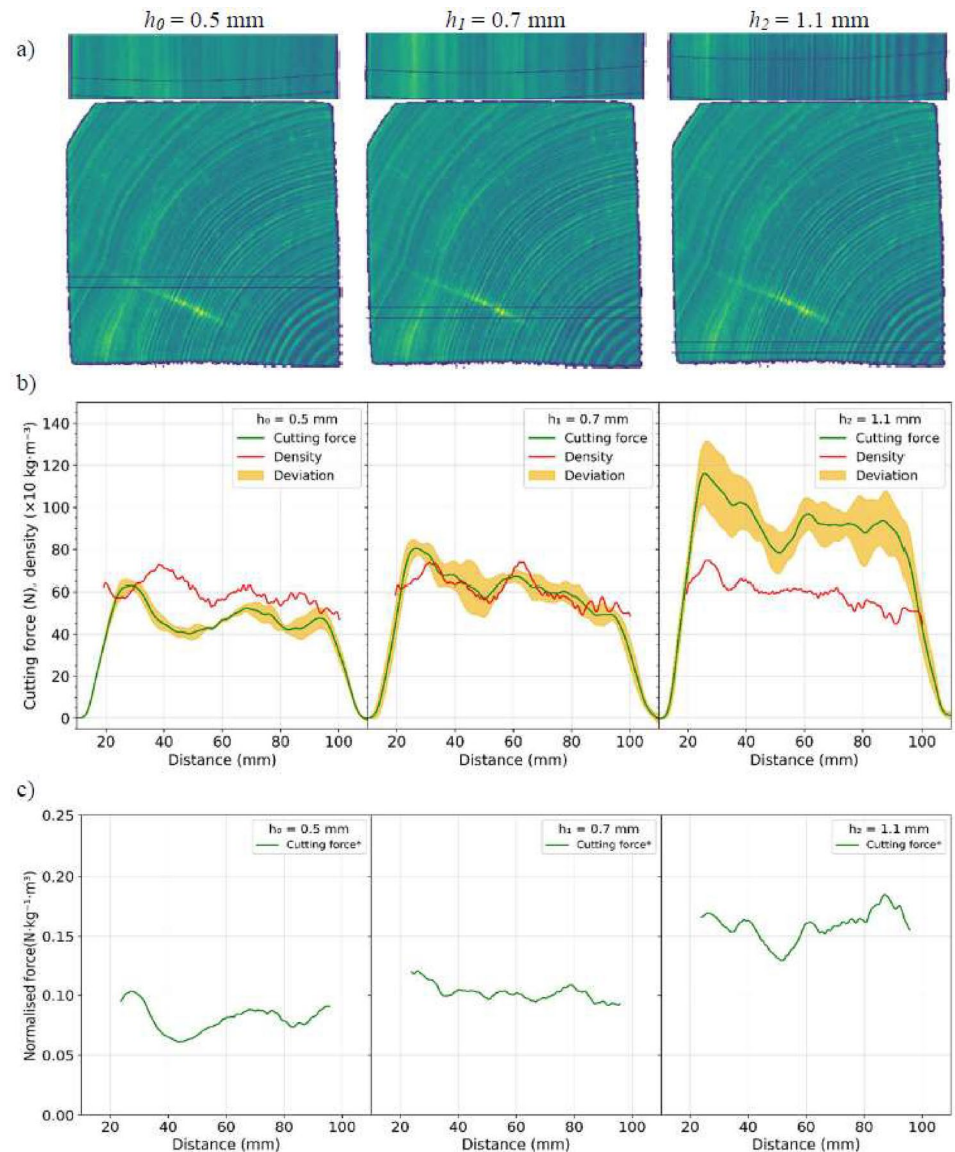
Three grooves were planned on each knotty side to cross the largest possible knot area, with feed per arm-revolution being 0.3 mm, 0.5 mm, and 0.7 mm, respectively. Three corresponding grooves were made on the clear wood side, with feed per arm-revolution at 0.5 mm, 0.7 mm, and 1.1 mm, respectively. The high spatial resolution of the CT data serves as a digital “twin” of the real wood, allowing precise identification of the cut regions and the local wood features encountered by the cutting tooth. Fifteen cuts were made for each groove, where the theoretical feed per revolution is equal to the uncut chip thickness h .

Due to the test machine setup, the tooth cut the wood workpieces in a quasi-linear manner, i.e., circular cutting with a large rotation radius, referred to as the arc path (Fig. 4). Consequently, during the initial series of incisions, the two corners of the workpiece were removed, while the central portion remained unaltered. Force readings from the first five cuts were therefore excluded, as the initial cutting process was not complete along the path.

2.3 Measuring and collecting data

The natural frequencies of the measuring block were determined by striking the tooth with a steel hammer in three orthogonal directions and measuring the frequencies of the corresponding force response. These were measured to be 4.4 kHz, 2.5 kHz, and 2.5 kHz in the primary cutting, feeding, and side directions, respectively. Analogue signals from the three sensors were amplified using three Type 2635 charge amplifiers (Brüel & Kjær, Denmark) and then sampled at 60 kHz using a PCI-6023E0 data acquisition card in LabVIEW 2013 software (National Instruments, USA). The digitised signals were then subjected to a Butterworth

Fig. 4 Cutting force and density profile when cutting clear wood: X-ray computed tomography (CT) image of the clear wood (a), cutting force and density profile (b), cutting force normalised by density (c). Asterisk (*) denotes cutting force normalised by wood local density. For each uncut chip thickness, the corresponding CT image in a is aligned vertically with the cutting force and density profiles in b and the normalised cutting force profile in c



filter to eliminate frequency components exceeding 800 Hz and subsequently converted into forces using the calibration matrix. The mean cutting force from the last 10 cuts of each groove was obtained as a 1D array along the length of the groove, referred to as the cutting force profile. At a sampling rate of 60 kHz and a cutting speed of 15.6 m.s^{-1} , each sample corresponded to a distance of 0.262 mm.

Groove positions were measured on the workpieces after the cutting tests and used to locate the groove positions on the three-dimensional CT density models, as actual cut grooves may deviate slightly from the planned positions. Voxels corresponding to the chips removed during the cutting process were extracted from the CT data as 3D arrays. Mean density across the chip-thickness direction (Fig. 3e) was then obtained as a 2D array (Fig. 4a). The mean density for the chips removed during the last 10 cuts was obtained as a 1D array, referred to as the density profile. As one voxel

represents a known distance of 0.3 mm, the cutting force profile was then adjusted to match the scale of CT images and density profile when plotting the results.

2.4 Methodology for determination of material properties from the cutting test

The mean cutting force in the main direction F_c for a single cutting tooth in a quasi-linear cutting process can be determined using the cutting forces model proposed by Atkins (2003, 2005). This methodology has been applied to cutting wood on a frame sawing machine by Orłowski et al. (2013); Chuchala et al. (2020a, b; Sinn et al. (2020) and is summarised in Eq. 1:

$$F_c = \frac{\tau \cdot \gamma \cdot \gamma \cdot S_t}{Q} h + \frac{R \cdot S_t}{Q}, \quad (1)$$

Equation 1 consists of two components. The first part describes the internal work of plasticity along the shear plane, where τ_γ is shear yield stress and γ is the shear strain along the shear plane. The value of γ can be calculated according to Eq. 2, assuming that Φ_c corresponds to the shear angle:

$$\gamma = \frac{\cos \gamma_f}{\cos(\Phi_c - \gamma_f) \cdot \sin \Phi_c}, \quad (2)$$

where γ_f is tool side rake angle (Fig. 3c).

The second component defines internal work required for the formation of a new surface, where R corresponds to the fracture toughness or specific work of material separation determined in the direction consistent with the cutting speed v_c . This fracture property can be analogous to fracture toughness mode I with the crack normal to the fiber direction (longitudinal-tangential fracture plane) (Jungstedt et al. 2023). However, these are not the same properties. The coefficient of friction correction Q appears in both components, representing an effect of friction between tool rake face and separated material. Q is computed according to Atkins (2003, 2005) and Orłowski et al. (2013) and can be represented as in Eq. 3:

$$Q = 1 - \frac{\sin \beta_\mu \cdot \sin \Phi_c}{\cos(\beta_\mu - \gamma_f) \cdot \cos(\Phi_c - \gamma_f)}, \quad (3)$$

where $\beta_\mu = \tan^{-1} \mu$ is a friction angle (rad) directly related to the coefficient of friction μ . The other parameters included in Eq. 1 are overall set (kerf width) S_t and uncut chip thickness h . Shear angle Φ_c was calculated following the approach of Merchant (1945), considering the specific cutting zone geometry and the friction coefficient (Eq. 4). This procedure is valid when deviations in the shear angle assigned to inherent material properties can be neglected for larger values of uncut chip thicknesses, as used in this study.

$$\Phi_c = \frac{\pi}{4} - \frac{1}{2} \cdot (\beta_\mu - \gamma_f), \quad (4)$$

Based on the works of Glass and Zielinka (2010) and Hlaskova et al. (2019), the friction coefficient was assumed to be $\mu = 0.6$.

However, density is a crucial physical property of wood and is primarily influenced by its structural properties and moisture content. Structural properties, and therefore density, can vary in different directions within a single piece. In previous studies, Chuchala et al. (2014) showed the effect of density on cutting forces. Based on these results, the following studies examined machinability properties normalised by wood density: Chuchala et al. (2020b), (2023);

Sinn et al. (2020); Licow et al. (2020). However, in these studies, only the global wood density was used; the local wood density was not accessible. In the present study, the cutting forces were normalised by the local density ρ of the machined material, i.e. the density profile determined using a CT scanner, as described in Sect. 2.3. A similar process of normalising the cutting forces by local density was initiated in the work of Huang et al. (2024). With this normalisation process, Eq. 1 can be written as follows:

$$F_c = \frac{\tau_\gamma^* \cdot \gamma \cdot S_t \cdot \rho}{Q} \cdot h + \frac{R^* \cdot S_t \cdot \rho}{Q}, \quad (5)$$

where τ_γ^* is shear yield stress determined per $1 \text{ kg} \cdot \text{m}^{-3}$ of material density and where R^* corresponds to the fracture toughness or specific work of material separation per $1 \text{ kg} \cdot \text{m}^{-3}$ of material density.

By implementing the above listed assumptions, Eq. (5) can be expressed as a linear regression function of the uncut chip thickness h (Eq. 6).

$$F_c^* = \frac{F_c(h)}{\rho} = c_1 \cdot h + c_0, \quad (6)$$

The regression coefficients (c_1 and c_0) of this linear regression function correspond to the slope and intercept, respectively. An independent variable of the regression is the uncut chip thickness h . The local force and density can be determined using the methodology described. Therefore, the density-normalised shear yield stresses and fracture toughness can be derived from the regression coefficients c_1 and c_0 , as follows:

$$\tau_\gamma^* = \frac{c_1 \cdot Q}{\gamma \cdot S_t}, \quad (7)$$

$$R^* = \frac{c_0 \cdot Q}{S_t}, \quad (8)$$

A similar approach has been reported for diverse materials and cutting kinematics (Hlaskova et al. 2018; Sinn et al. 2020; Chuchala et al. 2020a). In this analysis, both the density normalised shear yield stress $\tau_{\gamma\perp}^*$ and the fracture toughness $R_\perp^*$ are determined for cutting perpendicular to the wood fibres direction $\Phi_{G-\text{vc}}$, corresponding to the 90° – 90° case as defined by Kivimaa (1952).

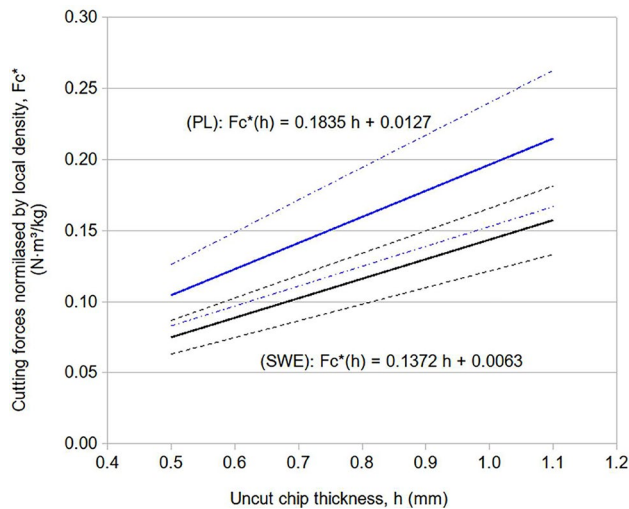


Fig. 5 Linear regression functions showing the relationship between local-density-normalised cutting forces and uncut chip thickness for Polish (PL) and Swedish (SWE) clear wood. The blue continuous line is the linear regression for Polish clear wood; blue dashed-dot lines define the area of variation for 95% probability (significance level $\alpha=0.05$) for clear Polish wood. The black continuous line is the linear regression for Swedish clear wood; black dashed lines define the area of variation for 95% probability (significance level $\alpha=0.05$) for clear Swedish wood. The regression line for the Swedish wood is below the regression line for the Polish wood

Table 1 Density-normalised fracture toughness R^* and shear yield stress τ_y^* (mean value and its range) for clear Polish and Swedish Scots pine

Name of wood	Normalised fracture toughness R^* [$\text{J} \cdot \text{m}^3 \cdot \text{kg}^{-1}$]	Normalised shear yield stress τ_y^* [$\text{MPa} \cdot \text{m}^3 \cdot \text{kg}^{-1}$]
Clear wood Polish	4.379 +0.172 -0.172	0.0328 +0.008 -0.008
Clear wood Swedish	2.172 +0.586 -0.586	0.0244 +0.0036 -0.0036

3 Results and discussion

The cutting force values obtained for clear wood during the experimental tests were compiled with the local density of the machined wood (Fig. 4b). This local density, determined based on CT images (Fig. 4a), was used to normalise the cutting forces (Fig. 4c). The normalised cutting force profiles (Fig. 4c) were then used to calculate the mean normalised cutting force for each specimen and for each uncut chip thickness h .

The calculated mean value of the normalised cutting force was one of the measurement points of the analysis, from which linear regression functions were determined for clear Polish and Swedish pine wood (Fig. 5). The continuous lines represent the linear regression for mean values, while dashed lines show areas of variation for probability 95% (significance level $\alpha=0.05$).

The linear regression equations obtained (Fig. 5) were used to determine the density-normalised values of fracture toughness R^* and the shear yield stresses τ_y^* for clear Polish and Swedish pine wood. The dashed lines representing linear regression functions were used to establish the dispersion range for these mechanical properties. Determined values of the analysed mechanical properties are presented in Table 1.

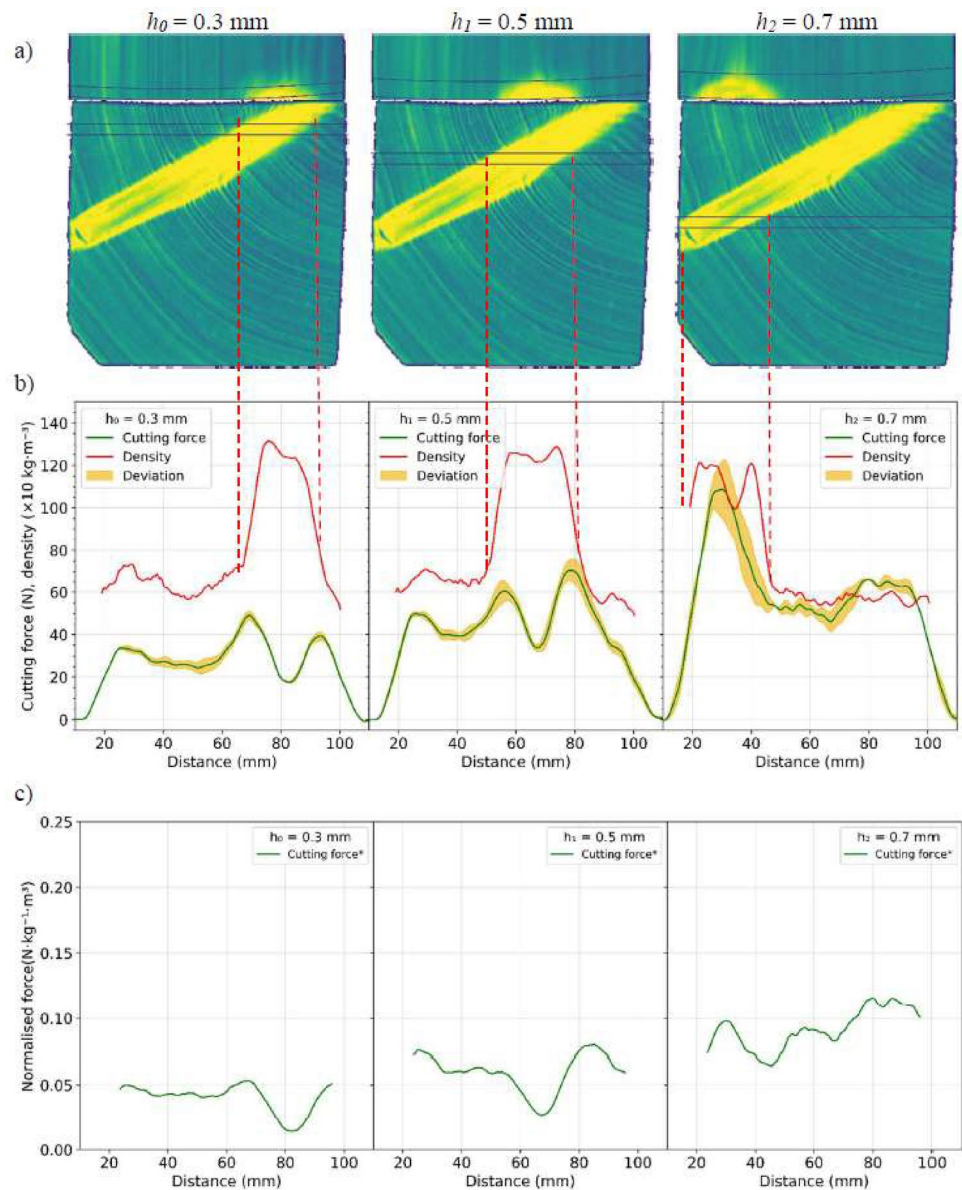
There are appreciable differences between the obtained values of the analysed mechanical properties for clear Polish and Swedish pine wood (Table 1). The density-normalised fracture toughness of Polish clear pine wood is twice that of Swedish clear pine. Additionally, the density-normalised shear yield stresses of Polish clear pine are about 30% higher than those of Swedish wood, though not as dramatically different as the fracture toughness (Table 1).

It is important to note that these values are normalised by density, meaning they are calculated per $1 \text{ kg} \cdot \text{m}^{-3}$ of material. Swedish pine wood is usually denser than wood from northern Poland. In these studies, the mean density of Swedish wood was $609.7 \text{ kg} \cdot \text{m}^{-3}$ (Standard Deviation, $\text{SD}=77.9$), while the mean density of the Polish wood was $540.1 \text{ kg} \cdot \text{m}^{-3}$ ($\text{SD}=117$), as determined from CT data at the cutting areas. These density differences are largely due to structural properties, such as the width of annual rings, as seen in Fig. 1. Specimens t0, t1 and t2 are Swedish wood samples, while t3, t4 and t5 are Polish wood specimens. The values of the mechanical properties obtained for clear Polish pine wood are similar to those reported by Chuchala et al. (2020b) for pine wood dried in an industrial kiln, also from northern Poland. Chuchala et al. (2020b) analysed the effect of the drying process on fracture toughness and shear yield stresses. In the case of the pine wood dried in an industrial kiln, the density-normalised fracture toughness was $4.03 \text{ J} \cdot \text{m}^3 \cdot \text{kg}^{-1}$, while the density-normalised shear yield stress was $0.035 \text{ MPa} \cdot \text{m}^3 \cdot \text{kg}^{-1}$. These values closely match the results for Polish clear wood in Table 1. However, the values reported by Chuchala et al. (2020b) were based on global density, whereas this study used local density from the cutting area.

A similar procedure was applied for knotty wood as was done for clear wood. However, in this case, only the fragments of the cutting force curves normalised by local density, that corresponded to knots, were analysed (Fig. 6).

The determined linear regression functions for the cutting forces normalised by the local density are shown in Fig. 7. The dispersion ranges of density-normalised cutting force values for knots are large, extending to the mean values of pine wood from the different origins. This wide variability is also reflected in the density-normalised fracture toughness values (Table 2).

Fig. 6 Cutting force and density profile when cutting knotty wood: X-ray computed tomography (CT) image of the knotty wood (a), cutting force and density profile (b), cutting force normalised by density (c). Asterisk (*) denotes cutting force normalised by wood local density. For each uncut chip thickness, the corresponding CT image in a is aligned vertically with the cutting force and density profiles in b and the normalised cutting force profile in c



The obtained values of density-normalised fracture toughness for pine knots from both origins are similar. Given the wide range of value dispersions at a significance level of $\alpha=0.05$, it can be assumed that these values do not significantly differ. It is worth noting that this large dispersion may result from the fact that the knots were cut in different directions relative to their pith. Given that a knot is structurally similar to a small log (Dinwoodie 2000; Moberg 2001; Hartwig-Nair et al. 2024), the cutting direction relative to the knot's axis has a significant impact on both cutting forces and material properties, which this study did not account for. Therefore, the mechanical property values obtained for knots should not be used for predicting cutting forces or other analyses.

Despite the large dispersion in values for density-normalised fracture toughness, the density-normalised shear yield stresses showed small dispersions. Furthermore, it was observed that the shear yield stresses obtained for knots are about half the value of those obtained for clear wood, and there is a noticeable difference depending on origin. This phenomenon may be due to the much higher lignan content in knots than in clear wood (Holmbom et al. 2003; Willför et al. 2003). Although the effect of lignans on the mechanical or machinability properties of wood has not yet been studied, lignans share similarities in their building blocks with lignin, despite serving different functions in wood (Behr et al. 2018). In contrast, lignin content of wood has a significant effect on its mechanical (Zhang et al. 2013) and physical properties, which affect the use of various wood

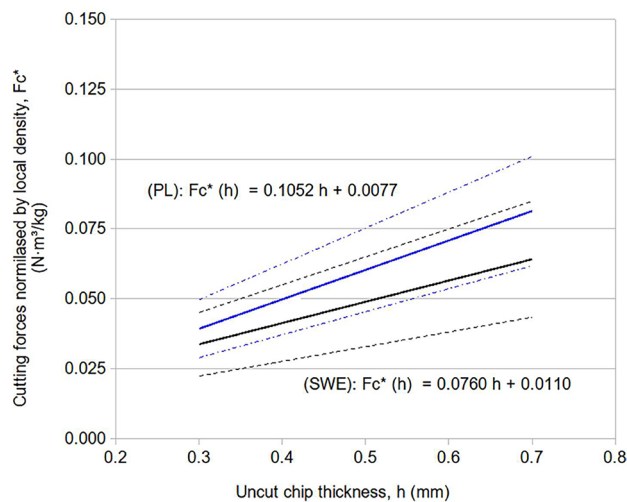


Fig. 7 Linear regression functions of the relationship between local-density-normalised cutting forces and uncut chip thickness for Polish (PL) and Swedish (SWE) wooden knots. The blue continuous line is the linear regression for Polish wooden knots; blue dashed lines define the areas of variation for 95% probability (significance level $\alpha=0.05$) for Polish wooden knots. The black continuous line is the linear regression for Swedish wooden knots; black dashed lines define the areas of variation for 95% probability (significance level $\alpha=0.05$) for Swedish wooden knots

Table 2 Density-normalised fracture toughness R^* and shear yield stress τ_y^* (average value and its range) for knots of Polish and Swedish Scots pine

Name of wood	Normalised fracture toughness R^* [J·m·kg ⁻¹]		Normalised shear yield stress τ_y^* [MPa·m ³ ·kg ⁻¹]	
Knots Polish	2.655	+1.207 -1.172	0.0188	+0.0041 -0.0041
Knots Swedish	3.793	+1.483 -1.517	0.0135	+0.0042 -0.0041

processing methods (Böresök and Pásztor 2021; Telmo and Lousada 2011).

Another more evident reason for the lower shear yield stress in knots may be their significantly higher brittleness compared to clear wood. This brittleness varies depending on the type of knot and the direction of loading, which has been observed during the continuous densification process of knotty Scots pine wood (Neyses et al. 2023). Knots generally have higher strength and hardness than clear wood (Kaiser and Kaiser 2020) and generate greater cutting forces and power during machining (Caceres et al. 2018; Licow et al. 2020). However, this is primarily due to their much higher density compared to clear wood (Fig. 6; Kaiser and Kaiser 2020). When mechanical and machinability properties are normalised by density, the resulting values reflect factors independent of wood density, such as structure or chemical composition. These aspects still require further analysis.

4 Conclusion

Machinability tests and analyses using X-ray computed tomography (CT) for determining fracture toughness and shear yield stress normalised by local density led to the following conclusions:

1. A wood machining process on a quasi-linear cutting station with a single cutting tooth can be used to determine fracture properties of materials by recording the cutting forces.
2. CT imaging provides finely detailed spatial insights into local wood density and knot structure, enabling more accurate normalisation of cutting forces than before, based on local density. Local cutting force values and the corresponding local wood density can be used in the normalisation process.
3. Polish pine clear wood specimens exhibited higher density-normalised fracture toughness and shear yield stress values than Swedish pine specimens, confirming that wood origin influences mechanical properties and machinability, and therefore these properties do not depend only on the variable wood density.
4. In the analysed Scots pine wood specimens, density-normalised shear yield stress values for knots were half the values found for clear wood.
5. Large dispersions were observed in the density-normalised fracture toughness values for knots, likely due to variations in cutting directions relative to the knot piths. Therefore, the mechanical property values obtained for knots should not be used for predicting cutting forces or other analyses. The future research should focus on preparing specimens to allow for cutting knots in specific orientations relative to their piths for more consistent results.

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tigation, Writing - Review & Editing. Dawid Stenka: Formal analysis, Writing - Review & Editing. Magnus Fredriksson: Methodology, Investigation, Writing - Review & Editing, Funding acquisition. Mikael Svensson: Conceptualization, Methodology, Investigation, Writing - Review & Editing, Funding acquisition.

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Data availability No datasets were generated or analysed during the current study.

Declarations

Conflict of interest The authors declare no competing interests.

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