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MACHINING PROPERTIES OF LESSER USED WOOD SPECIES FROM MOZAMBIQUE

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ABSTRACT

The present study was aiming at measuring cutting forces for wood of lesser used species from Mozambique such as *Acacia nigrescens* Oliv (namuno), *Pericopsis angolensis* Meeweven (muanga), *Pseudolachnostylis maprounaefolia* Pax (ntholo) and *Sterculia appendiculata K. Schum* (metil). Another aim was to use an expeditious method to compare performance of the species when cut. A machinability index calculated using Digraph and Matrix Methods was used for ranking the performance of the species when cut. Two different cutting tools 20o and 30o rake angle were used. Main cutting force in 90°-90° and 90°-0°cutting directions were measured by piezoelectric gauge. The results of the experiments showed that cutting forces followed normal trends to increase with density and decrease with increasing rake angle. The ratio between wood density and cutting forces in cutting directions 90°-90° and 90°-0° were 7 s^2m^{-4} and 17.3 s^2m^{-4}, respectively. The most difficult species to be machined was Namuno, whereas the easiest species to be machined was Metil.

KEYWORDS: Cutting tool, cutting force, tool wear, machinability, hardwood.

INTRODUCTION

Mozambique is an African country with vast forestry resources, including native tropical wood species with high commercial value that are recognised internationally. Thus, exportation of timber is a commercial option of considerable value for the country.

The Mozambican forest comprises 118 usable wood species but only 18 of these with already known properties and uses are exploited due to their high commercial value in selective logging systems (DNFFB 2002). In fact, in the Mozambican forests only a few commercial species are harvested because of lack of technical information and lesser popularity in the market place of many others wood species. Other reasons for research on Mozambican lesser used (LU) and unexploited wood species are the need to increase the resource base in the country and reduce the pressure on the better known wood species. Characterization of anatomical, physical, mechanical and technological features of selected native species has started in order to find their end uses (Ali et al. 2010, Uetimane et al. 2010, Lhate et al. 2010).

Several works analyse and discuss the dependence of cutting forces on tool geometry, cutting parameters, and workpiece properties. Some of the factors affecting cutting forces are rake angle; clearance angle, edge radius, kerf width, chip thickness, feed speed, wood grain, wood species, wood density, moisture content, and workpiece mechanical properties. Although a considerable amount of research has been carried out in this field, few studies have been made with respect to tropical wood species. Some cutting forces models have been elaborated to understand the mechanical behaviour of the materials tested and others to characterise the machinability of different wood materials (Marchal et al. 2009, Scholz et al. 2009, Cristóvão et al. 2012, Orlowski et al. 2013).

The need to understand and model wood cutting process is driven by a number of factors, among them, the selection of a cutting-tool material, design of cutting tools, estimation of cutting accuracy, determination of machinability of workpiece, and the chip formation process.

The present study was aimed at determining the machining properties of LU species such as *Acacia nigrescens* Oliv, *Pseudolachnostylis maprounaefolia* Pax, *Sterculia appendiculata* K. Schum and *Pericopsis angolensis* Meeweven.

MATERIAL AND METHODS

Material

Scientific and vernacular names of the species considered in this study were as given in Tab. 1. Two trees per species were obtained from open dry forest subjected to frequent fires set by local people as a result of shift cultivation and traditional hunting routines in the sampling stand. The stand was chosen in the northern Mozambique, namely in the Province of Cabo Delgado. The location of the province is Latitude 12° 45' 0'' S and Longitude 39° 30' 0'' E Each stem of the considered species was cut to three logs of 1.2 m length depicted as bottom, middle and top log. All logs were through-and-through sawn to 80 mm thick planks.

Tab. 1: Lesser used tropical hardwood species from Mozambique.

Scientific name	Vernacular name	Family
Acacia nigrescens[a]	Namuno	*Leguminosae*
Pericopsis angolensis[b]	Muanga	*Fabaceae-Faboideae*
Pseudolachnostylis maprounaefolia[a]	Ntholo	*Bopyroidea*
Sterculia appendiculata[a]	Metil	*Sterculiaceae*

Note: [a] lesser used species [b] emerging species

Sample preparation

All samples for cutting forces experiments were taken from butt log that was cut 0.7 m from the ground. All samples contained only mature heartwood. A main plank was through-and-through sawn from each butt log for samples. Smaller planks sized 80 x 80 x 1200 mm were air dried and then cut to 70 ×70 x 160 mm. In each end of the sample, 7 kerfs were cut either using a tool with rake angle 20°or 30°, for rip sawing (90°-90°) and planing (90°-0°), Fig. 1. Cutting directions were as defined by Kivimaa (1950). Each end of the same sample was cut either with a 20° rake angle tool or with a 30° rake angle tool.

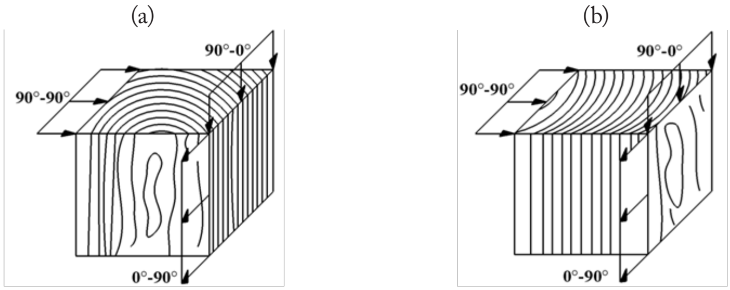

Fig. 1: Cutting directions according to Kivimaa (1950): a) Mode I; b) Mode II.

Density measurement

Wood density measurements were made by a computer tomography scanner (CT-scanner) (Fig. 2) as made by Lindgren et al. (1992). Wood density was read once per kerf (7 times per cross section) using Image J software, version 1.42. Tomograph images were also used to check for defects in samples. All kerfs were cut in slices free from defects.

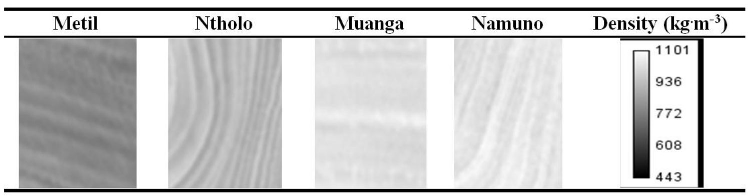

Fig. 2: Grey scales CT - images showing density level of LU species from Mozambique

Tool edge radius measurement

Before each cutting of two samples (one sample per tree), the edge radius of the tool was measured. The measurements were performed with the aid of Leica Qwin Microscope. The microscope was endowed with the capacity of digital image capturing. Tool edge radius was designed to be equal to 25 µm (Fig. 3).

Cutting forces measurement

Cutting forces were measured on 8 samples selected from 4 wood species (two samples per species and one sample per tree) using piezoelectric sensors. Cutting forces were read 11 times per kerf (77 times per cross section). This study considered only main cutting force. Schematic view of the equipment and cutting conditions were as given in Fig. 4 and Tab. 2. Main force measurement followed the methodology by Axelsson et al. (1993).

The cutting machine comprised mainly a rotating arm moved by an electric motor of direct current and a device for feed motion. The device for feed motion is endowed with a stepping electric motor for incremental shift of the tool holder for x and y axes. Three piezoelectric gauges allow the measurement of peripheral, axial, and radial cutting forces. The rotation of the arm and the axial displacement of the tool are synchronised movements to ensure a certain chip thickness.

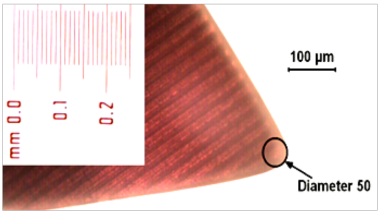

Fig. 3: Edge radius of the tool.

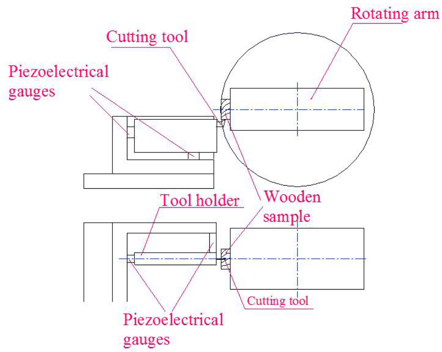

Fig. 4: Schematic view of the cutting forces measuring equipment.

Tab. 2: Cutting conditions.

Designation	Value	Designation	Value
Cutting direction	90°-90°, 90°-0°	Cutting speed	15 m.s^{-1}
Chip thickness	0.15 mm	Kerf width	3.9 mm
Rake angle	20° and 30°	Moisture Content	6-9%
Edge radius	25 µm	-	-

The data on cutting forces and density measurements were collected and analysed using SAS, Version 9.2 (SAS Institute Inc. 2009).

Wearing tests

The four species Metil, Muanga, Namuno and Ntholo were also tested for tool wear properties in another study (Cristovão et al. 2011). The results from this study have been used in the analysis part of current study, Tab. 3. The values on tool wear radius were obtained after a cutting length of 4896 m.

Digraph and matrix methods for machinability evaluation

In order to compare species' performance when cut, a machinability index was used. The machinability index was calculated using Digraph and Matrix methods. Machinability attributes considered in current study were as given in Fig. 5, cutting forces in direction 90°-90° (CF1), cutting forces in direction 90°-0° (CF2) and tool wear (TW).

$$\begin{array}{lll} & \text{Atributes} & \begin{array}{ccc} TW & CF1 & CF2 \end{array} \\ A = & \begin{array}{c} TW \\ CF1 \\ CF2 \end{array} & \begin{bmatrix} D_1 & a_{12} & a_{13} \\ a_{21} & D_2 & a_{23} \\ a_{31} & a_{32} & D_3 \end{bmatrix} \end{array} \qquad (1)$$

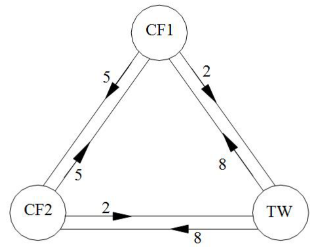

Fig. 5: Machinability digraph for LU wood species from Mozambique.

In current work every attribute was considered non-beneficial to machinability.

$$per(A) = \prod_{i=1}^{3} D_i + \sum_{i,j,k} (a_{ij} a_{ji}) D_k + \sum_{i,j,k} (a_{ij} a_{jk} a_{ki} + a_{ik} a_{kj} a_{ji}) \tag{2}$$

Eq. 1 gives matrix representation of machinability attributes taking into account the number of variables in present work (3 variables). Eq. 2 is the expression of machinability function considering the dimension of the matrix in Eq. 1.The permanent of matrix A, i.e., *per(A)* is defined as universal machinability function. The permanent is a standard matrix function and is used in combinatorial mathematics (Rao and Gandhi 2002).

The values of attributes D_i had to be normalized in order to use the scale, from 0 to 10. For non-beneficial attributes, the attribute value 0, on the scale 0 to 10, was assigned to the worst range value (D_{iu}) and the value of 10 was assigned to the best range value (D_{il}). The other intermediate values D_{ii} of the machinability attributes were assigned values in between 0 and 10 as per the following:

$$\begin{aligned} D_{ii} &= 10\{1-(D_i / D_{iu})\} && \text{for } D_{il} = 0 \\ D_{ii} &= \{10/(D_{iu} - D_{il})\} \times (D_{iu} - D_i) && \text{for } D_{il} > 0 \end{aligned} \tag{3}$$

The relative importance between a_{ji} and a_{ij} was distributed on the scale 0 to 10 and was defined as:

$$a_{ji} = 10 - a_{ji} \tag{4}$$

The comparison of species was also carried out by evaluating the coefficient of similarity/dissimilarity based on the numerical values of the terms of the machinability function in its grouping. The coefficient of similarity/dissimilarity lied in the range 0-1. Based on the performance, the coefficient of dissimilarity for two species was proposed as follows:

$$C_d = (1/Q) \times \sum_{i,j} \Psi_{i,j} \tag{5}$$

where: Q = maximum of $\left[\sum_{i,j} |T_{i,j}| \text{ and } \sum_{i,j} |T'_{i,j}| \right]$,

$T_{i,j}$ and $T_{i,j}$ denoted the values of the terms for machinability function of two species under comparison and $\Psi_{i,j} = |T_{i,j} - T'_{i,j}|$.

The coefficient of similarity was

$$C_s = 1 - C_d \tag{6}$$

RESULTS AND DISCUSSION

Overall, measurements of density and main cutting forces showed differences between species. Cutting forces followed normal trend to increase with increasing density. Fig. 6 shows an example of main cutting forces of Metil (Me), Muanga (Mu), Ntholo (N) and Namuno (Na) sorted by samples and rake angle in 90°-90° cutting direction. Samples were marked taking into account tree number (first figure following species initials) and sample number itself within the tree (last figure), for example Me11 stands for Metil, sample number 1 in tree number 1.

Statistical difference between species was significant enough, and therefore, in Fig. 7, the results were sorted by wood species and rake angle, whereas in Fig. 6 were sorted by sample and rake angle.

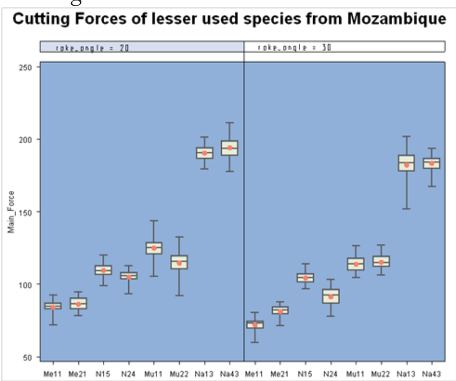

Fig. 6: Main cutting forces (90° -90° direction) sorted by sample and rake angle.

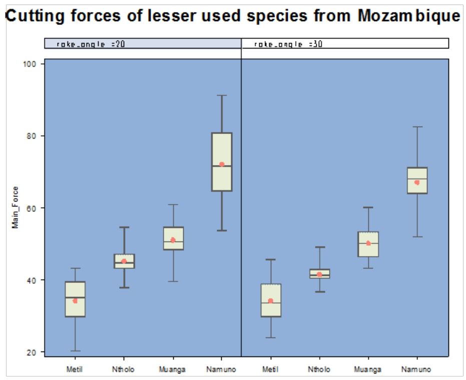

Fig. 7: Main cutting forces (90°-0° direction) sorted by species and rake angle.

Tab. 3: Density, main cutting forces in 90°-90° and 90°-0° and tool wear radius of lesser used species from Mozambique. Standard deviation (STD) shown in parentheses.

Wood species	Density (kg·m^{-3})	Cutting forces (N)		Tool wear radius *(µm)
		$F_{90°-90°}$	$F_{90°-0°}$	
Metil	604 (16)	81 (7)	34 (6)	5 (2.1)
Muanga	926 (14)	117 (8)	51 (4)	15 (4.9)
Ntholo	751 (28)	103 (9)	43 (3)	43 (4.1)
Namuno	1112 (14)	188 (9)	70 (9)	9 (3.8)

*Cristóvão et al. (2011)

A thorough explanation of Digraph and Matrix Method has been reported in the literature (Rao and Gandhi 2002). Due to anisotropic nature of wood, different cutting direction earn different values of main cutting force for the same species. Main cutting force is highest in 90°-90° cutting direction for all the species (Tab. 3). The range of cutting forces earned by metil partially overlap with the range of Scots pine in the study by Axelsson et al. (1993). Recorded differences are due to differences in wood density.

Tab. 4 illustrates the ratio between wood density and cutting forces, and ratio between cutting forces in 90°-90° and 90°-0°.

Tab. 4: Ratio between density and cutting forces and ratio between cutting forces.

Species	$\frac{Density}{F_{90^0-90^0}}$ (kg·m^{-3}/N)	$\frac{Density}{F_{90^0-0^0}}$ (kg·m^{-3}/N)	$\frac{F_{90^0-90^0}}{F_{90^0-0^0}}$
Metil	7	17.7	2.37
Muanga	7.8	18.3	2.32
Ntholo	7.3	17.3	2.37
Namuno	6	16	2.69

Surprisingly, the ratio between wood density and cutting forces in 90°-90° and 90°-0° cutting directions were around 7 kg·m^{-3}/N and 17.3 kg·m^{-3}/N, respectively. This suggests that with the same specific condition, by determining the wood density one can have a rough estimation of the cutting force in 90°-90° and 90°-0° cutting direction. However, it is well known that, sometimes, two species with the same density give very different cutting forces, or species with completely different densities have similar cutting forces (Eyma et al. 2004). Recently, Chuchala et al. (2013) pointed out that cutting forces are clearly correlated with wood density, even if it is not the only significant factor. Among the tested wood species, the cutting forces ratio between 90°-90° and 90°-0° cutting directions was 2.4. Since cutting force is correlated to power consumption, this implies that the power required to cause a failure during sawing (90°-90°) is 2.4 times greater than the power required during planing (90°-0°).

Tab. 5: Machinability attributes values (D_{ij}).

Species	Tool wear radius	Cutting forces 90°-0°	Cutting forces 90°-90°
Metil	10	10	10
Muanga	7.37	5.37	6.57
Ntholo	0	7.41	7.97
Namuno	8.95	0	0

Tab. 6: Relative importance values of machinability attribute (a_{ij}).

Attribute	Cutting forces 90°-90°	Cutting forces 90°-0°	Tool wear radius
Cutting forces 90°-90°		5	8
Cutting forces 90°-0°	5		8
Tool wear radius	2	2	

The current study adopted Rao's approach to assigning relative importance value between tool wear and cutting forces (relative importance coefficient of tool wear to cutting forces equal to 8) (Rao and Gandhi 2002).

Machinability indexes and ranking:

Metil: 1730, Muanga: 788, Ntholo: 478, Namuno: 303, Machinability index was calculated using Eq. 2.

The ranking of machinability shows that the easiest species to be machined is Metil and the most difficult species to be machined is Namuno. Namuno is highly penalized in terms of machinability due to its highest cutting forces. It is informative to note that if the species are ranked using density only or cutting forces only, Muanga would be ranked in third position, but if the ranking is done using matrix and digraph method, Muanga is shifted to second position. In the ranking considering tool wear only, Ntholo earns the last position (fourth).

Coefficient of dissimilarity was calculated using Eq. 5, and coefficient of similarity using Eq. 6 for every species. If two species are similar in performance, then the coefficient of similarity is 1 and the coefficient of dissimilarity is 0 (Rao and Gandhi 2002). In current work there were no similar species, Tab. 7. Tukey's pair-wise comparison of species based on density and cutting forces gave the same results (dissimilarity between species).

Tab. 7: Values of coefficient of similarity (Cs) between species.

Species	Muanga	Ntholo	Namuno
Metil	0.46	0.28	0.18
Muanga		0.61	0.38
Ntholo			0.63

Considering the coefficient of similarity in Tab. 6 and the ranking of species recorded above, machinability of Muanga, Ntholo and Namuno, was 46%, 28% and 18% that of Metil, respectively when the coefficient of relative importance of tool wear to cutting forces was 8.

Sensitivity analysis

The sensitivity analysis is aiming at judging the effect of relative importance values assignment on species ranking, since there is no consensual approach in literature about the assignment. The sensitivity analysis showed that the ranking was kept the same for the whole range of values for the relative importance coefficient.

CONCLUSIONS

The present study was aiming at determining cutting forces of LU species such as Namuno, Ntholo, Metil and Muanga. Another aim was to use an expeditious method to compare the performance of the species when cut. A machinability index calculated through Digraph and Matrix Method was used. The main findings of this work can be summarized as follows:

1. Cutting forces followed normal trend to increase with increasing density;
2. The ratio between wood density and cutting forces in cutting directions 90°-90° and 90°-0° were 7 s^2m^{-4} and 17.3 s^2m^{-4}, respectively;
3. The ratio between cutting forces and cutting direction in 90°-90° and 90°-0° was 2.4;
4. The most difficult species to be machined was Namuno, whereas the easiest species to be machined was Metil;
5. Sensitivity analysis showed that in this study variation of relative importance coefficient affected only similarity between species, and did not affect the raking.

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