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THE IMPACT OF TOOL HEIGHT ON THE WORKPIECE IN WOOD CUTTING WITH CIRCULAR SAWS

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ABSTRACT

The tool height influences the cutting force by changing the angle at which the blade penetrates the wood. This parameter was analyzed at two different heights. In the first set of measurements, previously used to assess the bluntness of the tool, a sharp saw was positioned 3 mm above the workpiece. The second set was also carried out with a sharp saw, but the height of the tool was set to 15 mm above the workpiece. In both cases, all other parameters were kept constant, so it was not necessary to introduce the concept of specific cutting resistance. By analyzing the average cutting forces, basic data was obtained showing that changing the saw height changes the average fiber cutting angle. When the saw projected 3 mm beyond the workpiece, the average cutting angle Φm was 21.25°; with a projection of 15 mm, Φm increased to 27.87°. A significant difference is observed between these two configurations, with an average cutting angle difference of 6.62º. The rake angle of the saw used in the analysis was 20º. This change in the average fiber cutting angle explains the variation in the required cutting force under otherwise identical conditions.

Keywords: machinability, cutting regime, cutting forces.

1. INTRODUCTION

The reliability and accuracy of machines and tools in the wood industry have a major impact on the final product. This problem is even more noticeable in mass production. In addition to the amortization costs caused by replacements and repairs, there is also more scrap in the workpieces and a higher use of service time and therefore less production time. The price of machining costs per product quantity most clearly reflects all of the above. The right choice of parameters for sharpening tools offers the opportunity to maximize the resources of these tools. In addition to the tool height, tool wear is also influenced by several other parameters: the tool material (e.g., HSS, carbide tools, nano-coatings) significantly determines its resistance to wear and impact loads; the temperature in the cutting zone, which depends on the type of machining; and the properties of the processed wood, such as density, hardness, moisture content, and the presence of mineral inclusions, also contribute to abrasive wear. The machining modes—including cutting speed, tooth feed, cutting depth, and cutting angle—have a direct effect on the mechanical and thermal load of the tool. The duration and continuity of work without interruption increases the thermal load and accelerates material fatigue, maintenance, and sharpening of the tool, i.e., regular removal of gumming and deposits and correct sharpening are the key to extending the service life. The stability of the settings and the precision of the machine (centering, vibration, and condition of the bearings) also have a major influence on the even wear and reliable operation of the tool. The question arises as to which working procedure should be applied to the tool so that it is utilized optimally and functions smoothly. Cutting power is one of the methods used to determine the dullness or poor power of a tool. Checking the wear and selecting the blunt tool change mode can provide some

answers as to what influences tool wear. One of the factors that influence the quality of machining and tool wear, and therefore cutting power, is the height of the tool in relation to the workpiece.

2. THEORETICAL BACKGROUND

The mechanical processing of wood is a complex process. Monitoring and controlling the machining processes requires a good knowledge of the phenomena that can influence the final machining result. From a technical point of view, the processing results can be divided into expected (desired) and unexpected, i.e., undesired, and in many cases unavoidable results. The desired results of wood processing would be the removal of excess material and the achievement of a finished piece with certain dimensions and a certain surface quality. Undesirable side effects of processing are released heat, which leads to increased temperature of tools and work objects, noise, vibrations, and more (see Figure 1).

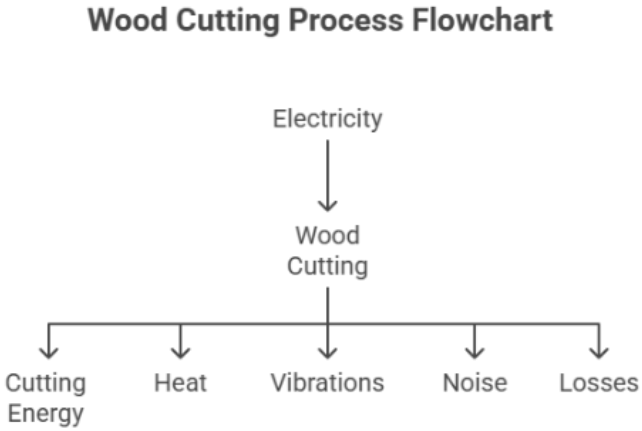


Figure 1. *Energy balance of cutting process.*

Input for the process of cutting wood is electricity, and output is cutting energy, heat, vibrations, noise, and other losses.

A large number of studies have focused on the determination of cutting forces (Ko *et al*., 1999; Vazquez-Cooz *et al*., 2003) or noise or vibration (Lemaster *et al*., 1985) that occur during processing. However, only a few of them have considered the overall energy balance during the processing of wood or wood-based materials (Iskra *et al*., 2005). This complex type of research requires suitable equipment to measure the total, active, and reactive power of the electric drive motor, cutting forces, heat released during cutting, noise, and vibrations. With such equipment, it would be possible to determine the balance of energy consumed during cutting and the factors influencing energy consumption, such as the stability of the tool, the machining time of the machine, and the quality of the machined surface (Iskra *et al*., 2005). The Faculty of Forestry has measuring devices for measuring, monitoring, and displaying the power used by the SRD1 and SRD2 electric motors, which can also be used to determine the power required for cutting wood.

Heat losses are the next largest component in the balance of total losses. This is the heat released during friction between the wood and the front surface and possibly the sides of the tool. They are more difficult to measure when you consider that some of the heat released during cutting accumulates in the tool, some in the work object and crisps, and some in the ambient air. In well-chosen woodworking regimes (for cutting speeds above 10 m/s), after a rapid initial rise, the temperature of the tool reaches a certain equilibrium temperature at which the heat generated during cutting is approximately equal to the heat released into the environment (Iskra *et al*., 2005). This could mean that the total increase in active energy during cutting, which occurs when the cutting speed is increased above 10 m/s, is converted into heat loss under the same other cutting conditions.

Vibration can have a major impact on machining results and the service life of tools and machines. The energy consumption of noise and vibration is not large, so it is not a big mistake if they are not taken into account.

As already mentioned, cutting power is influenced by cutting speed, feed rate, and cutting angles (Kovač, Mikleš, 2010). According to their measurements, there are optimal tool geometries that reduce the cutting force. The article presents the results when using a saw with a breast angle γ of -10º to 20º, depending on the type of cutting material used. Positive breast angles consume less cutting force than saws without an angle or with a negative angle. This can be explained by the fact that the breast angle γ has an influence on the entry and exit angle of the saw as well as on the mean angle of the fiber cut, as can be seen in Figure 2.

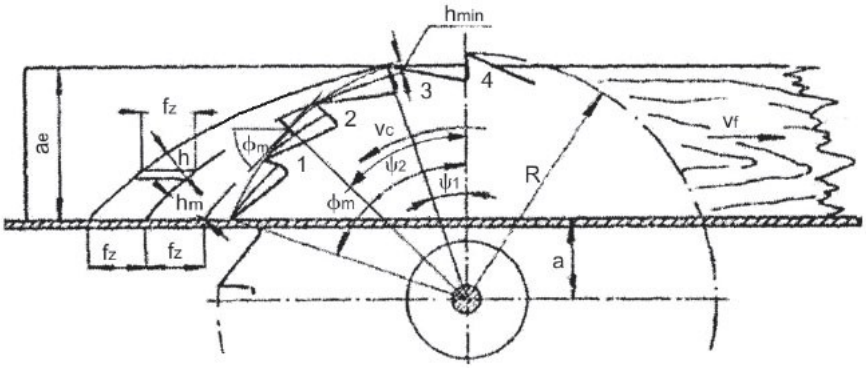


Figure 2. *Cutting process geometry,*
F_z – feed per tooth [m/s], a_s – cutting depth [m], v_f – feed rate [m/s], v_c – cutting speed [m/s], ψ_1 - input angle of the teeth [°], ψ_2 - output angle of the teeth [°], Φ_m – average fiber cutting angle [°], h_m – maximum chip thickness [mm].

Average fiber cutting angle could be calculated as follows:

$$\phi_m = \arccos\frac{a+(\frac{a_e}{2})}{R} \qquad [1]$$

3. MATERIALS AND METHODS

3.1. SRD 1

The UNO-LUX NS measuring and recording device is used to measure, monitor, and display the power of the wood cutting machine. The system also analyzes and processes the data obtained, stores it, and has the option of displaying it later. The system is based on the ULNS Power Expert software package, version 2.0, and functions as a combination of the fixed cable connection of the wood cutting machine with the power measurement system. The ULNS Power Expert software package is used to measure, record, display, and calculate characteristic power parameters during woodworking using an NI USB-6008 acquisition card and a suitable wattmeter with an industrial current signal of 0-20 mA. The program corresponds to the Windows platform and is optimized for a resolution of 1024x768.

The analogue signal measurement is based on a Hartmann & Brown wattmeter with a continuous current output of 0-20 mA. Using the switch on the housing, the measuring range can be selected between values of 5 KW, 10 KW, and 15 KW, depending on the expected load. The maximum current signal of 20 mA always corresponds to the selected measuring range. The current signal is forwarded from the control cabinet to the subsystem of the recording computer. The signal is sampled and converted using the USB 6008 acquisition card from National Instruments, which is shown in figure no. 4. The NI USB-6008 acquisition card is connected to a PC via a USB port. The measuring system, i.e., a wattmeter with a current output, is connected to the acquisition card at ports 1 and 2, namely AI0+ and AI0-. This card model is intended for voltage measurement, so the current signal is converted into a voltage signal via a high-precision resistor (1% tolerance) of 199 ohms.

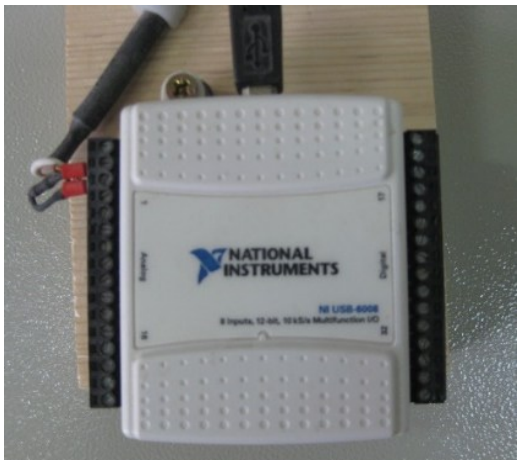


Figure 3. *Acquisition card USB 6008.*

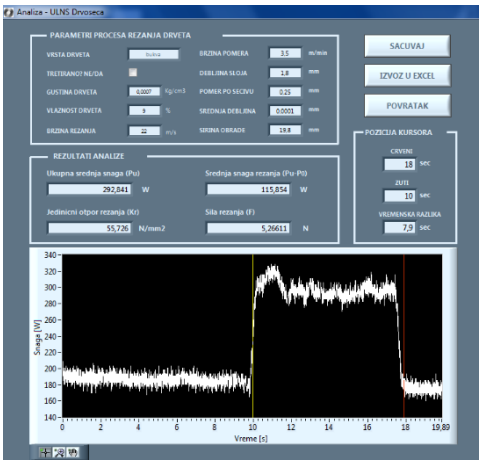


Figure 4. *Screenshots of cutting power. acquisition software.*

The measurement results are recorded, displayed, and processed using the software described in this article. All signals are scaled by software and converted into real values with corresponding units of measurement. It is important to mention that this measuring device is portable and can be connected to various machines with the limitation of the maximum permissible power (up to 15 KW), thus enabling the measurement of cutting power in various machining operations.

The recorded data is displayed in the data analysis window (Figure 4), and all recorded parameters can also be saved in the Excel program package.

3.2. SRD 2

The SRD2 device is suitable for laboratory and industrial measurement of the cutting power of machines with a three-phase electric motor for processing wood and wood-based materials. The device is also able to monitor the power consumption of three-phase motors over a period of time and record the data of the voltages and currents per phase, the active and reactive energy, the power factor, and the harmonics occurring in the power grid. It consists of a PowerLogic PM710 multimeter (Figure 5) from Schneider Electric, which is attached to the door of the enclosure in which the device is installed (Figure 6). The device has an RS232 port for connection to a computer, which enables remote monitoring and recording of the data obtained.



Figure 5. *PowerLogic PM 710.*



Figure 6. *SRD 2 installation setup.*

With the help of the computer software "Power View", the power of a three-phase motor can be measured and recorded in a relatively simple way at no load and under load, i.e., in our case during

machining. On the basis of the values obtained, it is possible to calculate the average power during cutting but also to determine the current and average cutting forces and the specific cutting resistance.

The PowerLogic PM710 multimeter is connected to a computer on which the data obtained from the measurement can be recorded and processed via the RS232 and USB interfaces. The Power View software makes it possible to monitor and record the values of the current parameters over a longer period of time. The recorded data is saved in an Excel file, and a diagram is created for the recorded values.

Figure 7 shows the part of the software package where the data to be monitored is selected. The software consists of 6 steps to define the type of measurement, the period to be analyzed, the device from which the data is recorded (the software can monitor several devices simultaneously), and the parameters to be analyzed. The ModbusReader PM710 SCADA software environment is also available. It enables laboratory and industrial measurements with a precise range and shorter time intervals. The software records the same parameters and displays them in real time.

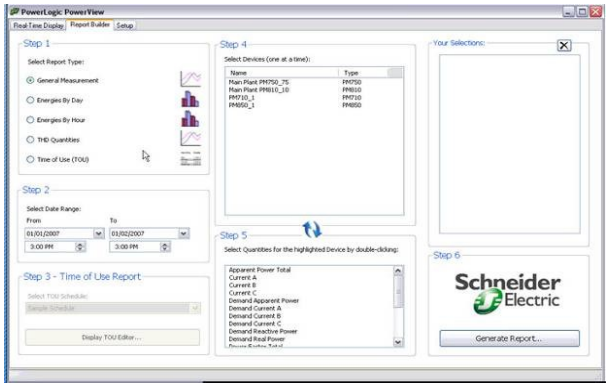


Figure 7. *Screenshot of Power View cutting power measurement window.*

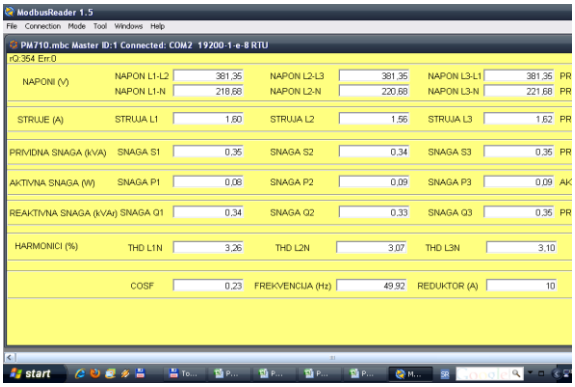


Figure 8. *Screenshot of ModbusReader PM710 software package.*

Figure 8 presents software during process parameter monitoring in real time. After finishing recording, the data obtained are stored in the appropriate previously determined directory.

To verify the method of determining the accuracy and bluntness of the tool, an example of the production of three-layer parquet in the Tarkett Company from Bačka Palanka was taken. All layers are made of wood: the top layer is made of hardwood, the middle layer is made of fir or spruce, while the bottom, levelling layer is made of spruce veneer. After calculating the cost price and the quantity share, the middle layer of slats has the highest cost price. The slats form the middle layer with their geometry and qualitative correctness, and any deviation can have a negative effect on the quality of the end product. Deviations from the established quality standard are due to the poor performance of the tools used to process the slats and the quality of the wood, which affect the quality of the end product.

Materials used during the experiment were fir (*Abies alba*) and spruce (*Picea abies*) planks. The experimental plan consisted of the following:

- Workpieces were cut with a new (unused) circular saw blade,
- 4 workpieces were cut with a 3 mm tool override (of which 2 were measured by the SRD1 and the remaining two by the SRD2 acquisition system),
- 2 workpieces were cut with 15 mm tool override (measured by SRD1).

Table 1. *Dimensions of workpieces and leftover battens.*

Workpieces dimensions:	Leftover battens dimensions:
length: 434 mm	length: 434 mm
width: 147 mm	width: 9 mm
thickness: 28 mm	thickness: 28 mm
Moisture content 7.5 % ± 0.1	

The tool specifications are as follows:
Manufacturer: Ake

Type: Mustang*
Teeth material: HSS
Diameter: 250 mm
Kerf: 2.0 mm
Body thickness: 1.4 mm
Number of teeth: 30+2
Tooth shape: MA with edged backside and BG tested
* The saw is coated with an oxide layer that prevents resin contamination

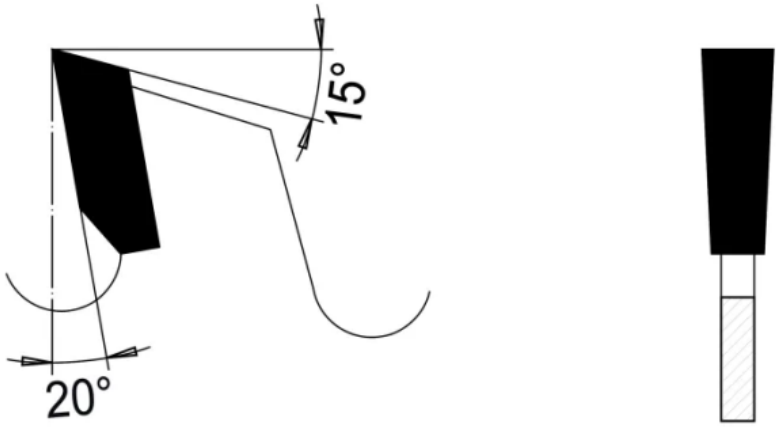


Figure 9. *Saw tooth geometry.*

A cutting operation was performed on the Minimax CU410K (figure 11) combined machining center at the Laboratory for Machines and Apparatus, Faculty of Forestry, Belgrade University.

Cutting parameters: rotational speed ~ 4.000 o/min; feed rate ~ 15 m/min.



Figure 10. AKE *Mustang circular saw.*



Figure 11. *Minimax CU410K.*

The statistical analysis, i.e., the hypothesis test to test the cutting forces, was carried out using descriptive statistics to check the regularity of the distribution of the results, and the relationship between the data groups was determined using analysis of variance. The measurements of the two cutting force monitoring devices can be recorded and processed in the MS Excel program. This is an essential part of processing the results so that only the essential parts of the measurements to be compared can be recorded. Since one measurement included all the cuts of a board (15÷17 cuts), it was necessary to separate the results of the individual cuts. Furthermore, for the results obtained with the SRD1 device, the determination of the average values of the cutting performance by the Power Expert software was used. The data on the mean values were then entered into an Excel document. The statistical analyses were carried out in the statistical software package.

4. RESULTS AND DISCUSSION

When checking all the results obtained and recorded on both devices, it was found that the results of the SRD1 and SRD2 devices do not match. There are two deviations that have occurred. The first deviation is in the measured values, i.e., SRD2 shows a higher cutting power than SRD1. This can be explained by the fact that when measuring with the SRD1 device, the voltage and current are only measured on one phase, and this result is multiplied by three in the calculation to obtain the final result. The SRD2 device, on the other hand, measures all three phases simultaneously and obtains the total active power consumed from these results. Another discrepancy in the results lies in the time intervals at which these two devices measure. The measurement protocol of the SRD1 device is constant and has an interval of 0.01 seconds, while this interval is not constant for the SRD2 device and is between 0.25 and 0.28 seconds. This inadequacy of the SRD2 device can be explained by the fact that the PM710 meter, which forms the basis of the device, is intended for continuous monitoring of electricity utilization parameters and is not designed for such rapid measurements.

Both devices had shortcomings that should be eliminated in the future. Due to the precision of the time intervals and the time measurement range, the data recorded by the SRD1 device was processed.

The effect of tool override was also determined using two groups of measurements. In the first set of measurements, a saw with a tool height above the workpiece of 3 mm was used, while in the second set, a tool height above the workpiece of 15 mm was used. In this analysis, all other parameters remained the same, so it was not necessary to introduce a specific cutting resistance, but all analyses were carried out using the cutting power of the saw.

By analyzing the results of the mean values of the cutting forces, basic data were obtained, which are shown in Tables 2 and 3, while Table 4 shows the data from the analysis of variance between these two types of cutting.

Table 2. *Main statistical values for 3 mm tool override power measurements.*

Alpha value (for confidence interval)	0.05		
Sharp saw 3 mm (Average cutting power [W])			
Count	34	*Skewness*	-0.7066
Mean	564.9559	*Skewness Standard Error*	0.391
Mean LCL	551.2792	*Kurtosis*	2.9905
Mean UCL	578.6326	*Kurtosis Standard Error*	0.7177
Variance	1.536,4514	*Alternative Skewness(Fisher's)*	-0.7397
Standard Deviation	39.1976	*Alternative Kurtosis (Fisher's)*	0.1885
Mean Standard Error	6.7223	*Coefficient of Variation*	0.0694
Minimum	464.83	*Mean Deviation*	31.1857
Maximum	640.74	*Second Moment*	1.491,2617
Range	175.91	*Third Moment*	-40.692,3056
Sum	19.208,5	*Fourth Moment*	6650431.84
Sum Standard Error	228.5593	*Median*	577.72
Total Sum Squares	10902657.9636	*Median Error*	1.4449
Adjusted Sum Squares	50.702,8974	*Percentile 25% (Q1)*	545.31
Geometric Mean	563.5852	*Percentile 75% (Q2)*	588.555
Harmonic Mean	562.1615	*IQR*	43.245
Mode	#N/A	*MAD (Median Absolute Deviation)*	20.685

		Coefficient of Dispersion(COD)	0.05 09

According to results from table 2, it is possible to notice that the average value of cutting force is 565 W with minimal and maximal values of 465 and 641 W, respectively.

Table 3. *Main statistical values for 15 mm tool override power measurements.*

Alpha value (for confidence interval)		0.05	
Sharp saw 15 mm (Average cutting power [W])			
Count	34	*Skewness*	0.7683
Mean	530.2482	*Skewness Standard Error*	0.391
Mean LCL	518.7874	*Kurtosis*	4.3601
Mean UCL	541.7091	*Kurtosis Standard Error*	0.7177
Variance	1.078,921	*Alternative Skewness(Fisher's)*	0.8042
Standard Deviation	32.8469	*Alternative Kurtosis (Fisher's)*	1.7832
Mean Standard Error	5.6332	*Coefficient of Variation*	0.0619
Minimum	475.93	*Mean Deviation*	24.9321
Maximum	634.79	*Second Moment*	1.047,188
Range	158.86	*Third Moment*	26.034,1341
Sum	18.028,44	*Fourth Moment*	4781275.0323
Sum Standard Error	191.5289	*Median*	526.925
Total Sum Squares	9595152.887	*Median Error*	1.2108
Adjusted Sum Squares	35.604,3919	*Percentile 25% (Q1)*	508.99
Geometric Mean	529.2852	*Percentile 75% (Q2)*	550.565
Harmonic Mean	528.3443	*IQR*	41.575
Mode	#N/A	*MAD (Median Absolute Deviation)*	22.26
		Coefficient of Dispersion(COD)	0.0467

Table 3 shows that the average value of the cutting power is 530 W, the minimum power is 476 W, and the maximum power is 635 W. Comparing this with the results from Table 2, it can be seen that the minimum and maximum values are similar, but that the average values are still different, as shown in Table 4.

Table 4. *Variance analysis for different tool overrides.*

Analysis of Variance (One-Way)							
Descriptive Statistics							
Groups	*Sample size*	*Sum*	*Mean*	*Variance*			
3	34	19.208,5	564.9559	10902657.9636			
15	34	18.028,44	530.2482	9595152.887			
Total	68		547.6021	1.593,8185			
ANOVA							
Source of Variation	*d.f.*	*SS*	*MS*	*F*	*p-level*	*F crit*	*Omega Sqr.*
Between Groups	1	20.478,553	20.478,553	15.6601	0.0002	3.9863	0.1774
Within Groups	66	86.307,2893	1.307,6862				
Total	67	106.785,8423					

Table 4 shows that the analysis of variance (ANOVA) reveals a very significant difference between the mean cutting values depending on the height of the tool in relation to the workpiece. This is confirmed by the value of the significance level (p-level), which in this case is 0.0002, and the significance limit in this case is 0.05. Figure 12 shows a graphical relationship between these two sets of data, as well as a linear function showing that less power is required when cutting with a tool that protrudes 15 mm above the workpiece.

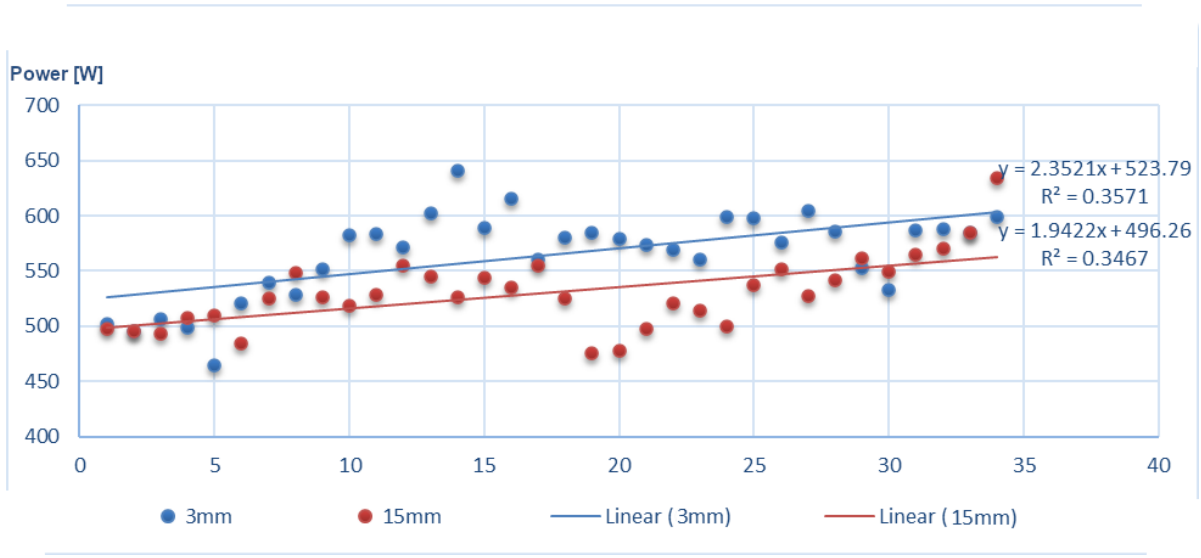


Figure 12. *Distribution graph for mean values of cutting power.*

If you raise the saw in relation to the work object, the mean cutting angle of the fibers changes so that when cutting in the first case, when the saw protrudes 3 mm from the workpiece, Φ_m=21.25º, while in the second case, when the saw protrudes 15 mm from the workpiece, Φ_m=27.87º. The difference between these two determined mean fiber cutting angles is 6.62°, and the breast angle of the saw used is 20°. This change in the mean cutting angle of the fibers explains the difference in the required cutting performance under the same other conditions.

CONCLUSIONS

Based on the results of this study, it was concluded that the height of the tool influences the cutting performance. There is a significant difference between cutting with a saw that protrudes 3 mm above the workpiece and a saw that protrudes 15 mm above the workpiece. This difference can be explained by the change in the mean cutting angle of the fibers (Φm) and the reduction in performance by increasing this angle.

Future tests should determine which tool height offers more favorable cutting conditions, and optimal mean fiber cutting angles should be determined.

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