ONLINE ISSN 2069-7430
ISSN-L 1841-4737
PRO LIGNO
www.proligno.ro
Vol. 14 N° 4 2018
pp. 124-130

STUDY REGARDING THE OPTIMIZATION OF MILLING PARAMETERS FOR A MINIMAL POWER CONSUMPTION

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Abstract:

Energy consumption has become one of the environmental issues regarding all industries because of the increased development that is recorded in the last years. Thus, a major topic for furniture industry also, is to reduce the cutting power consumed while processing wood and wood composite parts. The purpose of this paper is to analyze and model the effects of the cutting speed and feed speed upon power consumption while milling. The most important parameters (variables) on power consumption are cutting speed and feed speed, so, the wood samples-beech (Fagus sylvatica) were processed with five different feed rates and cutting speeds. The results of the experiment have indicated that power consumption increased with increasing cutting speed and feed rate.

Key words: *power consumption; optimization; beech.*

INTRODUCTION

With the increased demand in a better quality of manufactured products, development of industries and society, the energy consumption has recorded a rapid growth with a great impact on the environment. Thus, reducing the power consumption, all the environmental issues that came from power production should be diminished. In order to improve the quality and reliability of the wooden products, to increase the productivity and decrease the production costs, some factors like the technological level of the machine and especially the optimal machining conditions depending on the technical possibilities of the machine-tools must be taken into consideration (Racasan 2008).

In the literature is well known that the most frequently used optimization criterion are cutting force, tool wear, surface roughness and power consumption. There are several researchers that examined the influence of machining parameters on power consumption, using different species of wood. In their study, Aguillera and Martin (2001) analyzed the influence of cutting speed, feed rate and cutting depth on power consumption, cutting forces and surface roughness during planning two wood species with different density beech and spruce. The result of the study regarding power consumption was that the cutting power growth is proportional to the increase of cutting depth and wood density. Tiryaki S et al. (2016) also investigated and modelled the influence of feed rate, cutting depth and number of cutters on power consumption while planning beech and spruce.

Other researches were made on milling thermal treated wood. Ispas et.al investigated the effect of heat treatment on wood upon the machining properties and surface quality of machined wood. The obtained results indicated that the cutting power recorded on milling the heat-treated beech wood was up to 50% lower than the one recorded on untreated wood, but the roughness was slightly higher. The analysis of the energy consumption during milling thermally modified and unmodified beech wood taking into consideration the angular geometry of the milling cutter was made by Kubš et al. (2016).Thermally treated and untreated lodgepole pine wood (*Pinus contorta*) was another investigation topic (Kubš et al. 2017). Samples were treated at different temperatures and the cutting power of the milling process was recorded. Results indicated that increasing the feed speed, the cutting power also increased up to 30%, and similar results were recorded during increasing the cutting speed.

OBJECTIVE

The main objective of the present research is to analize the variation of cutting power while, milling one of the most used wood species- beech in two directions (longitudinal and transversal to the wood fibres direction) with different cutting sppeds, feed speeds and cutting edges.

MATERIAL, METHOD, EQUIPMENT

The material used in this research was beech (*Fagus sylvatica*). The wood had to follow some technological steps in order to obtain the samples: planning, cross-cutting, spliting and thicknessing the beech timber. These parts were glued in boards with PVA adhesive (Kleiberit Tempo). After gluing, the boards were also planned, thicknessed, cutted in samples of 400x400mm and calibrated on both sides (Fig.1.a).

Moisture content and density were measured on several samples. The moisture content was measured with a non-destructive moisture meter Type PM1 (Merlin) (Fig.1.b). Some sample boards were cut in small samples in order to find out the density. The weight was measured with a digital balance AD2000 and the volume with a digital caliper (Fig.1.c, d).

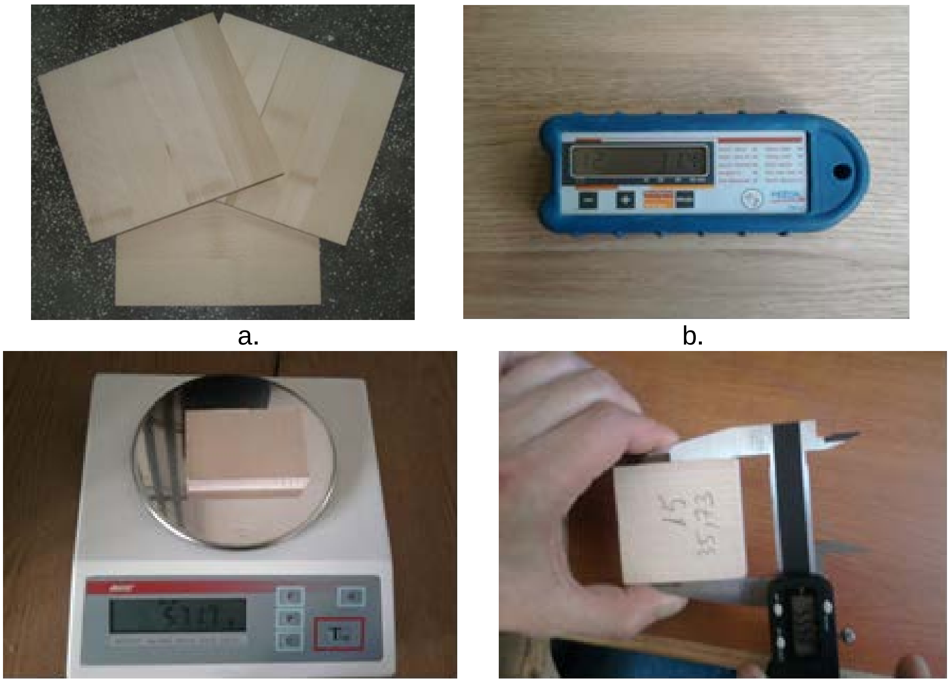
a. b.
c. d.

Fig. 1.
Material used for experiments:
a – samples; b – moisture content; c - weight measurement; d - volume measurement.

The samples had the moisture content between 9.8% and 11.4% (mean 10.37), and a density of 0.667 [g/cm3] (mean value).The experiments were performed using two metallic carbide router bits with 10mm cutting diameter, spiral and straight cutting edge (Fig.2.a, b).

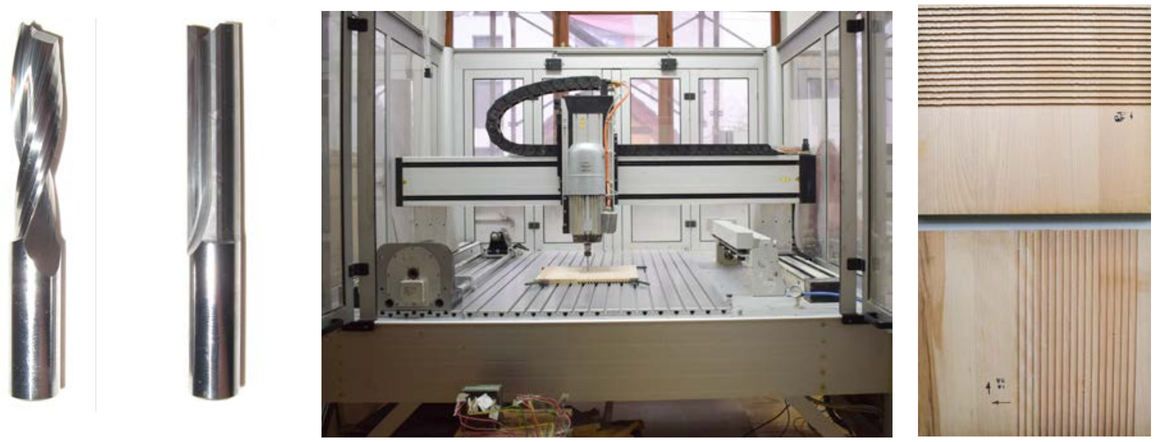
a. b. c. d.

Fig. 2.
Tools and machine used for experiments: a - carbide router bit with spiral cutting edge; b - carbide router bit with straight cutting edge; c - CNC processing centre; d - machined samples.

The cutting directions were 0^o (longitudinal) and 90^o (transversal) to the wood fibers direction. The depth of cut, for all samples, was h=5mm (Fig.2.d).

The samples were processed with five different feed speeds, having the folowing values: 5, 7.5, 10, 12.5 and 15m/min. The spindle rotation had also five different values: 9000, 10500, 12000, 13500, and 15000rot/min. This led to five values for the cutting speed: 4.71, 5.5, 6.28, 7.07 and 7.85m/s.

The processing machine was a CNC processing centre type ISEL GFV/GFY, which allowed the exact set-up of the router-bit rotation speed and of the feed speeds (Fig. 2.c).

The active power consumed by the spindle motor was measured by a Sineax P530/Q531 transducer for active and reactive power (Camille Bauer). Data obtained was recorded with a DAQ Board Keithley Model KUSB-3108. The apparatus was connected to the electric circuit according to the scheme presented in Fig. 3.

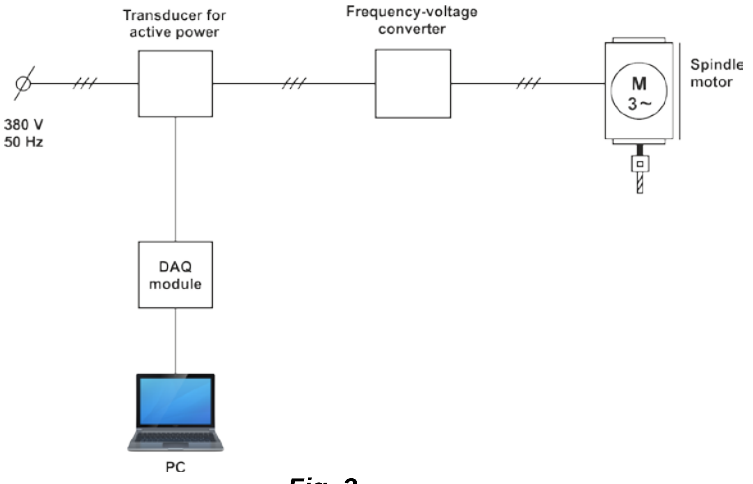

Fig. 3.
The conection scheme of the apparatus used for measurement.

Before performing the experiments, an experimental plan was established (Table 1). The method selected for the mathematical modelling was a non-linear factorial experiment.

Table 1

The experimental plan used.

Experiment	**No.**	**Independent variables (values)**	
		v [m/s]	**u [m/min]**
		x_1	**x_2**
Base experiments	1	7.07	7.5
	2	5.5	7.5
	3	7.07	12.5
	4	5.5	12.5
Supplementary experiments	5	7.85	10
	6	4.71	10
	7	6.28	5
	8	6.28	15
	9	7.85	5
	10	7.85	15
	11	4.71	15
	12	4.71	5
Core experiments	13	6.28	10
	14	6.28	10
	15	6.28	10
	16	6.28	10
	17	6.28	10

The data recorded from DAQ system represents the value of active power P_T that was consumed by the spindle motor during milling and includes the power consumed at idle running P_0 and the one consumed during milling P_M. Thus, in order to highlight the active power consumed only during milling some corrections were made according to the next formula:

$$P_M = P_T - P_0 \ [W] \qquad (1)$$

RESULTS AND DISCUSSION

In order to establish the mathematical models (such as multiple regression equations), based on the experimental data, a statistical analysis software (Data Fit) was used. The result was an equation (mathematical model) that describe the relationship between the independent variables (cutting speed - v [m/s], and feed speed - u [m/min]) and the dependent one (cutting power - P [kW]). The coefficient of determination (R2) for this equation was 0.98 for longitudinal direction, 0.96 for transversal direction for data obtained with the spiral cutting edge router bit and 0.95 for longitudinal direction, 0.96 for transversal direction for data obtained with the straight cutting edge router bit. Both forms of equations (coded and real one) are presented in the following table.

Table 2

Mathematical models (equations) obtained

Cutting edge	**Cutting direction**	**Obtained equation**		**Coefficient of determination (R^2)**
spiral	longitudinal	Coded	$Y = a+b*x_1+c*x_2+d*x_1^2+e*x_2^2+f*x_1*x_2+g*x_1^3+h*x_2^3+i*x_1*x_2^2+j*x_1^2*x_2$	0.98
		Real	$Y = -1.421+0.741*x_1+6.78*x_2-0.126*x_1^2-6.976*x_2^2+1.377*x_1*x_2+6.864*x_1^3+2.763*x_2^3-3.126*x_1*x_2^2-3.904*x_1^2*x_{2.}$	
	transversal	Coded	$Y = a+b*x_1+c*x_2+d*x_1^2+e*x_2^2+f*x_1*x_2+g*x_1^3+h*x_2^3+i*x_1*x_2^2+j*x_1^2*x_2$	0.96
		Real	$Y = -2.749+1.013*x_1+0.306*x_2-0.14*x_1^2-2.014*x_2^2-1.651*x_1*x_2+6.126*x_1^3+6.413*x_2^3-1.692*x_1*x_2^2+1.807*x_1^2*x_{2.}$	
straight	longitudinal	Coded	$Y = a+b*x_1+c*x_2+d*x_1^2+e*x_2^2+f*x_1*x_2+g*x_1^3+h*x_2^3+i*x_1*x_2^2+j*x_1^2*x_2$	0.95
		Real	$Y = -3.186+1.007*x_1+0.429*x_2-0.136*x_1^2-3.609*x_2^2-8.109*x_1*x_2+5.699*x_1^3+1.262*x_2^3-3.852*x_1*x_2^2+1.403*x_1^2*x_2$	
	transversal	Coded	$Y = a+b*x_1+c*x_2+d*x_1^2+e*x_2^2+f*x_1*x_2+g*x_1^3+h*x_2^3+i*x_1*x_2^2+j*x_1^2*x_2$	0.96
		Real	$Y = 0.707-0.121*x_1-0.121*x_2-1.052*x_1^2+3.927*x_2^2+4.508*x_1*x_2+9.199*x_1^3+4.941*x_2^3-6.311*x_1*x_2^2-2.448*x_1^2*x_2$	

The effect of the cutting speed, feed speed, cuting direction and cutiing edge on power consumption are shown in Fig. 4. According to the results the machining parameters have the following effect on active cutting power durring milling.

With the increase of the cutting speed, the power consumption is increasing. The lowest values were recoded while processing with v = 4.17m/s (spindle rotation of 9000rot/min), while the highest values were recorded on cutting speed of v = 7.85m/s (spindle rotation of 15000rot/min), on all samples.

The feed speed influence on cutting power, has a similar, but more visible evolution. The lowest values were recorded while processing with u = 5m/min, while the highest values were recorded on feed speed of u = 15m/s, on all samples.

The differences in power consumption regarding the cutting direction were not that high. While processing on the surface of the sample with a cutting depth of 5 mm, the cutting power is a little higher on the logitudinal direction to the direction of wood fibres, than on the transversal one.

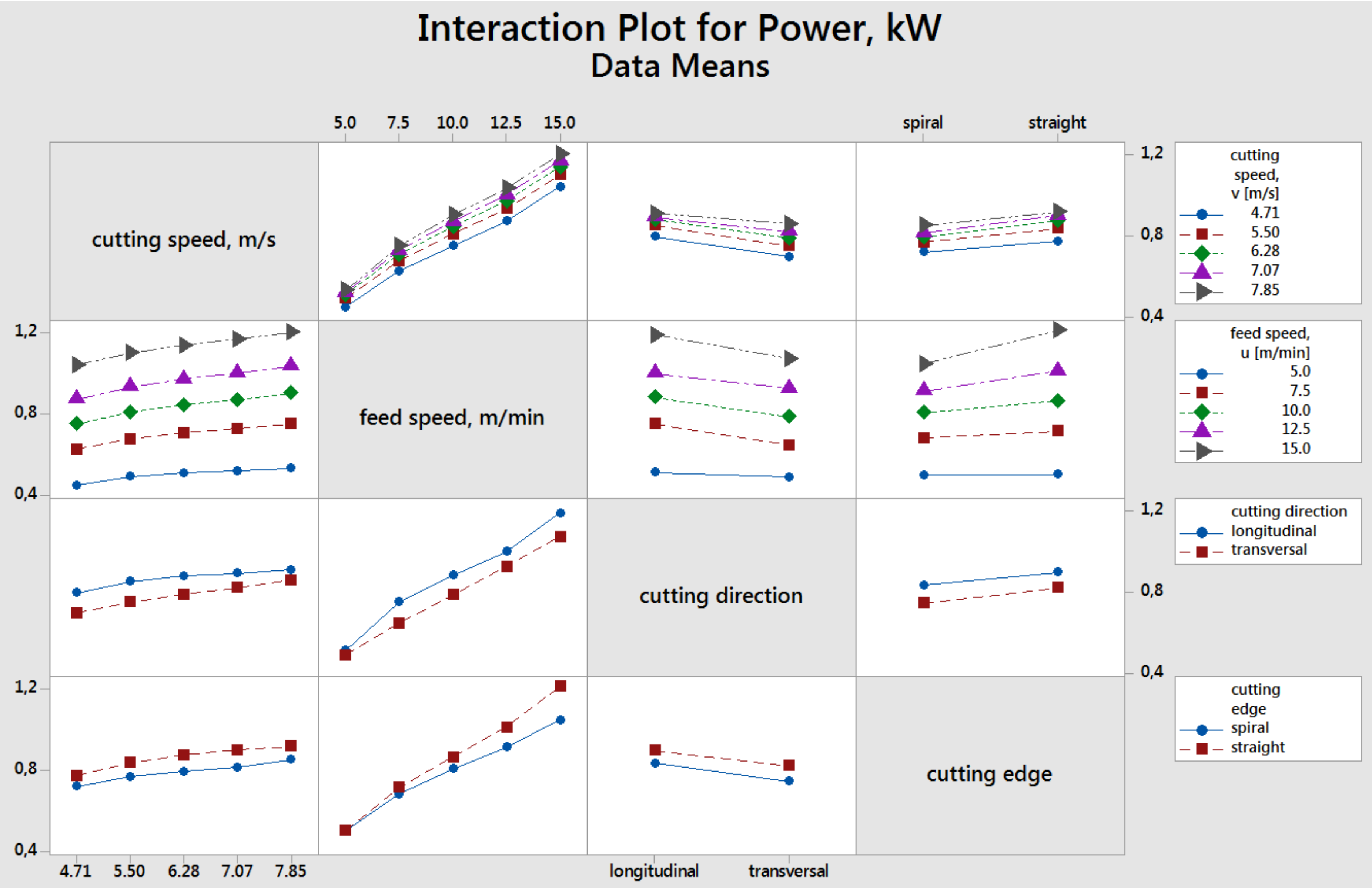

Fig. 4.
Interraction plot for power consumption.

Regarding the cutting edge, the router bit with the straight cutting edge recorded a higher power consumption than the one with the spiral cutting edge. In longitudinal direction the cutting power had values between 0.45kW and 1.19kW for the spiral cutting edge router bit and between 0.45kW and 1.32kW for the straigth cutting edge router bit while, in transversal direction the cutting power had values between 0.44kW and 1.07kW for the spiral cutting edge router bit and between 0.43kW and 1.23kW for the straigth cutting edge router bit.

Overall the highest power consumption (1.32kW) was recorded while processing with a cuttind speed of v = 7.85m/s, a feed speed u = 15m/min in a longitudinal direction to the wood fibres, and with the straight cutting edge router bit.

In order to choose the optimal machining contitions a criteria of minimal power consumption was applied. Minitab software provided the response optimization of cutting speed and feed speed function of cutting direction and cutting edge, and also the prediction for power (Table 3).

Table 3

Prediction for Power, kW

Response	Fit	SE fit	95% CI	95% PI
Power, kW	0.3432	0.0133	0.3167, 0.3697	0.2591, 0.4274

The results show that the optimal machining conditions for a mininmal power consumption durring beech milling on the surface of the wood parts with the CNC machine, for this experiment are: a cutting speed v = 4.71m/s, feed speed u = 5m/min in a transversal direction to the wood fibres, with the spiral cutting edge router bit.

CONCLUSIONS

As conclusions, the main effects of machining conditions (cutting speed and feed speed) cutting directions and cutting edges on power consumption should be taken into consideration. A graphical representation of these variables and their effect on power consumption is shown in Fig. 6.

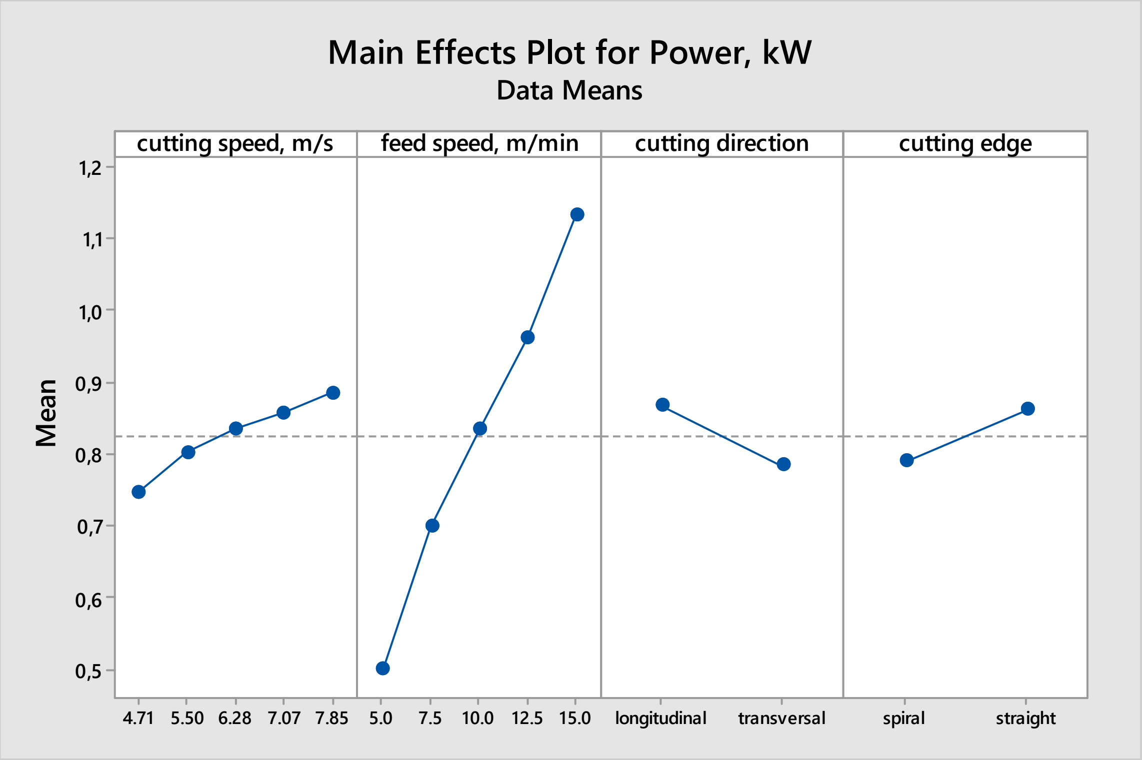

Fig. 6.
Main effects plot for power consumption.

Some conclusions are as follows:

- The cutting power didn't have such a visible effect on power consumption as the feed speed. An increase in the cutting speed from 4.71m/s (9000rot/min) to 7.85m/s (15000rot/min) increased the power consumption with only 10% - 20%. The main reason could be the particularity of CNC milling with a router bit of 10mm in diameter and high spindle rotation on the surface of the sample.
- An increase in the feed speed from 5m/min to 15m/min increased the active power consumption from 0.5kW to 1.15kW (mean values for the entire experiment).
- In the longitudinal direction, the cutting power recorded higher values that the ones from the transversal direction. The reason for this could be the fact that the processing was on the surface of the samples not on the sides (edges) (Fig. 2.d).
- The spiral cutting edge router bit recorded lower values of cutting power than the straight cutting edge router bit.
- The optimal machining conditions were a cutting speed v = 4.71m/s, feed speed u = 5m/min in a transversal direction to the wood fibres, with the spiral cutting edge router bit in order to minimize the power consumption.
- The result from this study cold be usefull to better position the direction of the wooden part that will be processed on surface with a CNC machine and router bits by means of reducing the power consumption.

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