Influence of Cutting Parameters on the Energy Consumption of a Leadwell V40 iT Machining Center

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Abstract: - One of the main objectives worldwide is to improve energy efficiency, and the manufacturing sector is no exception due the high levels of energy consumption necessary to carry out its transformation processes. As a result, the way machinery operates should be reconsidered. The purpose of this article is to present the results of a study on the influence of several cutting parameters on the energy consumption of a Computer Numerical Control (CNC) machine, a Leadwell V40 iT, during 3-axis machining. The parameters under analysis are feed rate, depth of cut, and stepover of the tool. Besides, the machining strategy was programmed in SprutCAM. An experiment was designed to determine the interaction of different cutting parameters and the energy consumed by the machine, which was measured with a Fluke 1735 Power Logger. The obtained data were statistically analyzed employing a factorial model to determine the optimal values of the three variables under study and thus establish the conditions that would produce the minimum energy consumption of the machine. The results show that the most critical factor in energy consumption is feed rate

Key-Words: energy efficiency**,** machine tools, CNC, Machining Center.

1 Introduction

Energy consumption in industrial processes grows higher and higher due to the massive production levels required in different industries to satisfy the needs of the market. One of the main objectives of the European Commission regarding climate change is to improve energy efficiency in 20% by 2020. These days the rational energy use is of the essence; thus, the consumption of each process should be monitored to improve the efficiency of industrial applications [1]. The machining industry is one of the sectors that demands most electricity and, consequently, any potential opportunity to save energy during the process should be considered, analyzed, and tested. Universities and research centers, along with the industry, should address this issue because energy saving in machine tools can be achieved by adequately designing its components or better using the equipment, in terms of the machining strategy as well as the selection of process parameters [2]. The reduction in the use of cooling liquid during machining, the optimal selection of tool trajectories, and even the reuse of the energy of the motor of the spindle have been recently examined. Several studies have compared energy consumption during drilling operations and evaluated tool wear and material removal rate [3].

Sustainable production refers to processes and systems that do not pollute, conserve natural resources and energy, and are economically feasible, safe, and healthy for employees. The level of sustainability of machining processes is yet to be determined but, in general, environmentally friendly and sustainable machining techniques involve lower flow rates of the cooling liquid and shorter cutting distances, which result in higher productivity [4]. Moreover, reducing energy use is essential to sustainable manufacturing. In the past, economic and technological considerations were prioritized without considering the environmental dimension; nevertheless, production rates and the quality of the cut should be improved, and the effects of manufacturing on the environment should be mitigated [5].

The industrial sector is an important energy consumer: it uses 42.6% of the electricity generated worldwide [6]. In Colombia, the energy demand of the manufacturing industry reaches 44.2% [7]. The energy consumption of different machine tools (more specifically CNC machining centers) has not established thus far because it varies depending on brands, shapes, sizes, and uses. Each company in the sector employs such machinery in a different way according to the criteria of the person who programs the equipment. Moreover, there are no specific guidelines available to program CNC machinery that determine optimal parameters of different cutting strategies in order to achieve minimum energy consumption in each job. For that reason, this article analyzes the influence of several cutting parameters on a milling strategy and the energy consumption of a CNC Leadwell V40 iT machining center.

2 Method

Design of Experiments (DOE) was implemented with three replicas and four central points. For this analysis, the full factorial experiment (2^3) included two measurement levels and three factors (Table 1).

Table 1. Full summary of the experimental design.

Full factorial design		Experiment matrix		
Design summary		X1	X2	X3
Factors: 3	Base design: 3.8	-	-	-
		+	-	-
		-	+	-
Runs: 28	Replicas: 3	+	+	-
		-	-	+
		+	-	+
Workpieces: 1	Total central points: 4	-	+	+
		+	+	+

Two aluminum workpieces (400 mm long, 100 mm wide, and 9.5 mm thick) were used to obtain the data (Fig. 1).

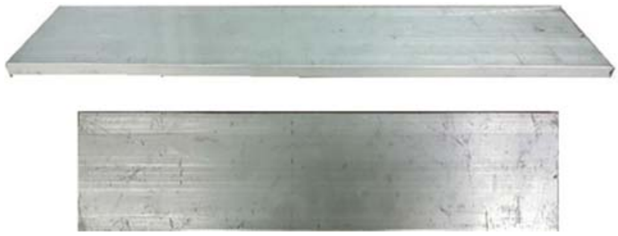

Fig. 1. Aluminum workpiece. Source: Authors' own work.

The total energy consumed during each experiment was measured using a Fluke 1735 Power Logger, a specialized tool for this type of evaluations, which was previously connected to the main power connection of the machine (Fig. 2).

Network	Test Leads
L1	A (L1)
Not connected	B (L2)
Not connected	C (L3)
Not connected	N

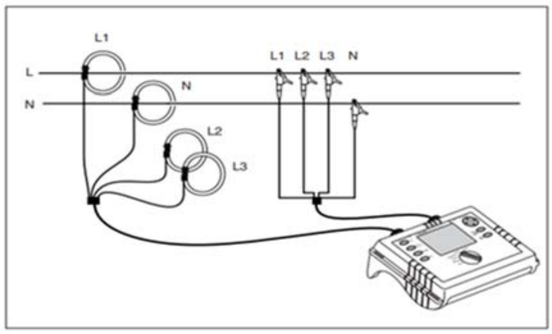

Fig. 2. Fluke 1735 – connection. Source: [8].

The CNC machine and the aluminum workpiece assembly were modeled using the programs ZW3D and SprutCAM, which are available under academic licensing at the Simulation, Modeling, and Prototyping Laboratory of INSTITUTO TECNOLÓGICO METROPOLITANO (ITM). Further, eight milling strategies were programmed in SprutCAM with variations in the three parameters under study: feed rate, depth of cut, and stepover (Fig. 3).

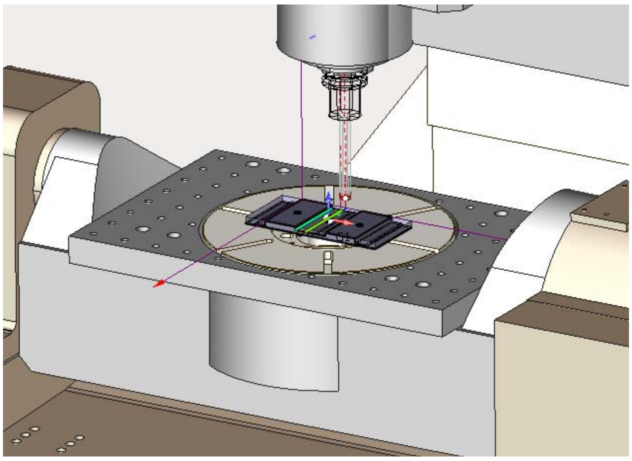

Fig. 3. Piece designed in ZW3D and programmed in SprutCAM 11.5. Source: Authors' own work.

Low (-) and high (+) levels were defined for each parameter: speed, 595 mm/min and 850 mm/min; depth of cut in the Z axis, 4.75 mm and 9.5 mm; and stepover, 50% (8 mm) and 75% (12 mm) of the diameter of the tool, respectively. It should be noted that the spindle speed was programed at 2800 RPM and the diameter of the selected tool, 16 mm; these two parameters were kept constant throughout the experiment. Since DOE considers central points, four additional cutting routes were programmed with the required parameters, as follows: feed rate, 722.5 mm/min; stepover, 62.5% (10mm) of the diameter of the tool; and depth of cut in the Z axis, 7.125 mm (Table 2).

The experiment was conducted at the laboratory mentioned above, where the Leadwell V40 iT machining center is installed (Fig. 4). Said center was used to set up the experiment and carry out 28 machining (milling) operations required by the DOE, along with their replicas, to obtain its energy consumption. The measured variable was consumed energy at the end of each cut, and the obtained results were entered in a statistical program to be subsequently analyzed (Table 3).

Table 2. Factors - Experimental ranges. Source: Authors' own work.

Factors		Experimental range	
		Level (-)	**Level (+)**
F_1	Feed rate mm/min	595	850
F_2	Depth of cut in the Z axis (mm)	4.75	9.5
F_3	Stepover (mm)	50% (8 mm)	75% (12 mm)
Central points: 4			
F_1	Feed rate mm/min	722.5	
F_2	Depth of cut in the Z axis (mm)	7.125	
F_3	Stepover (mm)	62.5%	

Fig. 4. 5-axis CNC Leadwell V40 iT. Source: Authors' own work.

The experiment was designed to measure the amount of energy consumed during each completed cutting route. Thus, a multivariate analysis can be carried out to establish the relationships and interactions of the parameters under study. This process also enables to determine the cutting values that result in the lowest possible electricity consumption. Statistical software was used to analyze the obtained data and conduct the proposed DOE analysis. This tool allows to obtain information and define the optimal parameters under study and their differences, which were confirmed by means of a variance ratio test with a 5% significance level. The hypothesis was that some factor or level had a statistically significant effect on the energy consumption of the CNC machine.

Table 3. Full dataset for DOE analysis. Source: Authors' own work.

Run	Speed [mm/ min]	Depth of cut in the Z axis [mm]	Stepover [mm]	Consumed energy [Wh]
1	722.5	7.125	10	46.4285
2	850	4.75	12	45.621
3	595	9.5	12	52.761
4	722.5	7.125	10	46.523
5	850	4.75	12	49.4315
6	595	9.5	12	54.3235
7	850	9.5	8	49.408
8	850	9.5	12	45.616
9	595	9.5	12	52.6195
10	595	4.75	12	52.251
11	595	9.5	8	56.9015
12	850	9.5	12	52.447
13	850	4.75	8	48.9195
14	722.5	7.125	10	47.3215
15	595	9.5	8	55.201
16	595	4.75	8	54.2155
17	850	9.5	8	51.62315
18	850	4.75	8	53.3095
19	595	4.75	8	50.797
20	595	4.75	12	51.8925
21	722.5	7.125	10	43.789
22	850	4.75	12	49.922
23	595	4.75	12	52.6395
24	595	4.75	8	45.6025
25	850	9.5	8	46.0465
26	850	4.75	8	48.0135
27	850	9.5	12	51.4
28	595	9.5	8	47.9695

The analysis enabled to confirm the effects of feed rate (595 mm/min and 850 mm/min), depth of cut in the Z axis (4.75 mm and 9.5 mm), and stepover (50% - 8 mm and 75% - 12 mm) on energy consumption as a result of the interaction of all the factors above. Besides, the experiment compared the relationship that results from combining the variables, revealed the results of the interaction of the factors, and thus guaranteed that the results were statistically significant.

Consequently, the DOE presented the average effects and levels of each factor for all the points under analysis and also enabled to estimate an average value for this study. Intra- and inter-experiment variances were thus obtained and automatically compared.

3 Results

Tables 4 and 5 present the results. Table 4 summarizes the model, which obtained a 27.49% adjusted R-squared; in other words, the model explained 27% of the variance. Although the R-squared was close to the lower limit, low P-values indicate an actual relationship between significant predictors and the response variable. Table 5 presents the variance analysis, and the only P-value below 0.05 is feed rate (0.02), which is therefore the most significant and critical value. Likewise, it can be observed that the model exhibits a curvature caused by the central points and the fact that the P-value of the curvature is well below 5%.

Table 4. Model output summary. Source: Authors' own work.

S	R-squared	R-squared (adjusted)	R-squared (predicted)
2.91762	48.97%	27.49%	0.00%

Feed rate is the most significant variable in Fig. 5 because it shows a greater slope than its counterparts. Central points are far, which confirms that the P-value of the curvature is zero.

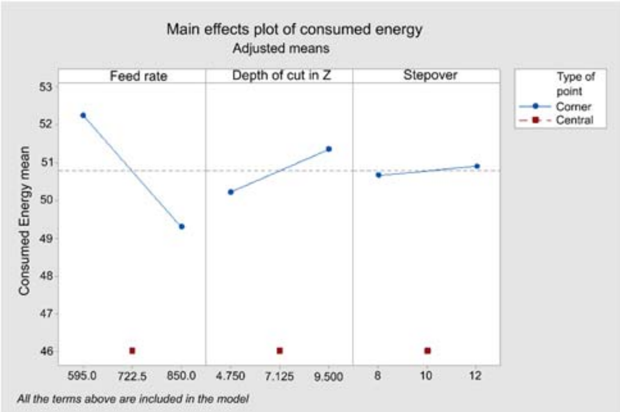

Fig. 5. Main effects plot. Source: Authors' own work.

Table 5. Coded coefficients – Analysis of variance - ANOVA. Source: Authors' own work.

Source	**GL**	**Adjusted Sum of Squares**	**Adjusted Mean Squares**	**F-value**	**P-value**
Model	8	155.233	19.4041	2.28	0.067
Linear	3	60.440	20.1467	2.37	0.103
Feed rate	1	52.263	52.2632	6.14	**0.023**
Depth of cut in the Z axis	1	7.822	7.8223	0.92	0.350
Stepover	1	0.355	0.3546	0.04	0.840
Two-term interactions	3	8.285	2.7616	0.32	0.808
Feed rate*Depth of cut in Z	1	5.092	5.0916	0.60	0.449
Feed rate*Stepover	1	3.141	3.1412	0.37	0.551
Depth of cut in Z*Stepover	1	0.052	0.0520	0.01	0.939
Three-term interactions	1	8.389	8.3891	0.99	0.333
Feed rate*Depth of cut in Z*Stepover	1	8.389	8.3891	0.99	0.333
Curvature	1	78.119	78.1185	9.18	**0.007**
Error	19	161.738	8.5125		
Total	27	316.971			

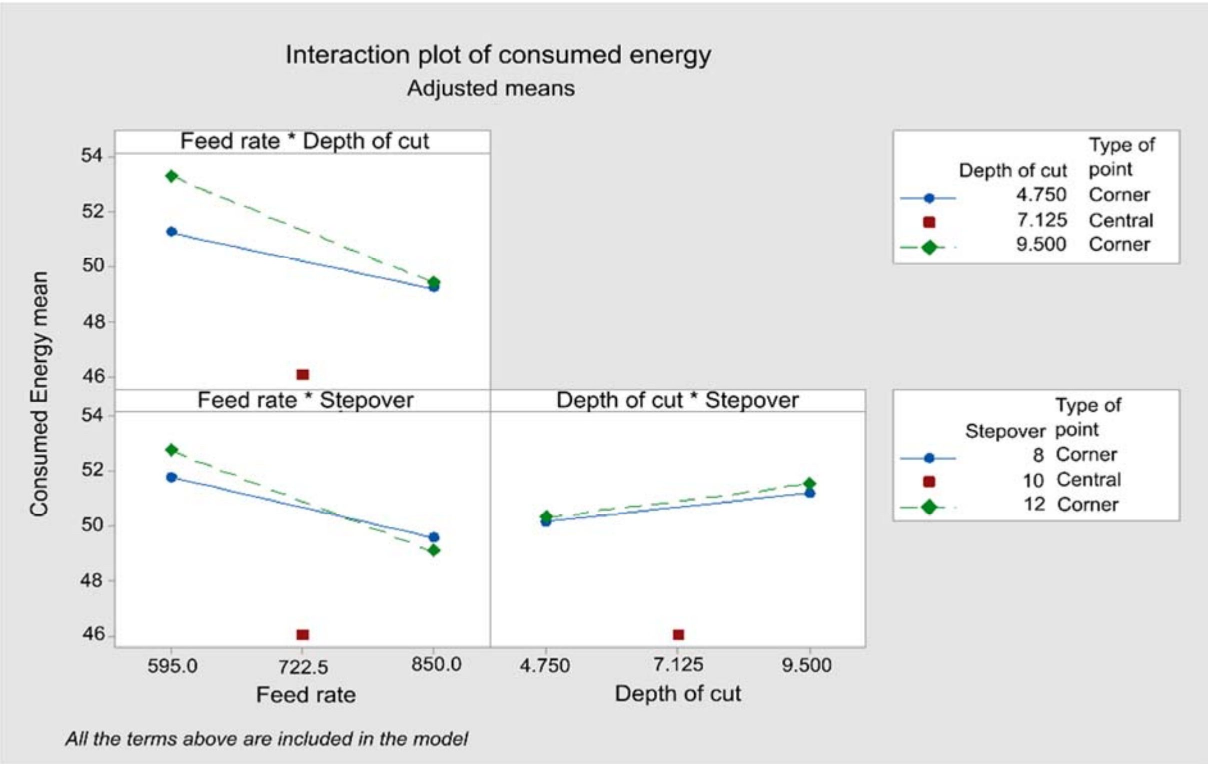

Fig. 6. Interaction plot of consumed energy. Source: Authors' own work.

Fig. 6 details the interaction between parameters as a function of consumed energy. Remarkably, the variable that exerts the most powerful effect on the design is feed rate.

In turn, Fig. 7 presents the Pareto chart of standardized effects, which confirms that the most critical variable is feed rate; the other factors and their interactions were not significant.

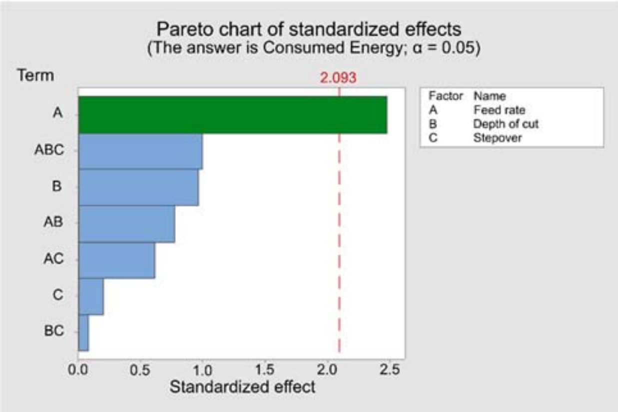

Fig. 7. Pareto chart of standardized effects. Source: Authors' own work.

Eq. (1) allows to predict the energy consumption of the designed model by entering the values of feed rate, depth of cut in Z, and stepover.

$$E = -10.8 + 0.0830F + 8.29D + 6.04S - 0.0113FD - 0.00837FS - 0.696DS - 0.000976FDS - 4.77CP \quad (1)$$

Where
E: Consumed energy [Wh]
F: Feed rate [mm/min]
D: Depth of cut in the Z axis [mm]
S: Stepover [mm]
CP: Central point

A statistical analysis was conducted to optimize the model and thus obtain the optimal values that minimize the amount of energy consumed by the process under study: feed rate, 722.5 mm/min; depth of cut, 7.125 mm; and stepover, 10 mm (Fig. 8). These settings enable to predict a minimum energy consumption of 46.0155 Wh with an 83.02% probability.

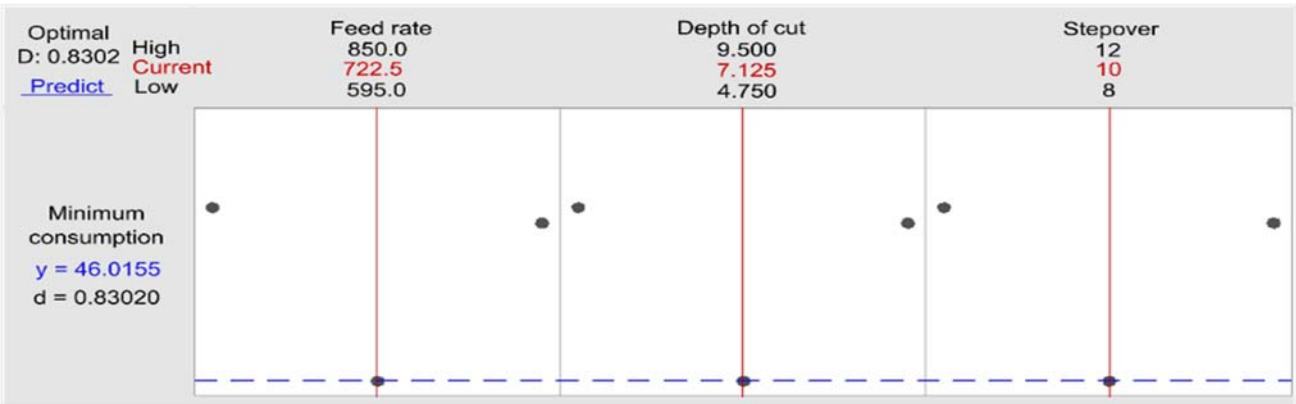

Fig. 8. Model optimization. Source: Authors' own work.

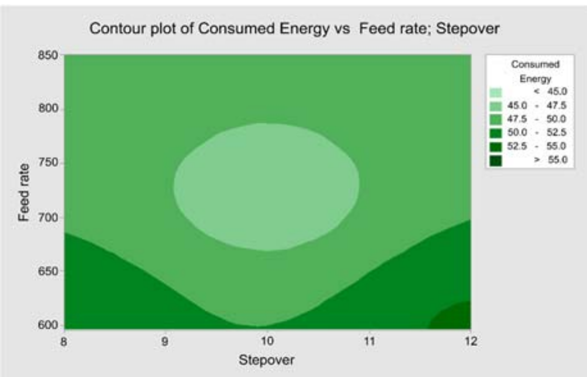

Fig. 9. Contour plot of consumed energy vs speed – Stepover. Source: Authors' own work.

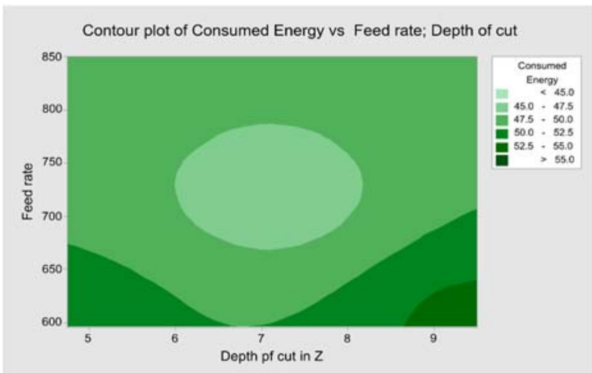

Fig. 10. Contour plot of consumed energy vs speed – Depth of cut. Source: Authors' own work.

4 Conclusion

This study confirms that R-squared is not highly probable because it is not significantly close to the upper limit. This indicates that a subsequent study should consider additional factors, thus increasing the DOE in (2^6) or (2^9) perhaps, because other variables involved in the cutting process may increase power consumption of the machining center. Nevertheless, although the R-squared was close to the lower limit, we can conclude, thanks to the Pareto chart and the P-value (below 5%), that the most significant factor in this case is feed rate.

The optimization of the model revealed the values that minimize the power consumption of a CNC machining center: feed rate, 722.5 mm/min; depth of cut 7.125 mm; and stepover, 10 mm. These parameters should result in an approximate consumption of 46.0155 Wh with an 83% confidence level. This can also be observed from the contour plots, where the minimum consumption equals approximately 45 Wh, the light green area at the center.

The curvature of the model was confirmed by the central points, because its P-value was 0.007, below 5%. Future studies should consider a second-order model because it will probably present a better behavior than the linear model obtained in this work. Furthermore, rapid ascent trajectory optimization should be conducted.

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