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ORIGINAL ARTICLE

Optimization of cutting parameters to minimize energy consumption during turning of AISI 1018 steel at constant material removal rate using robust design

Carmita Camposeco-Negrete[1] · **Juan de Dios Calderón Nájera**[1] · **José Carlos Miranda-Valenzuela**[1]

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Abstract Machine tools have an impact on the environment due to their energy consumption. New strategies with focus on the reduction of the energy consumed by manufacturing processes have received significant attention owing to the rise of the electricity costs. This paper presents an experimental study related to the optimization of cutting parameters in turning of AISI 1018 steel. The aim of the study was to minimize the quantity of electrical energy required by the machine tool in order to perform the cutting operation. The material removal rate was set to a constant value in all the experimental trials so as to analyze the effect that the cutting parameters have on the energy consumed. Robust Design was used to determine the effects of the depth of cut, feed rate, and cutting speed on the energy required by the machine tool, considering two sources of noise in the experimental trials. The results of this work show that the techniques covered by the concept of Robust Design can be used to minimize the energy consumed and variation of the machining process.

Keywords Energy consumption reduction · Robust Design · Turning · Sustainable manufacturing

1 Introduction

The manufacturing of goods has an essential role in the global economy as it provides jobs and economic strength. The manufacturing sector consumes both renewable and non-renewable materials, as well as significant amounts of energy.

Nowadays, manufacturing is addressing several challenges. One of them is regarding the reduction of the environmental impacts related to the production of goods. According to Balogun and Mativenga [1], the carbon footprint of a product has a relationship with the energy employed to manufacture that product.

Environmental studies indicate that most of the environmental impacts related to machine tools are due to their energy consumption [2]. Traditional estimates of the power required for turning processes are based on the process parameters, which are optimized in order to minimize the power needed for material removal.

Bhattacharya et al. [3] reported the effects that cutting parameters have on surface roughness and power consumption in high speed machining of AISI 1045 steel. In order to analyze these effects, the authors used an orthogonal array and the analysis of variance (ANOVA).

Fratila and Caizar [4] minimized the cutting power and the surface roughness during milling of $AlMg_3$. Taguchi optimization methodology was applied to evaluate the outcome of the parameters related to the operation.

According to the work reported by Mativenga and Rajemi [5], when a large value of depth of cut and feed rate was selected, the specific energy was reduced during the turning of EN8 (AISI 1040) steel billets. They employed an objective function to determine the minimum footprint and maximum tool life.

In the work presented by Asiltürk and Neseli [6], an orthogonal array was applied in order to study the influence of

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✉ Carmita Camposeco-Negrete
carmitacamposeco@gmail.com

Juan de Dios Calderón Nájera
jcalderon@itesm.mx

José Carlos Miranda-Valenzuela
jmiranda@itesm.mx

[1] Automotive Engineering Research Center (CIMA), Tecnológico de Monterrey Campus Toluca, Eduardo Monroy Cárdenas 2000, 50110 Toluca, Estado de México, México

cutting parameters on the surface roughness in turning of AISI 304 austenitic stainless steel under dry conditions.

Guo et al. [7] developed two models for turning of steel and aluminum and derived for a given machine tool: one for energy consumption and the other for surface roughness. The aim was to optimize cutting parameters to accomplish a precise surface finish with minimum energy consumption. Once the values of the surface roughness, depth of cut, and feed rate are selected, cutting speed is determined.

Hanafi et al. [8] optimized the cutting parameters involved in the machining of PEEK-CF30, so as to reduce the power consumption and the surface roughness, through the use of Taguchi techniques and grey relational theory.

Newman et al. [9] investigated if interchangeable machining processes during milling of a block of aluminum alloy 6042 necessarily consume the same amount of power. Four identical slots were machined out with the same tool and spindle speed. The final depth of the slots was the same, and the depth of cut and feed was varied to maintain the same cutting time and material removal rate for the four slots. The results showed that the power consumption may differ considerably, so power consumption of cutting processes can be used as a criterion in process planning. However, the spindle speed remained constant, so the influence exerted by this cutting parameter in the power consumption cannot be studied.

Helu et al. [10] reported the influence of green machining strategies on the surface roughness of turned titanium. The authors concluded that these strategies should be used during roughing turning instead of using them on finishing turning because the finish cuts define the final surface quality.

The aim of the work published by Bhushan [11] was to investigate the influence of cutting parameters during turning of 7075 Al alloy SiC composite using the Response Surface Method and desirability analysis. The objectives were to reduce the power consumed by the machine and to increase the tool life.

The aim of the work published by Yan and Li [12] was to reduce the cutting energy and maximize the M.R.R. in milling of 1050 steel using the Response Surface Method. Campatelli et al. [13] optimized the cutting parameters involved in milling of AISI 1050 steel so as to diminish the energy consumed in the cutting process.

The works mentioned above showed that cutting parameters have been optimized so as to minimize the power consumed by the machine tool and the surface quality of the workpiece or maximize the tool life of the cutting tool in machining of steel and aluminum.

Most of the investigations focused on finish turning and employed Taguchi techniques, such as orthogonal arrays and S/N ratio analysis, Response Surface Methodology (RSM), desirability analysis, and analysis of variance (ANOVA), among others, to optimize cutting speed, feed rate, and depth of cut. None of the studies maintained the material removal rate constant and varied the values of cutting parameters to find out which level of each parameter reduced the power consumption of the machine during turning.

Early in the development of quality engineering, the aim was to reduce the variability of a product caused by environmental conditions, deterioration, and variation of the pieces. Furthermore, the objective was to adjust the mean to a specific target value. As a consequence, the concept of Robust Design was introduced. Robust Design means designing a product that can function properly under various conditions of use [14].

Therefore, this paper presents a work done employing the Robust Design methodology for optimizing a turning process with constant material removal rate. The objective was to optimize cutting parameters in order to get the lowest value of energy consumed by the machine, considering two sources of noise: the presence or absence of cutting fluid and the machine tool used to perform the machining operation.

2 Robust design

The Taguchi method was developed by Genichi Taguchi in Japan to improve the implementation of off-line total quality control. The method is related to finding the best values of the controllable factors to make the problem less sensitive to the variations in uncontrollable factors. This kind of problem was called by Taguchi robust parameter design problem.

A product or a process is robust if its performance is not affected by noise factors. Consequently, Robust Design is a procedure used to design products and processes such that their performance is insensitive to noise factors. Using this procedure, product parameters or process factor levels are determined to optimize the functional characteristics of products and to have minimal sensitivity to noise.

In Robust Design, there are two steps in the optimization process: the first is to maximize the S/N ratio to decrease variability and the second is to adjust the mean to the target value.

Quality engineering says that a function should be adjusted to a target value only after reducing variability. Quality engineering is Robust Design based on the following three procedures: orthogonal array, S/N ratio, and loss function.

In Taguchi's methodology, the main role of an orthogonal array is to permit engineers to evaluate a product design with respect to robustness. In design of experiments, orthogonal means balanced. A major feature of the utilization of orthogonal arrays is the flexibility and capability for assigning a number of variables to them. Moreover, an important feature is the reproducibility or repeatability of the conclusions drawn from small scale experiments, in research and development work for process design [14].

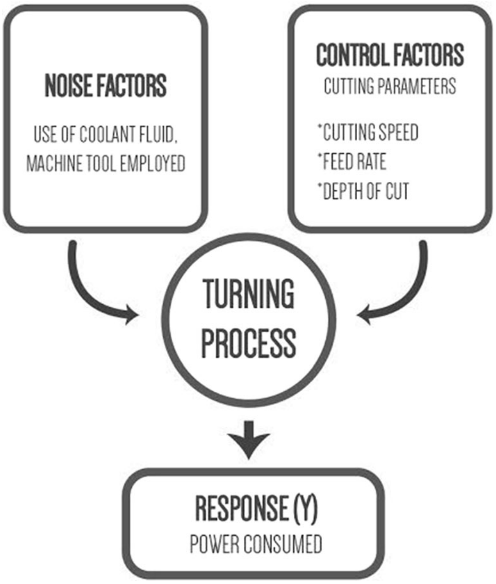


Fig. 1 P diagram of the turning process

Taguchi method distinguishes between control variables and noise variables. Two different designs are chosen for the two sets of parameters. The inner array is the design chosen for the controllable variables, and the outer array is the one chosen for the noise variables. The combination of the inner and the outer arrays gives the crossed array which is the list of all the samples scheduled.

For each sample in the inner array, the full set of experiments of the outer array is performed. An important point about the crossed array design is that it provides information about the interaction between the controllable variables and the noise variables. These interactions are crucial for a robust solution [15].

Taguchi introduced performance measures to be optimized, called signal-to-noise ratios (S/N). The S/N ratio is used to examine the effect of control factors. Depending on the nature of the investigated problem, an appropriate ratio must be chosen. The most well-known signal-to-noise ratios are:

Smaller-the-better: to be used when the response variable is to be minimized.

Larger-the-better: to be used when the response variable is to be maximized.

Nominal-the-best: to be used when a target is sought for the response variable.

Table 2 Values and levels of cutting parameters

Exp. no	Factor values			Factor levels		
	A (m/min)	B (mm/rev)	C (mm)	A	B	C
1	350	0.10	2.29	1	1	3
2	350	0.15	1.52	1	2	2
3	350	0.20	1.14	1	3	1
4	375	0.10	2.13	2	1	3
5	375	0.15	1.42	2	2	2
6	375	0.20	1.07	2	3	1
7	400	0.10	2.00	3	1	3
8	400	0.15	1.33	3	2	2
9	400	0.20	1.00	3	3	1

For each of these types, the optimal level of a process parameter is the level, which results in the highest value of S/N ratio transformation. In this work, the S/N ratio used was "smaller the better" due to the fact that the objective was to reduce or minimize the total power consumed by the machine tool during the cutting process. This S/N ratio was calculated as:

$$S/N = 10\log\left[\left(\frac{1}{n}\right)*\left(\sum y^2\right)\right] \tag{1}$$

where y is the observed data and n is the number of observation.

3 Experimental procedure

3.1 Classification of parameters

In the experimental trials, there are control factors related to the process parameters, noise factors, which are responsible for the variation of the system, and a response variable. These factors, referring to the case of the turning process, are represented using a P diagram (Fig. 1).

3.2 Process parameters

The parameters related to the turning process are shown in Table 1. These parameters were selected in order to obtain

Table 1 Process parameters for machining of AISI 1018 steel

Material to be machined	AISI 1018 steel billets
Material dimensions	Diameter of 38.1 mm (1.5 in), large of 150 mm
Cutting length	50 mm
CNC machine tool	HAAS SL10 and GILDEMEISTER CTX 410
Cutting tool	DCMT 11 T3 04 PM (Insert manufactured by Sandvik)
Cutting conditions	Absence or presence of cutting fluid

Table 3 Cutting tool specifications

Tool manufacturer	Sandvik Coromant
Tool ID	CoroTurn 107 DCMT 11 T3 04-PM
Cutting speed (Factor A)	230–470 m/min
Feed rate (Factor B)	0.08–0.23 mm/rev
Depth of cut (Factor C)	0.25–3 mm
Indexable insert form	D
Tool clearance	7°
Corner radius	0.4 mm

data about the power consumption during different cutting conditions in machining of AISI 1018 steel. The cutting length was chosen so the machining process could provide enough data to be analyzed.

3.3 Experimental design

In this work, the inner array design selected is an L9 design, composed of nine experiments, with three factors: cutting speed (factor A), feed rate (factor B), and depth of cut (factor C). In order to maintain a constant material removal rate (MRR), the values of the cutting parameters shown in Table 2 were calculated in order to obtain a MRR of 1333.33 mm^3/s. These values are within the operating window recommended by the tool supplier (Table 3), and they were associated with a level, where "1" is the lowest level and "3" is the highest.

The outer array design is an L4 design, which has two factors (called factor K and factor L) of two levels each one. Level 1 of factor K is the presence of cooling fluid and level 2 is the absence of that fluid. Level 1 of factor L is the machining operation performed in the HAAS SL10 lathe, and level 2 is the same operation performed in the GILDEMEISTER CTX410 lathe.

The experimental design is shown in Table 4, for three experimental trials.

3.4 Power measurement system

Current required from the grid during the turning process was measured through current transformers, and voltage was measured using a circuit that reduces 1000 times the voltage from the grid. The values of voltage and current were computed through a LabVIEW interface using a NI data acquisition card (NI USB-6211), in order to calculate the effective power needed for machining the material selected. Power measurements were recorded each 0.1 s from the main switch of each one of the lathes employed, and the energy consumed was computed by multiplying the average power consumed times the cycle time. According to Kara et al. [16], electricity metering at the machine tool should have a resolution between 10 ms and 1 min. Therefore, 0.1 s is inside that range. Then, an average of the power consumed during all the process was obtained (Fig. 2).

4 Results

Table 5 shows data for energy consumption (average of each experiment and cycle time).

4.1 Main effects plot

The main effects analysis is used to study the trend of the effects of each of the factors. Main effects plot for the three factors considered in the inner array (depth of cut, feed rate, and cutting speed) versus energy consumption is shown in Fig. 3.

Table 4 Experimental design

Outer array		L	1	1	2	2	1	1	2	2	1	1	2	2
		K	1	2	1	2	1	2	1	2	1	2	1	2
Inner array			Power consumed (Trial 1)				Power consumed (Trial 2)				Power consumed (Trial 3)			
A	B	C												
1	1	3												
1	2	2												
1	3	1												
2	1	3												
2	2	2												
2	3	1												
3	1	3												
3	2	2												
3	3	1												

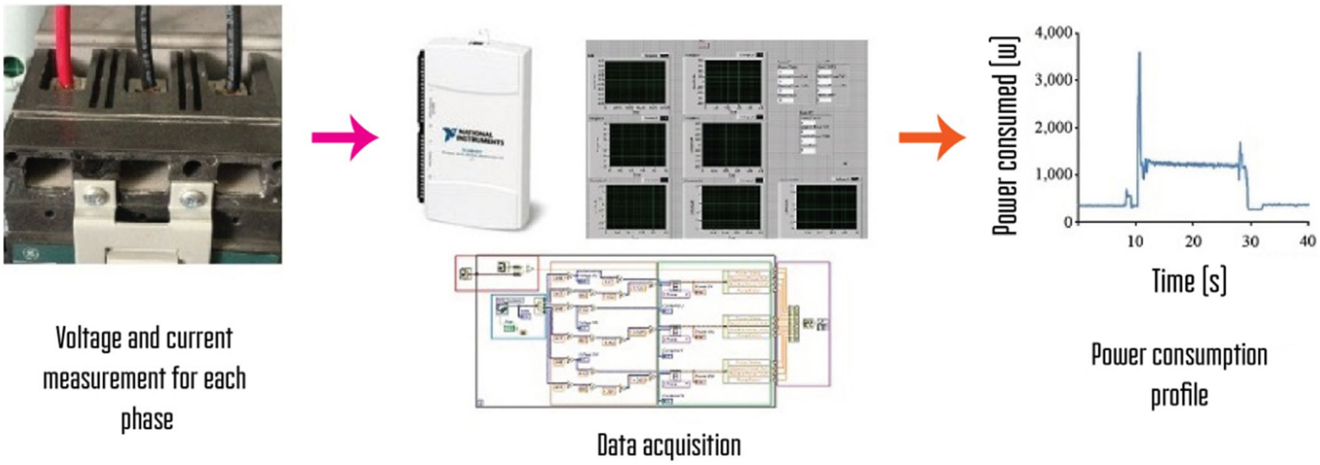


Fig. 2 Power measurement system

4.2 S/N ratio plot

The S/N ratio measures performance characteristics of the process and helps to reduce its variance and prevent its deviation from the target value. S/N ratio plot for the three factors is shown in Fig. 4.

5 Data analysis and discussion

For the nine experiments presented in Table 2, although the MRR is the same for all of them, the energy consumption varies according to the cutting parameters' selection.

As stated in the results showed in Table 2, the experimental trials that employed cooling fluid during the machining process demanded a greater amount of electrical energy when compared to the ones that did not use the cutting fluid.

Cooling fluid is applied on the cutting zone using an electric pump, and the pump consumes energy during its use phase. Therefore, if the coolant pump is employed, the amount of electrical energy required to execute the cutting operation is greater than the quantity of this resource needed when the machining operation does not require cutting fluid.

In relation to main effects plot (Fig. 3), the energy consumption per machining process decreases with levels A1 (cutting speed), B3 (feed rate), and C1 (depth of cut). The slope of the graphs in the Fig. 2 shows that feed rate and depth of cut are the parameters that influence the response variable the most.

The analysis conducted using the Robust Design method considered the results obtained in the experimental trials that employed coolant fluid and the ones gathered with the absence of this fluid, in order to get a valid result for both cases. When analyzing the levels of the control factors that minimize the energy consumed during the cutting operation, it is determined that these levels diminished the energy consumption in the case with the presence of coolant and in the one of no coolant use.

Referring to S/N ratio plot (Fig. 4), the levels of each of the three factors that should be used in order to reduce process variance are the same as the ones indicated by the mean effects plot. These levels decrease the response value and ensure the process will stay in its target value.

The minimum value of the energy consumed in the process can be achieved if cutting speed is at its lowest value. According to Aggarwal et al. [17], Hanafi et al. [8], and Brushan [11], cutting speed must be at its smallest value in order to minimize the energy consumed by the machine tool.

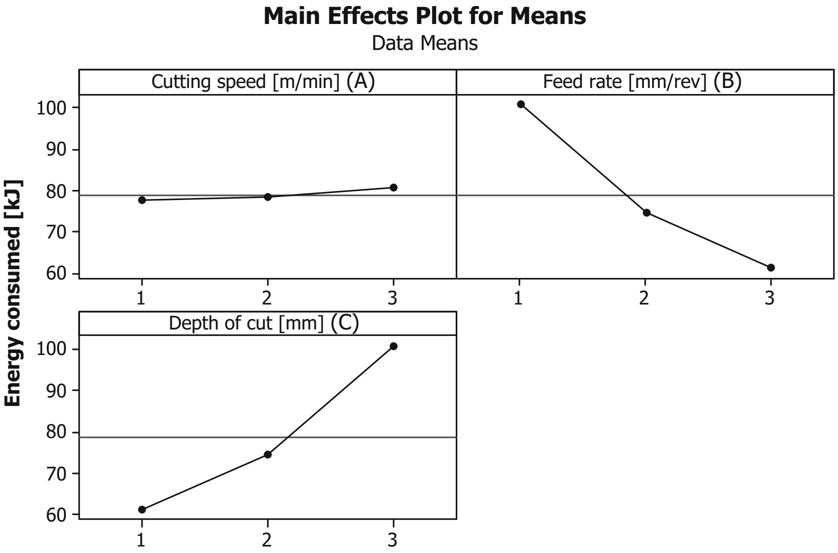
A higher value of cutting speed, due to the movement of the spindle, requires more energy to move it from rest to the indicated value of RPMs. According to Klocke [18], if cutting speed increases, cutting force is reduced so lower values of cutting speed increase cutting force, and as a consequence, energy consumption is increased.

Sandvik Corokey [19] points out that cutting speed is the parameter that reduces tool life the most. Furthermore, this

Table 5 Average power consumption in turning process

Outer array		L	1	1	2	2	1	1	2	2
		K	1	2	1	2	1	2	1	2
Inner array			Energy consumed (kJ)				Cycle time (s)			
A	B	C								
1	1	3	71.47	74.2	121.04	133.14	9.6			
1	2	2	51.64	54.28	88.85	97.22	6.5			
1	3	1	42.93	43.63	73.07	80.75	4.9			
2	1	3	68.97	71.10	123.99	135.69	9.0			
2	2	2	51.67	52.49	91.19	100.17	6.1			
2	3	1	42.00	43.04	76.29	82.66	4.6			
3	1	3	67.94	69.47	130.63	141.77	8.5			
3	2	2	50.41	52.17	97.35	105.91	5.7			
3	3	1	41.08	42.05	81.44	86.75	4.3			

Fig. 3 Main effects plot for energy consumption per machining cycle



parameter at higher values increases energy consumption. Cutting speed must be kept at its minimum value (350 m/min), to optimize energy consumption and to avoid excessive tool wear.

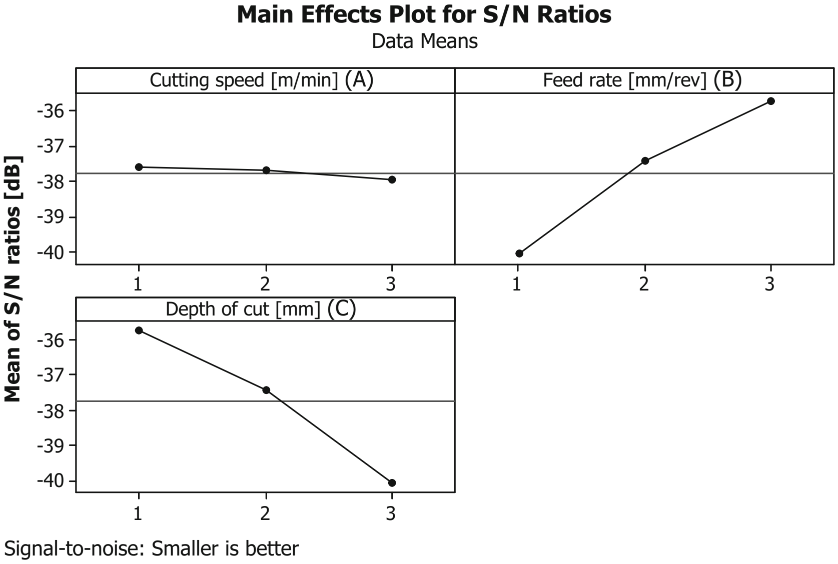
The value of feed rate that minimizes power consumption is the one indicated by its third level. If the value of this cutting parameter is the highest, axis motors need to move faster and the cycle time is reduced. Therefore, the energy consumption decreases. Minimum depth of cut is necessary for optimizing energy consumption during machining. An increment of this factor implies a rise of the value of the force needed to remove the material, so the system is forced to spend energy. As depth of cut increases, heat generated at the tool work piece interface also increases [18].

According to Dahmus and Gutowski [20], the energy consumed by the machine outside of chip formation is significant because less than 15 % of the total energy consumed by an automatic machine tool is related to the material removal. Therefore, it is important to go beyond the tool-chip interface in order to understand the energy consumption of the machine. For the nine experiments presented in Table 2, although the MRR is the same for all of them, the energy consumption varies according to the cutting parameters' selection.

This is due to the fact that each experiment has a different cycle time. If the cycle time of the experiment is greater, the energy consumption increases, compared to an experiment with less cycle time. In general, the lower the cycle time, the lower the total energy consumed by the machine tool.

The levels of the cutting parameters that minimize energy consumption optimize the response variable despite the noise factors included in the experimental trials. Also, the same results ensure that the process will stay at its target value.

Fig. 4 S/N ratio plot for energy consumption per machining cycle



6 Conclusions

In this study, Robust Design was used to identify the main effects of three factors (cutting parameters) on the energy consumed during turning of AISI 1018 steel with constant material removal rate. As shown in Table 5, experiments with the same MRR do not have equal values of energy consumed, because the energy consumption is related to the values of the cutting parameters chosen.

Therefore, different combinations of values of cutting parameters can have identical amounts of material removed but the energy consumption of each one of these combinations will not be the same.

This study thus concluded that the third level of feed rate (0.2 mm/rev), first level of depth of cut (1.14 mm), and first level of cutting velocity (350 m/min) lead to minimum energy consumption and less variation of the process from the target.

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