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4.5 Optimization of cutting parameters using robust design for minimizing energy consumption in turning of AISI 1018 steel with constant material removal rate

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Abstract

The strategies to reduce energy consumption are obtaining emphasis due to the constant increase in electricity prices, and concern of manufacturing companies and clients about the environmental impact that results from activities related to the production of goods. CNC machine tools, including those that perform turning operations, contribute significantly to the energy consumption in the manufacturing sector.

The present work outlines an experimental study to optimize cutting parameters during turning of AISI 1018 steel under roughing conditions and constant material removal rate, in order to get the minimum energy consumption of the machine tool. Robust design is employed to analyze the effects of depth of cut, feed rate and cutting speed on the response variable.

Keywords:
Energy Consumption Reduction, Robust Design, Turning.

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.
Therefore, the objective is to minimize energy consumption in all areas.

The energy consumed in the manufacturing sector is used in production processes which mainly emerge from production equipments. Machine tool is one of the typical production equipments widely used in the industry [1]. In machining processes, saving money and improving sustainability performance can be achieved by reducing energy consumption because energy is an essential resource for production [2].

Improving energy efficiency of manufacturing processes requires knowledge about the energy consumption as a function of the machine tool and cutting process itself. Energy consumption of the machine tool was found to be dependent on the average power demand and the processing time dictated by the cutting parameters [3].

Several works have been previously done so as to optimize machining process taking into account cutting parameters and employing the Taguchi method as a tool for optimization. The aim of the work reported by Bhattacharya et al. [4] was to investigate the effects of cutting parameters on surface roughness and power consumption by employing Taguchi techniques during high speed machining of AISI 1045 steel.

Fratila and Caizar [5] employed the Taguchi techniques to optimize the cutting parameters in order to achieve the best surface roughness and the minimum cutting power in face milling when machining $AlMg_3$. Asiltürk and Neseli [6] minimized the surface roughness in turning of AISI 304 austenitic stainless steel using the Response Surface Methodology (RSM). Hanafi et al. [7] optimized cutting parameters in machining of PEEK-CF30 using TiN tools under dry conditions, to achieve minimum power consumption and the best surface quality. Taguchi optimization and grey relational theory were used in the optimization process.

The work of Newman et al. [8], aimed to investigate 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 depth of cut and feed were varied to maintain the same cutting time and Material Removal Rate (M.R.R.) for the slots. This study concluded that the power consumption may differ considerably. However, the spindle speed remained constant, so the influence exerted by this cutting parameter in the power consumption cannot be studied.

Diaz et al. [3] studied the energy consumption of the machine during milling of AISI 1018, considering the Material Removal Rate (M.R.R.) as a variable. Nevertheless, the energy consumption of the machine tool when cutting parameters are varied, maintaining the M.R.R. constant, has been not considered.

The works mentioned above show that efforts have been made towards optimization of cutting parameters to minimize power consumption or surface roughness in the machining of steel and aluminum. Most of the investigations focused on turning and employed Taguchi techniques to optimize cutting velocity, feed rate and depth of cut. None of the studies employed the concept of Robust Design to optimize the machining process. Also, the material removal rate was not considered as a constant value so the values of cutting parameters could be varied to find out which level of each parameter reduced the energy consumption of the machine during turning.

Designing high-quality products and processes at low cost is an economic and technological challenge to the engineer. A systematic and efficient way to meet this challenge is the method called Robust Design, introduced by Genichi Taguchi. Its fundamental principle is to improve the quality of

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a product by minimizing the effect of the causes of variation (called noises) without eliminating them. Signal-to-noise ratio is employed to measure quality and minimize variation around a target value [9].

This paper presents a work done using the Robust Design method for optimizing a roughing turning process with constant M.R.R.. The objective of the experiment was to optimize cutting parameters so as to get the lowest value of energy consumed by the machine during all the machining process, not only in material removal. Two sources of noise were considered: the presence or absence of cutting fluid and the machine tool used to perform the turning operation.

2 ROBUST DESIGN

Robust design is an engineering methodology whose objective is to create high-quality, cost-effective products that perform well during its useful life independently of how and under which circumstances are used. These external circumstances that are outside the control of the design engineering are called noises.

Robust design increases the quality of products minimizing the effect of noise on the performance of the product. 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 [10].

In Taguchi's methodology, the main role of an orthogonal array is to permit engineers to evaluate a product design with respect to robustness. The original Taguchi methodology revolved around the use of a design for the control variables and another design for the noise variables. Then these two designs were crossed; that is, every treatment combination in the design for the control variables was run in combination with every treatment combination in the noise variable design. This type of experiment was called a crossed array design [10]. The design for the control factors is called the inner array design. The design for the noise factors is called the outer array design.

The S/N ratio is a function that can be classified into three categories: nominal is the best characteristic, smaller the better characteristic and larger the better characteristic. For each of these categories, the optimal level of a process parameter is the level which results in the highest value of S/N ratio transformation. When a critical quality characteristic deviates from the target value, it causes a loss. An S/N ratio combines a performance characteristic with its sensitivity to noise factors to measure the quality of a design.

3 TURNING PROCESS: EXPERIMENTAL PROCEDURE

3.1 Selection of process parameters

Turning experiments were performed on 150 mm length AISI 1018 steel cylindrical billets (L/D = 4); cutting length was equal to 50 mm. The experimental investigation was carried out on a HAAS SL10 lathe and on a GILDEMEISTER CTX410 lathe. The cutting tool used was a carbide insert, manufactured by Sandvik (DCMT 11 T3 04 PM). Cutting conditions were absence or presence of conventional flood lubrication.

3.2 Classification of parameters: P diagram

A block diagram representation of the turning process is shown in Figure 1. The response of the process is denoted by *y*. The factors that influence the response are classified into the following classes:

1. Control factors.
2. Noise factors. These factors cause the response *y* to deviate from the target specified.

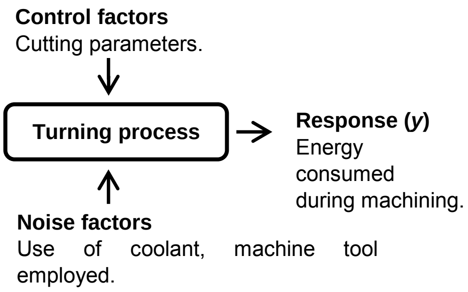

Figure 1. P diagram of the turning process.

The control factors are depth of cut [mm], feed rate [mm/rev] and cutting velocity [m/min]. Noise factors are the presence of conventional flood lubrication or its absence (dry machining), and the type of CNC machine tool employed for performing the process.

3.3 Experimental design

The inner array design selected is composed of nine experiments, with three factors: cutting velocity [m/min] (Factor "A"), feed rate [mm/rev] (Factor "B") and depth of cut [mm] (Factor "C"). In order to maintain a constant M.R.R., the values of the cutting parameters shown in Table 1 were calculated in order to obtain a M.R.R. of 1333.33 mm^3/s. These values are within the operating window recommended by the tool supplier, and they were associated with a level, where "1" is the lowest level and "3" is the highest.

The outer array design 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 2, for three experimental trials.

Table 1. Values and levels of cutting parameters.

Exp. no	Factor Values			Factor Levels		
	A	B	C	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

Table 2. Crossed array 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			*y* (Trial 1)				*y* (Trial 2)				*y* (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												

3.4 Power measurement system

Power required from the grid during the turning process was measured through a LabVIEW interface, and it was recorded each 0.1 s from the main switch of each one of the lathes. In order to obtain the value of the energy consumed by the machine, average power was computed and then multiplied by the cycle time.

4 RESULTS

The results obtained regarding average energy consumption in turning process are shown in Table 3.

Table 3. Energy consumed by the machine tool 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			*y* avg [kJ]				Cycle time [s]			
A	B	C								
1	1	3	74.2	133.1	71.5	121.0	9.6			
1	2	2	54.3	97.2	51.6	88.8	6.5			
1	3	1	43.6	80.8	42.9	73.1	4.9			
2	1	3	71.1	135.7	69.0	124.0	9.0			
2	2	2	52.5	100.2	51.7	91.2	6.1			
2	3	1	43.0	82.7	42.0	76.3	4.6			
3	1	3	69.5	141.8	67.9	130.6	8.5			
3	2	2	52.2	105.9	50.4	97.3	5.7			
3	3	1	42.1	86.7	41.1	81.4	4.3			

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 (cutting velocity, feed rate and depth of cut) versus energy consumed is shown in Figure 2.

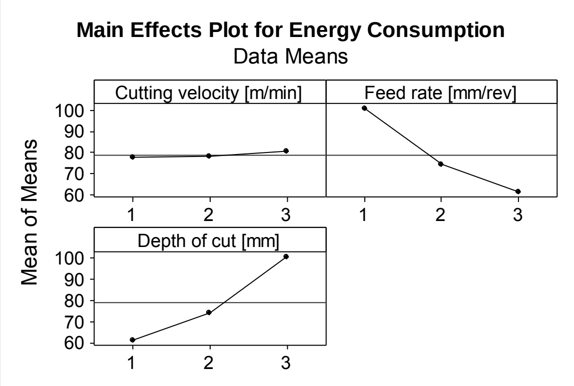

Figure 2. Main effects plot for energy consumed per machining cycle.

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. The S/N ratio is calculated based on the smaller the better characteristic because the aim of the experiments was to minimize energy consumption in the machining process. S/N ratio was calculated as

$$S/N=10\log[(1/n)*(\Sigma y^2)] \quad (1)$$

where y is the observed data and n is the number of observation. S/N ratio plot for the three factors is shown in Figure 3.

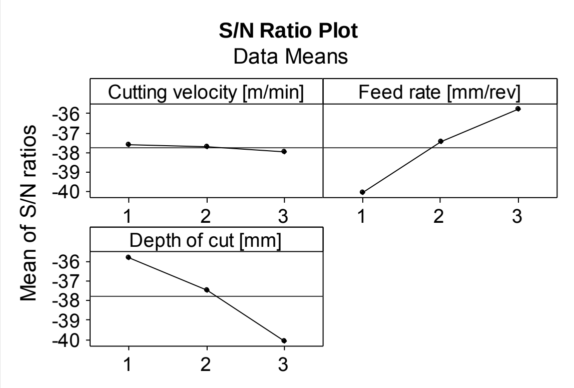

Figure 3. S/N ratio plot for energy consumed per machining cycle.

5 DATA ANALYSIS AND DISCUSSION

According to the main effects plot (Figure 2), the energy consumed per machining process decreases with levels A1, B3, C1. The slope of the graphs in the Figure 2 shows that feed rate and depth of cut are the parameters that influence the response variable the most.

Referring to S/N ratio plot (Figure 3), 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 main effects plot. These levels decrease the value of the energy consumed and ensure the process will stay in its target value.

Energy consumed per machining process is lower when the values of depth of cut and cutting velocity are diminished and feed rate is increased. A higher value of feed rate reduces the time required to machine the material and, as a consequence, less energy is needed to perform the operation.

Minimum cutting velocity is necessary for obtaining the minimum energy consumed in the machining operation. A higher value of cutting velocity implies more energy to move the spindle from rest to the indicated value of RPMs.

Sandvik Corokey [11] points out that cutting velocity is the parameter that reduces tool life the most. Furthermore, this parameter at higher values increases energy consumption. Cutting velocity must be kept at its minimum value (350 m/min), to optimize energy consumption and to avoid excessive tool wear.

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 workpiece interface also increases.

According to Dahmus and Gutowski [12], 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 1, although the M.R.R. 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.

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 2, experiments with the same M.R.R. 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 (0.2mm/rev), first level of depth of cut (1.14mm) and first level of cutting velocity (350 m/min) lead to minimum energy consumption and less variation of the process from the target value in the case of machining AISI 1018 steel with constant material removal rate.

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