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Trade-off analysis between machining time and energy consumption in impeller NC machining

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ABSTRACT

Electrical energy is directly linked to society's prosperity across the globe; much of this due to the diverse innovations on manufacturing processes. Keeping pace with the high energy demand growth will require constant efforts in terms of investment and research in order to bring new alternatives of usage. This paper outlines the application of multiple response optimization in order to analyze the trade-off between machining time and energy consumption in 5-axis impeller rough machining to find a possible balance between them. It is well known that a higher speed reduces machining time but increases energy consumption, and vice versa. A quantitative form of the relationship between the involved factors was obtained by utilizing response surface methodology (RSM) together with the desirability function method. Four independent factors were selected, namely, spindle speed, feed rate, depth and width of cut. The responses are the consumed energy and the machining time. The results showed that selecting an appropriate feed rate is crucial to balance the trade-offs between energy and time. Spindle speed is the major factor for energy consumption, while width of cut is the most influential factor for machining time.

1. Introduction

Energy efficiency has increasingly become a relevant issue in recent years due to the economic and environmental factors involved. Industries are aware of the importance of the energy usage because of costs savings or environmental regulations. Machining is one of the major activities in manufacturing industries and it is responsible for a significant portion of the total consumed energy [1]. Performing machining processes with better energy efficiency will, therefore, significantly reduce the total industrial consumption of energy. But it is crucial to consider energy efficiency without sacrificing productivity. Energy savings up to 40% can be obtained based on the optimum choice of cutting parameters, tools and optimum tool path design. A substantial improvement can be achieved just by adequately balancing the factors involved in the machining processes without the need of investment on new material or machinery [1]. It is also well recognized on previous researches that rough machining is an influential step for the process efficiency because it occupies most of the total machining time. The estimation of NC machining time is of importance because it provides manufacturing engineers with information to accurately predict the productivity of an NC machine [2]. But finding the characteristic behavior of the machining process and the factors involved is still a difficult task. Machine tools are complex and dynamic systems, there are no applicable theories to explain the behavior of these systems and, there is a diverse variety of materials, machining parameters, cutting tools, machining tools that have a direct impact on the behavior analysis [3].

Significant work has been done on energy optimization; and much research has been done to approach this issue with environmental sustainability concerns but leaving unattended the productivity factor. Others have focused their efforts on tool life, surface roughness, and productivity rates without considering the energy utilization involved during the machining.

In [4], the authors presented the synergy effect between minimum costs and minimum energy, illustrating how the energy intensity and energy cost of a machined component can be minimized and hence reduce carbon dioxide emissions by calculating the optimum tool life, cutting velocity and spindle speed. In [5], a grey relational analysis and Taguchi optimization was used in order to simultaneously optimize the minimum power consumption and the best surface quality; also with the purpose of reducing environmental footprint.

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A valuable work related to the optimization of energy was carried out in [6], introducing a multi-objective optimization based on weighted grey relational analysis and response surface methodology. Those tools were applied to optimize the cutting parameters in milling to evaluate the trade-offs between sustainability, production rate and cutting quality.

There is an optimal condition for every cutting operation; this condition can allow a certain margin of clearance to work with optimal results, thus opening the opportunity for balancing other cutting operation simultaneously. This optimal point depends mostly on the material type and complexity of the machined piece. Once this optimal condition is found, maximization can occur on material removal rate, surface roughness, tool life, or energy consumption. But maximization can be obtained with one or two cutting operations at a time, rather than all at once. Thus, the only way to optimize all the responses is to find a balance between them. Having a spindle as fast as possible without burning the tool and feeding as fast as possible without breakage is the optimal spot for maximizing material removal rates, suggesting that it is possible to shorten the machining time at the expense of the energy consumption and it is there where the trade-off exists.

This paper presents a multiple response optimization by applying response surface methodology together with the desirability function approach in order to search an optimal setup of the independent factors for 5-axis rough machining of an impeller. Response surface methods (RSM) are usually employed when it is necessary to find factor settings that produce the best response, find factor settings that satisfy operating or process specifications and model a relationship between the quantitative factors and the response. The main idea of RSM is to use a sequence of designed experiments to obtain an optimal response.

Four independent factors were selected to analyze the energy consumption and machining time, namely, the spindle speed, feed rate, depth, and width of cut. A series of experiments were performed to obtain meaningful data of the process behavior.

2. Methodology

In many experiments more than one response is of interest to the researcher. Furthermore, sometimes it is necessary to find a solution for controllable factors which result in the best possible value for each response. This is the context of multiple response optimization, where it is necessary to seek a compromise between responses. In most cases the improvement of one factor affects the performance of another; in this sense, a balance between factors can be the best optimization for a multiple response problem. In this study a balance between machining time and energy is analyzed, based on data gathered from experimental investigations. The optimization steps followed in this research are as presented in Fig. 1.

First, the optimization objectives were determined, in this case energy and time. Secondly, the factors influencing the optimization objectives were selected, namely, the spindle speed, feed rate, depth and width of cut. Thirdly, design of the experiments was used to arrange the experimentation setup. After performing the experiments and recollecting the data a preliminary regression model was created by using the response surface methodology. This model was corrected by eliminating the unnecessary terms identified by doing an analysis of variance. After eliminating the unnecessary terms, the final regression models were obtained for each response. The desirability function approach was applied to these models to transform the multiple response problem into a single response problem and finally find and optimal setting to optimize the objective responses. The results shown by the optimization process were validated by performing five extra experiments to test the reliability of the optimal setup to rough an impeller.

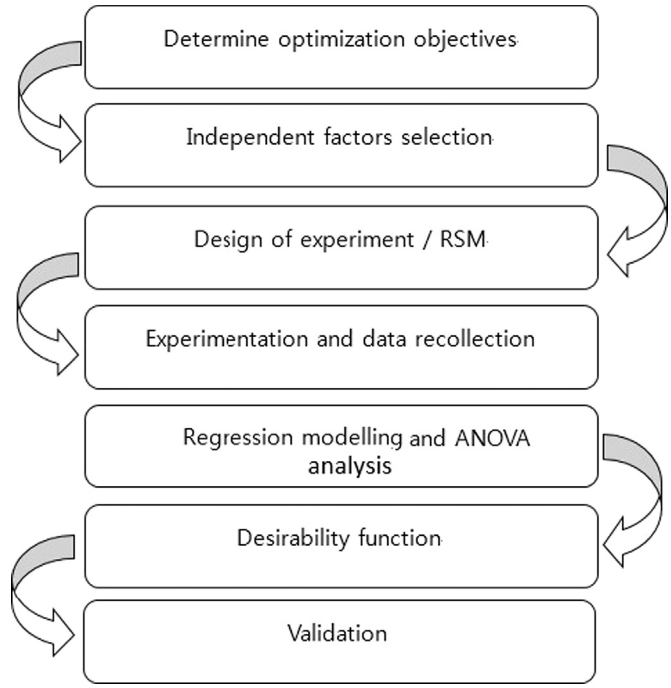

Fig. 1. Optimization steps for the balancing of trade-offs for roughing an impeller.

The main objective for this study is to analyze a possible balance between production time and energy consumption concerning a 5-axis impeller rough machining process. This means that the optimization is performed considering different machining conditions for the independent factors involved in the process.

2.1. Response surface methodology

Response surface methods (RSM) are often recommended when it is necessary to examine the relationship between one or more response variables and a set of quantitative experimental variables or factors. RSM is useful when controllable factors are selected in order to identify the optimal setting that will optimize the response. Two important models are commonly used in RSM. The first-degree model, as shown in Eq. (1)

$$y = \beta_o + \sum_{i=1}^{k} \beta_i x_i + \epsilon \quad (1)$$

And the second degree model in Eq. (2),

$$y = \beta_o + \sum_{i=1}^{k} \beta_i x_i + \sum_{i<1} \sum \beta_{ij} x_i x_j + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \in \quad (2)$$

where y is the response under analysis, β_o is the coefficient that represents the response at the center of the experiments where all the variables are zero at coded form; β_i, β_{ii}, and β_{ij} also show the linear, quadratic, and linear-by-linear interaction effects of the parameters and x_i are the independent factors affecting the responses. All of these coefficients can be found by applying the least squares method and multiple linear regression analysis. After knowing the coefficient values it's possible to apply analysis of variance (ANOVA) in order to identify the significant relationships and eliminate unnecessary terms on the regression models.

In this research a central composite design was used because it brings the opportunity to build a second order model for the response variable without needing to use a complete three level factorial experiment. Central composite designs are often recommended when the design plan calls for sequential

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