American Journal of Engineering Research (AJER)
e-ISSN: 2320-0847 p-ISSN : 2320-0936
Volume-5, Issue-7, pp-227-232
www.ajer.org
Research Paper Open Access

Application of Statistical Design Methods and Simulated Annealing Algorithm in Milling Process Optimization

H. Gohari[1], H. A. Hegab [2], Neamat G. S. Ahmed [3, 4]

[1] Mechanical Engineering Department, Faculty of Engineering, Ferdowsi University of Mashhad, Iran
[2]Mechanical Design and Production Engineering Department, Faculty of Engineering, Cairo University, Egypt
[3]DIG, Politecnico DI Milano, Italy
[4]Department of Industrial Engineering, Faculty of Engineering, Fayoum University, Egypt

ABSTRACT:*Investigating of cutting forces and vibrations has a critical significance in analyzing and understanding of machining processes as it can provide more details about the cutting tool life, and surface quality and integrity. The purpose of this work is to find the optimal milling process parameters in order to reduce the effect of the forced vibrations induced from the cutting process. Minimizing the cutting forces fluctuation can result in a constant deflection during the milling process, so it can lead to eliminating the chatter and resonance phenomena during the machining process. In order to determine the optimal process parameters, cutter diameter, helix angle and depth of cut have been considered as input design factors and the average surface roughness as a machining characteristic which can be used to evaluate the induced cutting vibrations. Experimental tests have been performed based on Taguchi experimental design method. A mathematical regression model has been developed and used as an objective function in the simulated annealing algorithm for the process optimization. In addition, Analysis of variance (ANOVA) has been implemented to find the highest significant parameters and the optimal parameters levels. Another technique has been performed too based on the mechanistic cutting force model in order to simulate the cutting forces which indicate the forces fluctuations at the optimal parameters levels. The results from the previous three techniques show the same optimal milling parameters which can be used in designing new tools in order to eliminate the effect of chatter and forced vibrations.*

Keywords:*Vibration in Machining, Simulated Annealing, Taguchi Experimental Design, Chatter, Resonance, Analysis of Variance (ANOVA)*

I. INTRODUCTION

The milling process is one of the most important processes used in the manufacturing of industrial-typical products. Milling is a machining process in which chip formation has been achieved by means of the relative movement between tool and workpiece. Often, a multi-edged tool has been used in this process leading to higher material removal rate (MRR) and smooth surface roughness [1]. The appropriate surface roughness can be achieved by means of a single machining process, this method is efficient for mass production [2]. The relative movement between tool and workpiece creates harmonic force where tool edge and workpiece are contacted. Due to harmonic nature of these forces, a certain amount of vibration is created in the system. In most studies done so far, the effect of resonance on machining process has been investigated [3]. Forced vibration is often considered in boring and grinding. The low level of stiffness in boring and high level of wheel rotation in grinding process are the main reasons for using this method [4]. Chatter has been investigated in various manufacturing processes such as milling and turning. Self-excited vibration called chatter is considered to be a significant limitation in machining. Once this phenomenon occurs, these vibrations grow rapidly and destabilize the machining process [5]. High level of noise, wavy surface and discontinuous chips are considered the main disadvantage of chatter phenomenon, and making the chatter phenomena easy to be recognized. Two main sources account for self-excited vibration; mode coupling and regeneration of waviness [4]. In the case that forces are non-harmonic and, variations are zero, self-excited vibration and resonance phenomenon will not occur. A large number of studies have been performed on tool geometry optimization such as helix angle optimization, which has a large impact on regeneration of waviness [6]. In machining by means of helix tools, once frequencies have been identified, the number of spindle rotation is determined in such way that creates maximum depth of cut as well as the lack of chatter phenomenon. Various studies have tried to find the optimal spindle rotational speed [7–9]. Also, a number of studies tried to calculate the depth of cut by simulating machining process such as time-domain simulation, discrete time intervals simulation or linearization of equations in order to identify the stability threshold [10,11]. As stated above, almost studies either focused on chatter or forced vibrations phenomenon have been used. Through analyzing the cutting forces, the current paper tries to determine such condition in machining in which forces obtain the lowest amount of variation and prevent the occurrence of the chatter and resonance phenomena simultaneously. Thus, the necessary steps for achieving the best surface roughness in order to reduce the effects of chatter and force vibrations have been presented and discussed during this work.

II. MILLING FORCES SIMULATION USING MEANS OF HELIX TOOL

Various approaches have been used to determine the cutting forces experimentally such as using dynamometer. Based on the constants obtained from orthogonal tests and cutting tool geometry, the cutting forces are determined in this work. In order to simulate the machining process, the tool features have been considered as indicated in Figure 1. In order to calculate the cutting inducedforces, the tool has been sliced in equal intervals in the height direction, and then forces are determined. The algorithm for calculating these forces has been shown in Figure 2. As it can be shown in this figure, the forces on the cutting edge have been calculated firstly. By summing these forces the total force of all edges can be calculated. In the next step, the direction of tool rotation has been determined and forces have been recalculated. the cutting forces for each element in x and y-direction can be calculated using equations 1 and 2 based on the engagement angle, depth of cut, feed rate and cutting constants [4].

$$F_x = \sum_{i=1}^{m} F_{ti} \cos\varphi_i - F_{ni} \sin\varphi_i = \frac{K_s bc}{2} \sum_{i=1}^{m} \sin\varphi_i \cos\varphi + 0.3 \sin^2\varphi_i \quad (1)$$

$$F_y = \sum_{i=1}^{m} F_{ti} \sin\varphi_i - F_{ni} \cos\varphi_i = \frac{K_s bc}{2} \sum_{i=1}^{m} \sin^2\varphi_i - 0.3 \sin\varphi_i \cos\varphi_i \quad (2)$$

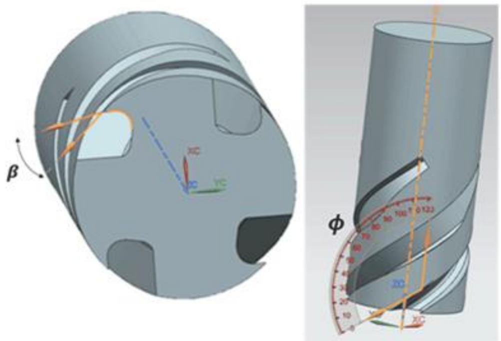

Figure 1: Tool geometry characteristics [12]

III. THEORY OF EXPERIMENTAL DESIGN

Parameters beyond the depth of cut and spindle speed affect the quality of the final surface roughness. Example these factors include tool diameter, helix angle and the number of edges. Parameters studied in this paper include diameter, helix angle, and depth of cut. In order to investigate the effect of these parameters on the quality of final surface roughness, experimental tests are performed. According to Table 1, diameter and depth factors each include four levels while helix angle factor contains two levels.

Table 1: Main factors and their levels

Factors	Symbol	Level 1	Level 2	Level 3	Level 4
Diameter (mm)	A	10	8	6	4
Depth (mm)	B	3.5	1.5	1	2.5
Angle (deg)	C	30	45	-	-

In order to gather the required data, a number of tests based on Taguchi experimental design within the frame of the L_{16} orthogonal array as indicated in Table 2 have been investigated and performed [13,14].

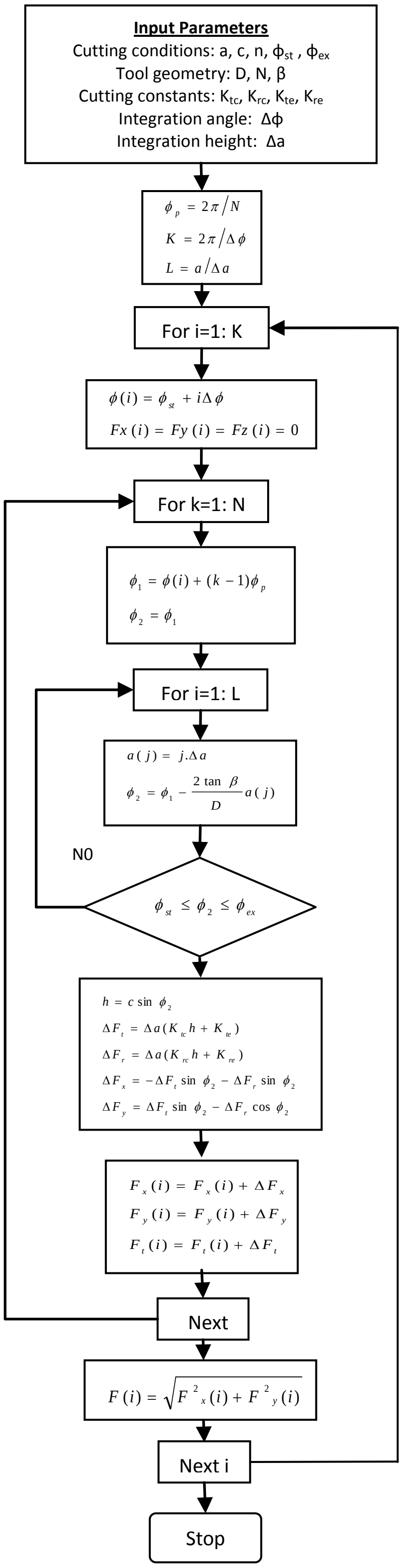

Figure 2: Flowchart of calculation of milling forces [4]

Table 2: L16 Taguchi experimental design

No.	Diam.	Depth	Angle	Ra (µm)
1	10	3.5	30	6.88
2	10	2.5	30	5.58
3	10	1.5	45	3.87
4	10	1.0	45	3.98
5	8	3.5	30	5.79
6	8	2.5	30	4.07
7	8	1.5	45	2.86
8	8	1.0	45	2.74
9	6	3.5	45	1.68
10	6	2.5	45	1.23
11	6	1.5	30	1.43
12	6	1.0	30	1.92
13	4	3.5	45	2.42
14	4	2.5	45	2.45
15	4	1.5	30	2.93
16	4	1.0	30	2.24

IV. EXPERIMENTATION

The experiment sample has been clamped on the milling table. Based on existing feature in the table of experimental design, the appropriate tool has been selected and machining has been performed. In Figure 3 the required tools for performing experiments is obtained and the way workpiece has been clamped on the milling table has been indicated in Figure 4. There arevarious methods for measuring tool vibration such as using surface roughness measuring device and accelerometer. Because of the noise factors associated with this process, the best approach for measuring vibrations is measuring the average surface roughness measuring device.

V. ANALYSIS OF VARIANCE (ANOVA)

Employing analysis of variance (ANOVA) has been used to analyze the influence of the design parameters on the measured machining quality characteristics. (ANOVA) based on the mean response values for each run and the statistics of the analysis are shown in Table 3. The results show that the 3 design factors have a major effect on the average surface roughness at 99% confidence level. In addition, the control factor (parameter) effects in terms of a summation of average surface roughness are displayed graphically in Figure 5, so it can show the optimal parameters levels. The optimal parameters levels are; 6mm cutter diameter, 1mm depth of cut, and 45° helix angle.

Figure 3: Milling tools used in experiments

Figure 4: Experimental setup

Table 3: ANOVA results

	*SS	*DOF	Variance	Fo	Results
A	28.41	3	9.47	56.96	Significant @ 99% confidence level
B	5.61	3	1.87	11.25	Significant @ 99% confidence level
C	5.77	1	5.77	34.71	Significant @ 99% confidence level
Error	1.33	8	0.166		*Statistical Sum
Total	41.13	15			***Degree of freedom

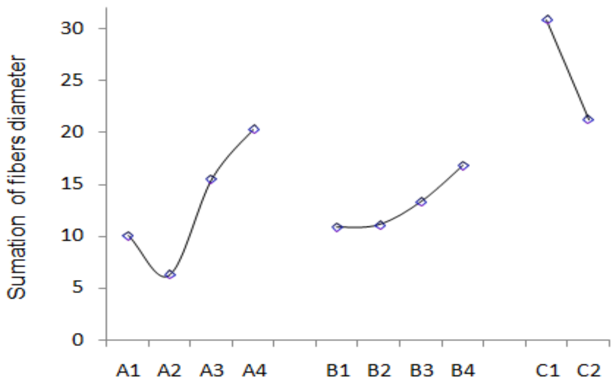

Figure 5: Plot of control effect for all process designs factors

VI. PROCESS MODELING

The purpose of statistical modeling is predicting process output for creating the possibility of examination and execution of vibrations and understanding the optimal amounts for parameters. In this study regression model as obtained through Minitab has been used. The resulting model has been shown as follows in equation 3:

Ra = 17.4968 - 2.19572 A - 5.07879 B - 14.2184 C + 0.165781 A2 + 8.73656 BC (3)

There are various approaches for calculating the model constants. The most common technique of which is the least square error. The obtained regression model has R^2 equal 96.59 % which has acceptable precision.

VII. PROCESS OPTIMIZATION

Simulated annealing is a neighboring explorer presented in 80th for solving non-linear and complex problems [11]. This algorithm is a random search technique inspired by the metallurgical process of metal annealing. In annealing, a melted metal gradually cools down. The gradual decrease in temperature leads to the formation of regular crystal structure without any flaw in the material, which reduces the level of energy to the minimum amount. Therefore, the gradual decrease in temperature is a necessity in this process. The same principle has been used in this optimization technique of cooling in order to minimize the amount of objective function. The function nature of this algorithm is in such a way that for movement a new neighboring is randomly produced and evaluated. The movement to new response will be performed in two ways; (a) the new answer is better than the current answer and; (b) the amount of possibility function for movement is higher than a random number in the interval (0, 1).

Otherwise, the explorer will generate and evaluate a new answer. This step by step movement continues until the conditions for stopping algorithm has been satisfied. The amount of movement prediction function is calculated each time by means of equation 4.

$$P_r = \exp(-\frac{\Delta z}{C_k}) \quad (4)$$

In this equation, Δz is the difference between the amount of objective function between the current answer and the new answer. Index of K is the number of repetitions and Ck is the control parameter known as temperature. Often, at the beginning of searching, the amount of primary temperature is chosen high so that the algorithm has a higher chance to move to non-improving responses. However, as the number if repetitions increase, this temperature gradually decreases along with attrition rate through the following relation as shown in equation 5:

$$C_{k+1} = \alpha \times C_k \quad (5)$$

The attrition rate (α) is often selected between 0.95 and 0.99. According to the above discussion, the possibility of choosing worse answers decreases as the number of movements increase. In other words, at the beginning of the search, the role of random nature of algorithm is higher than its definite nature in accepting new neighboring. However, as the search develops further, movements are often performed based on objective function and the role of random nature of algorithm in accepting new answer decrease. More details about this algorithm and some of its applications can be seen in therelated literature [15].

The area is affected by the regional temperature in which the temperature is lower than the melting temperature, yet, the metrological structure of the chip undergoes severe changes because of high temperature. In this area, because of high temperature, crystallization is often bigger than normal, leading to lower levels of roughness compared with normal conditions. The fact that the area has a lower width shows lower input temperature and lower structural changes. Since in most condition, an unfavorable phenomenon occurs in a high level of changes, it is clear that in order to gain stable conditions; a number of changes must be minimized. The results of optimization for the problem have been presented in Table (3).

Table 4: Optimum output levels

Input Design Factors			Output
Angle	Depth	Diam.	Ra
45	3.743	6	0.958

VIII. THE ANALYTICAL APPROACH

Dynamic features of forces and the way they have been gained were discussed above. In order to simulate the movement of a tool according to the vibration features of the system, the model was first determined in Matlab and then various elements of the system were executed. Figure 6 indicates machining forces in optimal depth and two suboptimal depths.As can be shown in Table 3, the optimal depth of cut has been found 3.74 mm. Although increasing depth of cut will increase the cutting forces which are the main cause of machining vibration, the cutting forces variationat this level of cutting depth becomes minimum. Therefore, the surface roughness will be better than the other depth of cut levels. Figure 6 verifies this phenomenon by implementing the analytical approach.

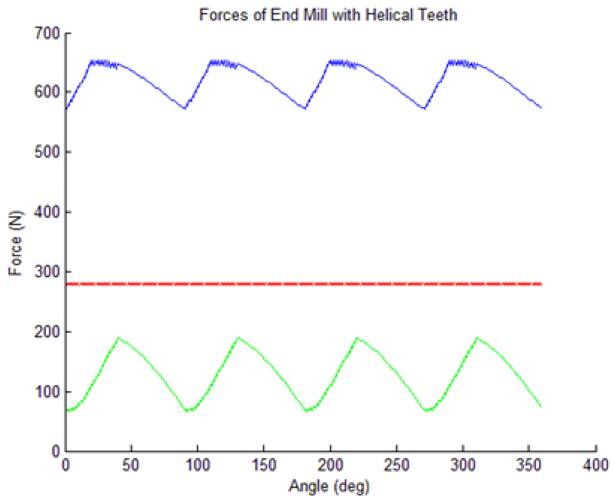

Figure 6: Machining forces simulation for milling machining with a tool by 4 edges and 45-degree helix angle.

IX. CONCLUSIONS

In this study, machining process of end milling for the purpose of obtaining appropriate levels was examined. Tests were performed based on Taguchi approach. For the purpose of optimization, the model obtained from the regression techniques has been used as an objective function in simulated annealing algorithm. In addition, ANOVA model has been obtained to determine the optimal parameters levels. Then, based on cutting constants obtained from the orthogonal test, the simulation was performed. The tool was sliced in equal intervals and forces were calculated in each interval. In this simulation, the effect of helix angle and tool diameter on the optimal depth of cut was calculated. The results obtained from dynamic modeling indicate its compatibility with experimental tests. The results from this study can be used to design new tools while eliminating the effect of resonance and chatter. It must be mentioned that changes in the geometry of the tool will change its quality features such as stability, stiffness, and wear rate. Thus, the current research can be used as a base for other studies on the design of helical milling cutters.

REFERENCES

[1]. Kalpakjian S, Schmid SR, Kok C-W. Manufacturing processes for engineering materials [Internet]. Pearson-Prentice Hall; 2008 [cited 2016 Jan 31]. Available from: http://www.ulb.tu-darmstadt.de/tocs/201536889.pdf

[2]. Lee W-Y, Kim K-W, Sin H-C. Design and analysis of a milling cutter with the improved dynamic characteristics. International Journal of Machine Tools and Manufacture. 2002;42(8):961–7.

[3]. Anderson CS, Semercigil SE, Turan Ö. A passive adaptor to enhance chatter stability for end mills. International Journal of Machine Tools and Manufacture. 2007;47(11):1777–85.

[4]. Tlusty J. Manufacturing processes and equipment. Prentice Hall; 2000.

[5]. Campa FJ, López de Lacalle LN, Urbicain G, Lamikiz A, Seguy S, Arnaud L. Critical thickness and dynamic stiffness for chatter avoidance in thin floors milling. In: Advanced Materials Research [Internet]. Trans Tech Publ; 2011 [cited 2016 Jan 31]. p. 116–21. Available from: http://www.scientific.net/amr.188.116

[6]. Yusoff AR, Sims ND. Optimisation of variable helix tool geometry for regenerative chatter mitigation. International Journal of Machine Tools and Manufacture. 2011;51(2):133–41.

[7]. Tlusty J, Smith S, Winfough WR. Techniques for the use of long slender end mills in high-speed milling. CIRP Annals-Manufacturing Technology. 1996;45(1):393–6.

[8]. Quintana G, Ciurana J, Teixidor D. A new experimental methodology for identification of stability lobes diagram in milling operations. International Journal of Machine Tools and Manufacture. 2008;48(15):1637–45.

[9]. Ziegert JC, Stanislaus C, Schmitz TL, Sterling R. Enhanced damping in long slender end mills. Journal of Manufacturing Processes. 2006;8(1):39–46.

[10]. Altintas Y, Stepan G, Merdol D, Dombovari Z. Chatter stability of milling in frequency and discrete time domain. CIRP Journal of Manufacturing Science and Technology. 2008;1(1):35–44.

[11]. Zhongqun L, Qiang L. Solution and analysis of chatter stability for end milling in the time-domain. Chinese Journal of Aeronautics. 2008;21(2):169–78.

[12]. Kim JH, Park JW, Ko TJ. End mill design and machining via cutting simulation. Computer-Aided Design. 2008;40(3):324–33.

[13]. Kuo TY, Lin HC, Liao TY, Kuo CH, Han TJ. Taguchi Method for 304 Stainless Steel Nd-YAG Laser Beam Welding. In: Advanced Materials Research [Internet]. Trans Tech Publ; 2011 [cited 2016 Jan 31]. p. 3112–5. Available from: http://www.scientific.net/AMR.287-290.3112

[14]. Bharti PS, Maheshwari S, Sharma C. Experimental investigation of Inconel 718 during die-sinking electric discharge machining. International Journal of engineering science and technology. 2010;2(11):6464–73.

[15]. Van Laarhoven PJ, Aarts EH. Simulated annealing: theory and applications [Internet]. Springer Science & Business Media; 1987 [cited 2016 Jan 31]. Available from: https://books.google.ca/books?hl=en&lr=&id=-IgUab6Dp_IC&oi=fnd&pg=PR9&dq=Simulated+Anealing:+Theory+and+Applications&ots=RzCv2BwUKD&sig=mJCcVlQCd147KFVB3iRX2oxEszo