Periodica Polytechnica
Mechanical Engineering

61(1), pp. 30-35, 2017
DOI: 10.3311/PPme.9114

RESEARCH ARTICLE

Optimization of Cutting Parameters to Minimize the Surface Roughness in the End Milling Process Using the Taguchi Method

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Received 23 February 2016; accepted after revision 21 September 2016

Abstract
This paper presents a study of the Taguchi design application to optimize surface quality in a CNC end milling operation. The present study includes feed per tooth, cutting speed and radial depth of cut as control factors. An orthogonal array of L9 was used and the ANOVA analyses were carried out to identify the significant factors affecting the surface roughness. The optimal cutting combination was determined by seeking the best surface roughness (response) and signal-to-noise ratio. The study was carried-out by machining a hardened steel block (steel 1.2738) with tungsten carbide coated tools. The results led to the minimum of arithmetic mean surface roughness of 1.662 μm, being the radial depth of cut the most influent parameter, with 64% of contribution for the workpiece surface finishing.

Keywords
milling, cutting parameters, optimization, surface roughness, Taguchi method

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1 Introduction

The machining is one of the most important manufacturing processes in the industry today. This is usually defined as the process of removing material from a workpiece or part in the form of chips. A mechanical part could be machined using different techniques without major differences in the final results. However, the efficiency is not the same for all techniques. In other words, to obtain the same part, there is a machining technique most appropriate that gives the best quality for the lower machining time and energy consumption. The choice of the technique depends on the goal to be achieved and, for machining, is related to the part material and its geometry, as well as, machines and tools available. According to the machining goal and the choice of cutting tool, there are different combinations of parameters, like feed rate, spindle speed, axial or radial depth of cut to obtain different results in terms of quality of machined surface and tool wear [1-3]. Each cutting parameters combination will result in a different surface roughness and tool life. However, for many different parameters to control with several levels for each one is very difficult to define the best combination that provides the lower surface roughness and maximum tool life. The most important features in the manufacturing industry is to predict the surface quality, tool life and the manufacture costs for a particular combination of machining parameters.

The quality of machined surface is evaluated by the surface roughness of the machined part, being the most critical quality characteristic. Some researchers tried to predict the surface roughness of machining process through mathematical algorithms [4-6], but those studies are very slow and expensive since they required a large number of experimental tests, using several parameters combinations. Nevertheless, an interesting solution to minimize the combinations number of experimental tests could be the implementation of optimization techniques. In the last two decades were instigated many numerical techniques applied to the optimization of machining parameters [7] being the most frequently used the fuzzy logic [8], the genetic algorithms [9] and the Taguchi method [10-12]. In this work is implemented the Taguchi method for surface roughness optimization in an end-milling operation.

The Taguchi approach [13, 14] is based in statistical analysis of tests that can economically satisfy the product or process for a defined optimal design. One advantage of this method is that multiple factors are considered at once, including noise factors. Taguchi method when combined with other statistical tools, like analysis of variance (ANOVA), principal component analysis (PCA) [15] or grey relational analysis [16], transforms into a powerful tool for optimization of the machining parameters.

Some authors have studied the turning machining process associated with Taguchi method [16-19] to optimise the most common controllable parameters, such as: cutting speed, feed rate and depth of cut. The main goal is to reduce the surface roughness, through the application of Taguchi method based on the highest signal-to-noise ratio for surface roughness. Other studies have focused in the milling process [15, 20-22], being one of the most used metallic chips removal processes in industry. As in turning process, the main controllable factors are the feed rate, depth of cut and cutting speed (or spindle speed) and, for the most of this works, the authors used three levels for each factor through the use of Taguchi L9 array. In many studies of milling optimization using Taguchi method referenced in the bibliography, the surface roughness measurements are performed on the surface perpendicular to tool axis, usually horizontal [15, 20, 21] or on both surfaces, perpendicular and parallel to tool axis, and is computed the average value [22]. However, the contour operation is very common in metallic machining and is important to control the lateral surface roughness which can be measured in parallel direction of toll axis. In this work the authors analysed the influence of each machining parameters in the surface roughness on parallel direction of tool axis for the end milling operation. The main goal is the determination of the optimal combination of milling parameters to obtain the lower surface roughness value.

2 Taguchi method for design of experiments and experimental details

2.1 Taguchi method

Genichi Taguchi (Tokamachi, Japan, 1924–2012) was a statistician and an engineer. He developed a methodology to improve the quality of manufactured goods by using a fractional-factorial approach whenever there are several factors involved and is accomplished with the aid of orthogonal arrays. Taguchi has made influential contribution to industry. The key elements of his quality philosophy include the following aspects:

- The philosophy of off-line quality control, robust design of products and processes;
- Taguchi loss function;
- Innovations in the statistical design of experimental tests.

The Taguchi method involves reducing the variation in a process through robust design of experiments. The main objective of this method is to produce high quality product at low cost to the manufacturer.

The key idea behind this method is the quality of a product required by the society is same how related to the loss caused during its life cycle. A high quality product will cause less loss to the society. The loss can be measured in different parameters like time or noise. In general, if the product result is not as the consumer expects, the loss is big since the quality is far from the user expectations. So, this is not desirable for the industry, neither for the society.

Taking into account the quality needed, Taguchi included in his method some loss functions that recognize the customer's desire to have products that are more consistent and meets the producer's desire to make them low-cost.

Taguchi's philosophy says that quality should be designed into a product, not inspected into it. This is achieved through a system design, parameter design and tolerance design. If a producer decides to choose the quality "inspected into" a product, it means the product is produced at random quality levels and those are too far from the user desired levels. Quality is more easily achieved by the reduction of deviation from a target, through the minimization of the influence of uncontrollable factors. This means one should have a high signal-to-noise ratio (S/N).

Taguchi considered three categories of the performance characteristic in the analysis of the S/N, namely: nominal is the best, larger is the better and smaller is the better. The follow equations define mathematically the referred categories.

Nominal is the best

$$S/N_t = 10 * \log\left(\frac{\bar{y}^2}{s_y^2}\right) \quad (1)$$

Larger is the better (maximize)

$$S/N_L = -10 * \log\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right) \quad (2)$$

Smaller is the better (minimize)

$$S/N_s = -10 * \log\left(\frac{1}{n}\sum_{i=1}^{n}y_i^2\right) \quad (3)$$

where $\bar{y}$ is the average of observed data, s_y^2 is the variance of y, n is the number of observations and y is the observed data.

The S/N_t is applied when the objective is to reduce variability around a specific target, S/N_L is used if the system is optimized when searching for the large as possible response and S/N_S when the response is as small as possible. For each type of the characteristics, with the above S/N ratio transformation, the higher the S/N ratio the better is the result.

The S/N_S was selected for this study, since the objective is to improve the surface finishing of side milling workpiece, by measuring the surface roughness.

2.2 Design of experiments

The first step for design the experiments is to identify the quality characteristics and to select the process parameters. In the machining processes, the most common controlled parameters are the cutting speed (V_c), feed rate (F_z) and radial depth of cut (a_e). There are other parameters that could also be controlled, like insert radius or the geometry of tool. However, these parameters are more restricted and are associated to the properties of tools, which is not the goal of this study. The quality characteristic of surface roughness is one of the most important properties in the machining processes, being the objective of this study to determine the levels of milling parameters that minimize the surface roughness.

After defining the process parameters and the quality characteristic that will be controlled, is necessary to designate the number of levels of process parameters. The practicable range for the cutting parameters was recommended by the tools manufacturing, i.e., cutting speed in the range of 112-250 m/min, feed rate in the range 0.075-0.25 mm/tooth and the radial depth of cut in the range 0.112-0.312 mm. The three levels of the cutting parameters selected for this study are shown in Table 1, being the axial depth of cut considered irrelevant and set constant with the 0.3 mm.

Table 1 Cutting parameters and their levels.

Symbol	Cutting parameters	Level 1	Level 2	Level 3
A	V_c: Cutting speed [m/min]	112	180	250
B	F_z: Feed rate [mm/tooth]	0.075	0.150	0.250
C	a_e: Radial depth of cut [mm]	0.112	0.250	0.312

To choose the adequate orthogonal array is necessary to calculate the total degrees of freedom. According to Ross [13], the degrees of freedom are defined as the number of relations between process parameters, which are necessary to define the best level, as well as, how much better it is. The degrees of freedom are defined as the number of process parameter minus one. In this analysis, a three-level process parameter counts for two degrees of freedom, being the interaction between the cutting parameters neglected. As a result, there are six degrees of freedom with three cutting parameters. The degrees of freedom for the orthogonal array must be equal or greater to those for the process parameters. In the present study, was used an L9 orthogonal array. This array has 26 degrees of freedom and it allows combining three-levels of process parameters. So, the analysis of all parameter position using the L9 orthogonal array will require twenty seven experiments. The experimental design for the three cutting parameters using the L9 orthogonal array is presented in Table 2.

Table 2 Taguchi L9 array.

Test Number	A Cutting Speed	B Feed rate	C Radial depth cut	D Error
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

2.3 Experimental details and results

The experimental tests were performed through a machining operation of face milling around a cylindrical workpiece. The initial dimensions of workpiece were 200 mm of diameter and length of 200 mm. The material of the cylinder was the mould steel GMTC 1.2738 with a hardness of 45 Rockwell C, which has the chemical composition shown in Table 3. This material was chosen for two main reasons, first because is a very hard steel which is interesting to analyse the tool behaviour during the machining process. The second reason, is related with the specific tool application, usually the Portuguese mould industry uses this kind of inserts.

Table 3 Taguchi L9 array [23].

Chemical composition %	
C	0.35 – 0.45
Si	0.20 – 0.40
Mn	1.30 – 1.60
P	Max 0.035
S	Max 0.035
Cr	1.80 – 2.10
Ni	0.90 – 1.20
Mo	0.15 – 0.25

The tests were carried out on a Deckel Maho DMC 63V vertical machining centre using WC coated tools. The tool inserts were WNHU 04T310 manufactured by Palbit®. The milling operations were around a circular path with a constant axial depth (0.3 mm) in one way until 50 mm of vertical length. In Fig. 1 is presented the workpiece on the milling machine table after the machining tests and during roughness measurements.

There is several surface roughness amplitude parameters employed in industry, being the most common the root-mean-square roughness, the arithmetic mean roughness (R_a) and the maximum peack-to-valley roughness [24]. For the present study, was used the R_a parameter. The roughness was measured along of cylinder axial direction and in three equidistance orientations separate by 120º angle (P1, P2, P3), see Fig. 2, using the Mitutoyo SJ-301 Portable Surface Roughness Tester. The average surface roughness was measured within the sampling length of 2.5 mm. For each orientation were taken five vertical measurements and neglected the lowest and the highest result. Final average R_a value is taken by considering the average value of the whole measurements.

Fig. 1 Workpiece on the milling machine table.

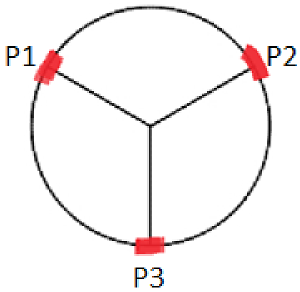

Fig. 2 Schematic representation of measurement points on the specimen.

In the Table 4 is presented the average of the surface roughness measurements in the three directions (R_a_P1, R_a_P2, R_a_P3) and the computed signal-to-noise S/N. The most important quality features in machining is the surface roughness. So, the suitable S/N ratio for this purpose is the "smaller the better" category.

From the Table 4 is possible to identify that the best results are obtained in test number 7, followed closely by the value obtained in test number 4.

3 Data analysis

The Taguchi analysis procedure can be described in four steps. In the first, is implemented the evaluation signal-to-noise ratio and allows to define the level of variation for each parameter. This is followed by a comparison of arithmetic mean surface roughness among all the tests. The third is based on analysis of variance, which is used to define the influence of each parameter. Finally, is implemented the final test to validate the results.

Table 4 Tests results and S/N ratio.

Test Number	A	B	C	R_a_P1 [µm]	R_a_P2 [µm]	R_a_P3 [µm]	S/N ratio [dB]
1	1	1	1	1.92	2.16	2.08	-6.264
2	1	2	2	2.04	1.97	1.95	-5.969
3	1	3	3	1.99	1.78	1.89	-5.523
4	2	1	2	1.63	1.84	1.63	-4.641
5	2	2	3	1.95	1.79	1.87	-5.443
6	2	3	1	2.41	2.31	2.48	-7.608
7	3	1	3	1.72	1.57	1.70	-4.421
8	3	2	1	2.22	1.84	2.06	-6.376
9	3	3	2	1.86	1.79	1.82	-5.208

3.1 Analysis of the signal-to-noise ratio

The signal term in the Taguchi method, represents the wanted value (mean) for the output attribute and noise represents unwanted square deviation value for the output attribute. Thus, S/N ratio is the ratio of the mean to the square deviation. The S/N ratio is used by Taguchi to measure the quality attribute or characteristic from the wanted value. The smaller S/N the better category is applied with the objective of minimizing the surface roughness. The results of S/N for the nine combinations L9 are presented in Table 4. Their analyses allow discriminating the effect of each cutting parameter for the different levels. The mean S/N ratio for each cutting parameter at levels 1, 2 and 3 can be computed by averaging the S/N ratios for correspondent experiments. The mean of S/N ratio for each level of cutting parameters presented in Table 5, common defined as the mean S/N ratio response table for the surface roughness average (Ra). The total mean of S/N ratio is -5.717 dB.

Table 5 Response table mean S/N ratio for Ra factor and significant interaction.

Symbol	Cutting parameters	Mean S/N ratio [dB]			
		Level 1	Level 2	Level 3	Max-Min
A	V_c: Cutting speed	-5.919	-5.897	-5.331	0.588
B	F_z: Feed rate	-5.108	-5.929	-6.113	1.005
C	a_e: Radial depth of cut	-6.749	-5.273	-5.129	1.620

In the Fig. 3 is shown the S/N ratio response graph for Ra. One gets a high S/N ratio for smaller variance of surface roughness around the desired value. Nevertheless, the relative importance among the milling parameters for the surface roughness still required to be identified so optimal combinations of the milling parameter levels can be determine more accurately using an ANOVA analysis.

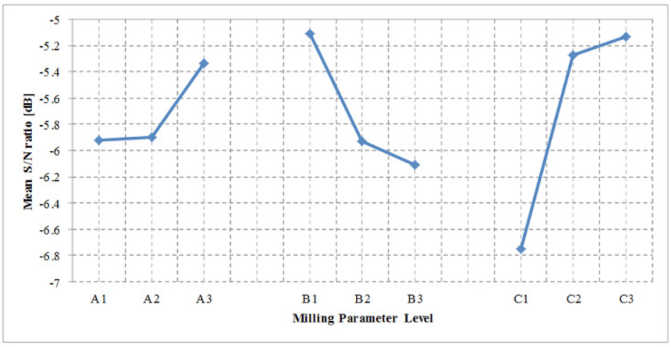

Fig. 3 Workpiece on the milling machine table.

3.2 Analysis of variance

The goal of the analysis of variance is to determine which design parameters affect meaningfully the surface roughness. This goal is achieved by splitting the variability of the S/N ratios that is measured by the sum of the squared deviations from the total mean S/N ratio, in the contributions of each cutting parameters and the error. The results of variance of each cutting parameter are shown in Table 6.

The F-Ratio test is statistic tool to verify which design parameters affect significantly in the quality characteristic. This is defined as the ratio of the mean squared deviations to the mean squared error. Generally, when show a value greater than four, it means the variation of the design or cutting parameter has an important effect in the quality characteristic.

The analysis of the F-Ratio values reveals that the feed rate and the radial depth of cut are the most significant cutting parameters. With almost 64%, followed by the feed rate and then cutting speed, respectively, with 23% and 9% contribution. The optimal cutting parameters for the surface roughness are the cutting speed at level 3, the feed rate at level 1 and, finally, the radial depth of cut at level 3.

Table 6 ANOVA results for surface roughness.

Source	Degree of freedom	Sum of Squares	Mean Squares	F-ratio	Contribution (%)
A: V_c	2	0.6573	0.3287	1.72	08.67
B: F_z	2	1.7159	0.8580	4.49	22.63
C: a_e	2	4.8267	2.4133	12.63	63.66
Residual	2	0.3821	0.1911		05.04
Total	8	7.5821			100.0

3.3 Confirmation test

Once the optimal level of the design parameters has been selected, the final step is to validate the improvement of the surface quality using the optimal level of the design parameters. The estimated S/N ratio $\hat{\eta}$ using the optimal level of the design parameters can be computed using the following equation [10].

$$\hat{\eta} = \eta_m + \sum_{i=1}^{q} \left(\bar{\eta}_i - \eta_m\right) \quad (4)$$

where η_m is the total mean S/N ratio, $\bar{\eta}_i$ is the mean S/N ratio at the optimal level and q is the number of the main design parameters that affect the quality characteristic.

The estimated S/N ratio using the optimal cutting parameters for surface roughness (R_a) can then be obtained and the corresponding roughness value (y) can also be calculated by using Eq. (4). The optimal cutting parameters are the levels with the highest value of the mean S/N ratio for each parameter and in the present work is A3B1C3 that can be verified in Table 5 or Fig. 3.

In that case, $\hat{\eta} = -4.135$ and the predicted value is $y = 1.61$. In Table 7 is possible to observe the results.

As the initial cutting parameters were considered the levels closest to the S/N ratio mean, for the present case was the combination A2B2C2.

Table 7 Results of the confirmation experiment for surface roughness.

	Cutting parameters	Optimal cutting parameters	
		Prediction	Experimental value
Levels	A2B2C2	A3B1C3	A3B1C3
Surface roughness [µm]	1.94	1.61	1.59
S/N ratio [dB]	-5.756	-4.135	-4.036
Improvement of S/N ratio		1.720	

Analysing Table 7, we reach to the conclusion that the parameters level combination for A3B1C3 which corresponds to the test number 7 led to lowest surface roughness. However, the A3B1C3 combination was repeated to confirm and validate the values obtained in the test number 7. By comparing the confirmation test with the combination A2B2C2 was verified 1.720 dB of improvement in the S/N ratio. In terms of surface roughness improved approximately 22% when comparing with the mean value of R_a for all experimental tests. The experimental results confirm the prior parameter design for the optimal cutting parameters with the multiple performance characteristics in milling operations.

4 Conclusions

The application of the parameter design of the Taguchi method in the optimization of milling operations is presented. The following conclusions can be drawn based on the experimental results of this study:

Taguchi show to be very robust method and allowed to improve the surface roughness.

For a specific range of parameters, the experimental results from the Taguchi method and ANOVA analysis one could identify the test 7 with a cutting speed of 250 m/min, the feed rate of 0.075 mm/t and the depth of cut of 0.312 mm as the best cutting parameters, leading to average surface roughness of 1.662 µm.

By comparing the results from confirmation test implemented for the optimal combination (A3B1C3) and the combination A2B2C2, was verified an improvement of 22% for the mean value of R_a.

From the ANOVA analysis we could identify the most influent parameter to be radial depth of cut with a contribution of 64% for the surface average roughness.

The validation experiments were conducted to verify the optimal cutting parameters. The target roughness value was identified with the value of 1.61 μm, being the value obtained with the test 7 the closest one. This validates all analysis and sets as the best cutting parameters of the test 7. A new analysis centered on these values will allow identifying the new cutting parameters and getting closer to the optimal parameters.

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