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Robust design of flank milling parameters based on grey-Taguchi method

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Abstract

The robust design of flank milling parameters is dealing with the optimization of the cutting loads, milled surface roughness and the material removal rate (MRR) in the machining of an Al-alloy casting plate for injection moulds. The considered flank milling parameters include the coolant employment, number of end mill flutes, cutting speed, feed per tooth, axial depth of cut, and radial depth of cut. Grey-Taguchi method is combining the orthogonal array (OA) design of experiments (DOE) with grey-relational analysis (GRA), which enables the determination of the optimal combination of flank milling parameters for multiple process responses. The basic idea of GRA is to find a grey-relational grade (GRG), which can be used for the optimization conversion from a multi-objective case to a single-objective case. GRG is also used to estimate the parameter effects on the overall performance response.

Keywords: Milling; Optimization; Grey-Taguchi; Robust parameter design

1. Introduction

Al-alloy mould tools can be economically engaged in applications such as low-pressure injection moulds or large blow moulds for the automotive industry. Mould makers need a cast plate that provides a good machinability, dimensional stability, and consistent mechanical properties throughout the thickness of the plate. Mould cast plates can be efficiently machined by flank milling with end mills. Flank milling cuts with the side of the tool, removing great amounts of material in a single pass and yields high surface quality [1]. High cutting speed induces heat generation, which indirectly decreases the tool life, which is one of the major technological limiting factors in mould manufacturing industry [2]. Therefore, high-speed cutting (HSC) is not always needed. In flank milling, the high MRR might be better achieved with deeper and wider cuts at lower cutting speeds.

Robust parameter design (RPD) is a methodology for improving the quality of products and processes. The goal of RPD is to choose the levels of the process parameters that optimize a particular quality response while minimizing its variation. Formalization of RPD began with Taguchi, who proposed DOE to identify the settings of process parameters that would yield robust performance as well as suitable data analysis techniques [3]. Taguchi uses OA, which ensure unbiased estimation of the parameters effects on the responses, and form a basic feature of all Taguchi experiments. In general, Taguchi method is dealing with the single-objective optimization. However, RPD of the flank milling process is a typical multi-objective optimization problem, which can be solved by employing the GRA [4].

In this study, RPD of flank milling is based on grey-Taguchi method, which employs L18 ($2^1 \times 3^7$) OA. The goal is to find the optimal combination of process parameters that simultaneously minimize milled surface roughness and resultant cutting force, F_r, while maximizing MRR. The optimization is realized without calculating signal-to-noise ratios, and transforms multi-objective problem into a single-objective problem using GRG.

2. Flank milling with end mills

Flank milling with carbide end mills can provide large productivity and surface quality advantages for machining of a large class of surfaces in mould tooling industry. The high resultant cutting force can cause excessive load on the tool and system deflections which can yield poor surface quality and plate form holding. In flank milling operation, MRR is determined by the axial depth of cut, radial depth of cut and the table feed rate, which is a product of the cutting speed, feed per tooth, and the number of end mill flutes. Inherent to milling machines is that cutting speed is independent of table feed. Thus, the MRR cannot be increased by increasing the cutting speed. An increase in the cutting speed will, in contrast, decrease the feed per tooth

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and reduce the chip thickness [5,6]. If an increase in the MRR is required, the table feed must be increased. This may be achieved in various ways with different effects:

- The decrease of the cutting speed and maintenance of the table feed will increase the chip thickness which directly relates to the feed per tooth and increases the MRR.
- The increase of table feed but maintenance of the cutting speed also increases the chip thickness and feed per tooth.
- The decrease of the number of flutes and maintenance of cutting speed and table feed will increase the chip thickness and MRR.

From the above-mentioned dependencies it is clear that flank milling is a machining process with a great number of influencing parameters, which are interdependent and difficult to quantify. Therefore, it is important to accurately design process parameters according to process requirements.

3. Experimental details

The machining of Al-alloy workpieces of 140 mm × 70 mm × 30 mm dimensions was conducted on the vertical machining centre, Mori Seiki-Frontier-M. Al-alloy 5083 (4.5%Mg–1%Mn–0.15%Cr) has low internal stresses, the property which lends itself to excellent form stability during the milling process. For a non-heat treatable alloy it maintains a relatively good strength and toughness, even at elevated temperatures.

The cutting conditions depend on the workpiece material, end mills, required surface roughness and machine tool characteristics. The end mills are chosen according to the workpiece material and desired process performance. Feed rates and depths of cut also depend on tool material strength and wear resistance. Milling experiment employed uncoated carbide (K10 micrograin) end mills with 2 ($\lambda = 30°$), 3 ($\lambda = 30°$) and 4 ($\lambda = 38°$) flutes of 18 mm length, as shown in Fig. 1. The cutters dimension of Ø12 mm × 73 mm assures sufficient tool rigidity [7].

During each end mill rotation each flute is brought into contact once, which results in the interrupted cut, where the cutting force fluctuates according to the angle of contact and the number of end mill flutes. The workpiece to be milled is mounted on the multi-component dynamometer (Kistler 9259A) shown in Fig. 2, which measures two components of machining force applied by the tool: feed force, F_f, in the feed direction and a feed normal force, F_n, perpendicular to feed direction. The resultant force equals $F_r = \sqrt{F_f^2 + F_n^2}$. The measurement chain further includes a charge amplifier (Kistler 5001), a spectrum analyzer (HP 3567A) and a PC for data acquisition and analysis. The surface roughness measurements were carried out with a stylus type measuring instrument (Mitutoyo Surftest SJ-301). The roughness profile assessment has been conducted according to ISO standard, which employs a Gaussian filter, a sampling length of 0.8 mm and evaluation length of 4 mm.

Fig. 1. Carbide end mills.

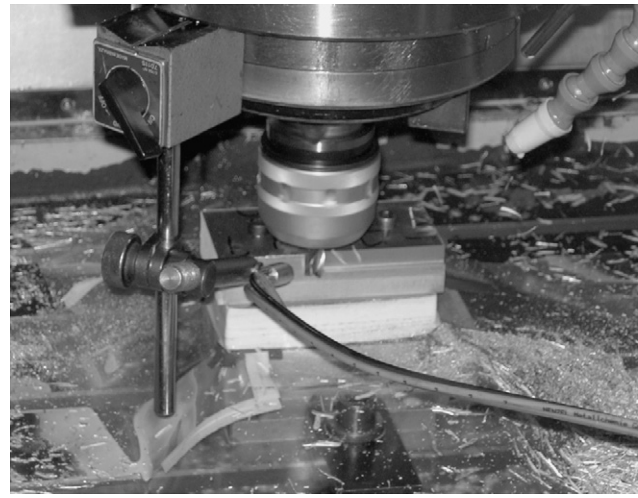

Fig. 2. Cutting force measurement.

4. Grey-Taguchi optimization

4.1. Design of experiments

The DOE includes six controllable flank milling parameters at two and three levels, of which real and coded values are tabulated in Table 1. The coolant parameter is varied on two levels, which means that milling was conducted dry or with the application of coolant emulsion. The three level parameters include number of end mill flutes, z, cutting speed, v_c, feed per tooth, f_z, axial depth of cut, a_p and radial depth of cut, a_e.

The experimental frame is a region determined by lower and upper limits of parameters settings that are of major interest. The range of kinematical parameters is limited by the capability of the machining centre. The cutting speed, feed per tooth and depths of cut are selected according to the recommendation of the end mills supplier.

In the framework of Taguchi method L18 ($2^1 \times 3^7$) OA has been employed to explore the process interrelationships within the experimental frame. The OA has 8 columns and 18 rows. Each flank milling parameter was assigned to a column, according to standard linear graph [3]. The DOE for the six process

Table 1
Milling parameters and their levels

Process parameter	Symbol	Level 1	Level 2	Level 3
Coolant application	A:	ON	OFF	
Number of flutes (teeth)	B: z	2	3	4
Cutting speed (m/min)	C: v_c	150	225	300
Feed per tooth (mm/z)	D: f_z	0.06	0.09	0.12
Axial depth of cut (mm)	E: a_p	8	12	16
Radial depth of cut (mm)	F: a_e	2	3	4

Table 2
Design of experiments

Run	A: Coolant	B: z (teeth)	C: v_c (m/min)	D: f_z (mm/z)	E: a_p (mm)	F: a_e (mm)	R_a (μm)	F_r (N)	MRR (mm^3/s)	GRG
1	OFF	2	150	0.12	16	3	0.72	929.5	764	0.6005
2	OFF	4	300	0.09	8	3	1.14	453.5	1146	0.6811
3	OFF	2	225	0.06	8	4	0.3	451.7	382	0.7281
4	ON	3	225	0.09	16	4	0.36	611.2	1719	0.7890
5	ON	2	300	0.12	16	4	0.47	768.0	2037	0.7959
6	ON	3	300	0.12	8	2	0.87	382.1	764	0.7006
7	OFF	3	225	0.12	8	3	0.49	661.5	859	0.6763
8	OFF	4	225	0.06	16	2	0.53	383.1	764	0.7387
9	ON	2	150	0.06	8	2	0.16	257.8	127	0.8193
10	ON	4	300	0.06	16	3	2.06	391.0	1528	0.6853
11	OFF	4	150	0.12	12	4	1.14	821.4	1528	0.6413
12	ON	2	225	0.09	12	3	0.23	482.7	645	0.7454
13	ON	3	150	0.06	12	3	0.26	400.0	430	0.7543
14	OFF	3	300	0.06	12	4	0.29	461.5	1146	0.7766
15	ON	4	150	0.09	8	4	0.78	485.1	764	0.6765
16	OFF	3	150	0.09	16	2	0.5	467.1	573	0.7036
17	OFF	2	300	0.09	12	2	0.31	470.7	573	0.7310
18	ON	4	225	0.12	12	2	1.11	327.3	1146	0.7290

parameters is given in Table 2. Since the OA contains eight columns, last two columns of the array have been left empty to estimate experimental error. The OA follows a random run order. The run order is a completely random ordering of the experiments that should be followed when running the experiments in order to reduce experimental error.

4.2. Grey-relational analysis

The GRA associated with the Taguchi method represents a rather new approach to optimization of machining operations. The grey-Taguchi method has been applied to optimize multiple performance responses of arc welding process [8], drilling process [9] and electro discharge machining [10].

The first step of GRA includes the linear normalization of the DOE data according to the type of performance response. In the context of Taguchi methodology, surface roughness and resultant force are the lower-the-better performance responses:

$$x_i(k) = \frac{\max \eta_i(k) - \eta_i(k)}{\max \eta_i(k) - \min \eta_i(k)} \tag{1}$$

whilst on the other hand, MRR is higher-the better performance response:

$$x_i(k) = \frac{\eta_i(k) - \min \eta_i(k)}{\max \eta_i(k) - \min \eta_i(k)} \tag{2}$$

where $x_i(k)$ is the normalized value, $\min x_i(k)$ is the minimal value of $\eta_i(k)$ for the kth response and $\max x_i(k)$ is the maximal value, respectively. The normalized values are ranged between zero and one; the larger vales yield better performance and the ideal value should be equal to one, $x_0(k) = 1$. The grey-relational coefficient (GRC) determines the relationship between the ideal and actual normalized response:

$$\xi_i(k) = \frac{\Delta\min + \zeta\Delta\max}{\Delta_{0i}(k) + \zeta\Delta\max} \tag{3}$$

where $\Delta_{0i}(k) = \|x_0(k) - x_i(k)\|$, ζ is the distinguishing coefficient set between zero and one; in our case study it was set to $\zeta = 0.9$, $\Delta\min = \forall j^{\min} \in i \forall k^{\min} \|x_0(k) - x_j(k)\|$ is the smallest value of Δ_{0i} and $\Delta\max = \forall j^{\max} \in i \forall k^{\max} \|x_0(k) - x_j(k)\|$ is the largest value of Δ_{0i} [10]. In the last GRA step the grey-relational grades (GRG) are calculated by averaging the GRCs for each performance response. The GRG values are tabulated in the last column of Table 2. The structure of the OA enables the separation of each process parameter at different levels as summarized in Table 3 and shown in Fig. 3.

The optimal process parameter level yields the highest particular GRG in Fig. 3.

The last step of grey-Taguchi method is to verify the improvement of the multiple performance characteristic at the optimal levels of designed process parameters. The confirmation experiment, Table 4, yields the highest GRG.

Table 3
Grey-relational grade

Process parameter	Symbol	Level 1	Level 2	Level 3	Max–min
Coolant application	A:	0.7439	0.6975		0.0464
Number of flutes (teeth)	B: z	0.7367	0.7334	0.6920	0.0447
Cutting speed (m/min)	C: v_c	0.6993	0.7344	0.7284	0.0352
Feed per tooth (mm/z)	D: f_z	0.7504	0.7211	0.6906	0.0598
Axial depth of cut (mm)	E: a_p	0.7137	0.7296	0.7188	0.0159
Radial depth of cut (mm)	F: a_e	0.7370	0.6905	0.7346	0.0465

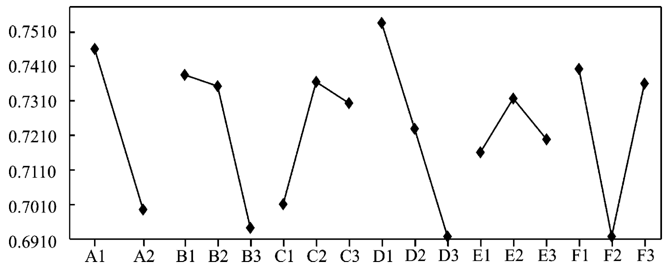

Fig. 3. Grey-relational grade plot.

Table 4
Process performance at optimal parameter levels

Coolant	ON
z	2
v_c (m/min)	225
f_z (mm/z)	0.06
a_p (mm)	12
a_e (mm)	2
R_a (μm)	0.20
F_r (N)	248.8
MRR (mm^3/s)	286
GRG	0.8242

5. Conclusions

This paper deals with the application of grey-Taguchi method to optimize flank milling parameters. The method integrates OA, employed to run the experiments and GRA for multi-objective response optimization. The optimal set-up of process parameters simultaneously minimizes milled surface roughness and resultant cutting force and maximizes MRR. Further, in the context of RPD the response variations are minimized, which is important for the increase of the process capability, c_{pk}. It has been proven that the multiple performance characteristic of the flank milling process is improved by using grey-Taguchi method.

Usually, grey-Taguchi method includes the analysis of variance (ANOVA), which provides the F-value or the P-value, that quantify effect of a particular process parameter on a single or multi performance response. The estimation of particular process parameter effect on the multi-performance response can be also supported by GRG. Basically, the higher is the max–min GRG ratio, the higher is the particular process parameter effect (Table 3, Fig. 3).

With regard to the discussed optimization problem it is clear that flank milling with an end mill with two or three flutes is superior to four-fluted tool. The maximal cutting speed did not yield optimal performance. Reduced feed rates improve the process performance and tool life. The radial depth of cut of 3 mm is not advantageous to improve multiple process performance.

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