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Optimization of Effects of Cutting Parameters and Cutting Tool Path by using Grey Based Taguchi Method

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In this study, an experimental investigation of surface roughness and cutting forces in milling of Al 7075 aluminum using multi-layered coated DLC cutting tools is presented. The influences of the feed rate, tool path strategy and depth of cut on surface roughness and cutting force are examined. In order to optimize the milling process, Taguchi Grey-based optimization method is used. The optimal machinability of Al 7075 aluminum using multi-layered coated DLC cutting tools is successfully determined.

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PACS/topics: cutting path strategies, Taguchi, Grey relation analysis

1. Introduction

Aluminum alloys are extensively used as a main engineering material in various fields, such as automotive industry, in the mould and die components manufacturing and in the industry in which weight is the most important factor [1]. Cutting of aluminum alloys is a major manufacturing process in the automotive industry and in the manufacturing of mould and die components.

Milling with an end mill and insert is one of the important machining processes for engraving, for surface contouring, for making profiles, slots, and pockets in precision molds and dies. The machining process is used in both rough and finishing operations [2]. Among the modern machining tools, CNC milling machines are extensively used in machining. Various CAM software is used for programming CNC milling machines, which are used in cast manufacturing as well as in machining of numerous products.

Tool path for machining is calculated using these programs based on various available path algorithms, such as one-way, zigzag, spiral and others. Selection of these methods affects machining time and surface quality of the machined material [3–5]. Determination of the tool material and cutting geometry is essential. Efficiency is reduced when the machining conditions are non-standard, even if the suitable tool is selected. Theoretical studies should be carried out for each material to be machined and each type of cutting tools in order to provide high efficiency and economical machining [6–11].

It is specified that determination and application of cutting tool strategies and movements are critical in milling of volume casts, aeronautical and cutting casts [6, 7, 12–15]. Selection of the suitable cutting strategy and movement provides a reduced machining time and production cost and increased surface quality, tool life, and efficiency. In particular, tool displacement types affect the cutting forces. It was shown that tool displacement errors should be minimized in order to reduce the occurring cutting forces.

In recent years the movement towards eliminating the use of cutting fluids by dry machining is one of the most important challenges in the field of metal cutting, because the use of cutting fluids increases costs for waste disposal and environmental loads [16–18]. In particular, aluminum alloys are well known as critical materials with regard to dry machining [16, 17]. Without the use of any cutting fluids, these materials severely adhere to the tool surface and form a built-up edge due to their low melting point and high ductility, leading to deterioration of the surface integrity of the work-piece and tool failure.

Diamond-like carbon (DLC) coated tools are considered to be suitable for dry machining of aluminum alloys [19, 20]. However, a flooded cutting fluid is required in practical use to avid adherence of aluminum chips to DLC-coated tools [21].

In this study, surface roughness and cutting forces were investigated experimentally in milling of Al 7075 aluminum material (which is used in such fields as space and aircraft industry) by DLC coated end-mill cutting tools. Effect of tool path, feed and cutting depths on surface roughness and cutting forces was examined. Taguchi technique was used for optimization of the milling process. The optimal cutting parameters were A3B1C1 for surface roughness and cutting force i.e. spiral tool path, feed rate of 500 mm/min, and depth of cut of 0.25 mm.

2. Materials and methods

2.1. Materials

Specimens used in the experimental study are made of Al 7075 aluminum alloy, the chemical composition and mechanical characteristics of which are given in Tables I and II, respectively. JOHNFORD VMC-850/550+APC CNC Fanuc 0T x-y-z axis CNC Milling Machine with a motor power of 30 HP was used in the experiments. DLC-mill L9330 DLC coated end-mill was used for cutting.

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MAHR-Perthometer surface roughness tool was used for measurements of surface roughness. KISTLER 9265B dynamometer was used for measurement of cutting force in combination with the KISTLER 5019b type charge amplifier. DynoWare software was used for analysis.

TABLE I

Chemical composition of Al 7075

Al	Cu	Mn	Si	Ti	Zn	Cr
Base	2.0	0.30	0.13	0.20	0.5	0.28

TABLE II

Mechanical characteristics of Al 7075

Strength [MPa]		Elongation	Density	Hardness
Tensile	Yield	[%]	[kg/m^3]	[HB]
570	505	11	2800	160

2.2. Experimental design and measurement

Experiment was designed using Taguchi technique. This way it has been possible to achieve more comprehensive results with a smaller number of experiments, to reduce time and cost of the study [22–24]. As the roughness of the processed surface and the magnitudes of cutting forces are required to be as small as possible in determination of the quality characteristics, the principle of "the smallest is the best" was used for the quality values expected from the experiments.

In this experimental study, tool path, feed and cutting depths were chosen as parameters. Multiple-layer DLC coated end-mills were used in all experiments. The parameters and their levels are presented in Table III, while L9 experimental design and the surface roughness and cutting forces obtained from the experiments are given in Table IV.

TABLE III

Experimental variables

Parameters	Tool path	Feed [mm/min]	Cutting depth [mm]
level I	one-way	500	0.25
level II	zig-zag	650	0.50
level III	spiral	800	0.75

TABLE IV

L_9 Experimental setup and surface roughness and cutting force values

Experiment no.	Variables	Tool path	Feed [mm/min]	Cutting depth [mm]	Ra [μm]	Cutting force [N]
1	$A_1B_1C_1$	1	1	1	0.319	30.76
2	$A_1B_2C_2$	1	2	2	0.435	33.69
3	$A_1B_3C_3$	1	3	3	0.820	37.99
4	$A_2B_1C_2$	2	1	2	0.450	28.98
5	$A_2B_2C_3$	2	2	3	0.516	34.32
6	$A_2B_3C_1$	2	3	1	0.633	35.33
7	$A_3B_1C_3$	3	1	3	0.433	23.42
8	$A_3B_2C_1$	3	2	1	0.507	24.52
9	$A_3B_3C_2$	3	3	2	0.725	26.28

2.3. Taguchi based Grey relational analysis

The obtained experimental results and the determined parameters were optimized with Grey based Taguchi method. Using the regression model, the equation between dependent parameters and independent parameters was found. The Taguchi method uses a special design of orthogonal arrays to study the entire parameter space with only a small number of experiments.

While only one outcome is optimized in the Taguchi method, multiple outcomes can be optimized in the Grey relational analysis [24, 25]. In this study, Taguchi method was used in the experimental design step and the Grey relational analysis was used in the optimization step.

Grey relational analysis optimization process was carried out in three following steps [24, 25];

1. Normalization of experimental results (the lowest – the best).
2. Calculation the Grey relational coefficient.
3. Calculation of the Grey relational degree.
4. Determination of optimal experimental parameters.

In the normalization step, the experimental results were normalized using the following equation according to "the lowest – the best" principle.

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

where, $x_i(k)$ refers to the value from the series i and row k after normalization process, $\min y_i(k)$ refers to the minimum value from the series i, $\max y_i(k)$ refers to the maximum value from the series i and $y_i(k)$ refers to the original value from the series i and row k.

In step two, Grey relational coefficient was calculated via Eq. (2);

$$\xi_i(k) = \frac{\Delta \min + \zeta \Delta \max}{\Delta 0_i(k) + \zeta \Delta \max}. \tag{2}$$

Here, ζ is a distinguishing coefficient between 0 and 1, $\Delta 0_i$ is the amount of deviation between the reference series and the normalization values, $\Delta\min$ refers to the minimum value of the deviation sequence from the reference series and $\Delta\max$ refers to the maximum value of deviation sequence from the reference series.

In step three, Grey relational degree was calculated by Eq. (3);

$$\gamma_i = \frac{1}{n}\sum_{k=1}^{n}\xi_i(k). \tag{3}$$

3. Results and discussion

In the experimental step according to Taguchi L9 experiment design the values of surface roughness and cutting force were measured. The results are shown in Table IV. Grey relational analysis (normalization, calculation of delta values and of Grey relational degree) was applied to the experimental results as shown in Tables V and VI.

The Grey relational coefficients were calculated using Eq. (2) and results are shown in Table V.

The Grey relational degrees, related to each experimental result were calculated (Fig. 1) and the experimental results were ranked in order from highest Grey relational degree to lowest and are presented in Table V.

For the determination of optimal levels of the factors, the Grey relational degree for each factor level was calculated. The results are shown in Table VI.

As seen from Table VI, A3 (tool path: spiral), B1 (feed: 500 mm/min) and C1 (depth of cut: 0.25 mm) were selected as the optimal parameter levels, based on the results. The optimal levels of parameters will correspond to the lowest surface roughness and lowest cutting force values.

TABLE V

Normalized data, delta values and Grey relational degree for milling machine

Exp no.	Cutting force [N]	Surface roughness [μm]	Normalized data		Delta values		Grey relational degree	
			Cutting force	Surface roughness	Cutting force	Surface roughness	GRA values	GRA rank
1	30.76	0.319	1.000	0.496	0.504	0.000	0.749	2
2	33.69	0.435	0.714	0.295	0.705	0.286	0.526	5
3	37.99	0.820	-0.234	0.000	1.000	1.234	0.311	9
4	28.98	0.450	0.677	0.618	0.382	0.323	0.587	4
5	34.32	0.516	0.515	0.252	0.748	0.485	0.454	7
6	35.33	0.633	0.227	0.183	0.817	0.773	0.386	8
7	23.42	0.433	0.719	1.000	0.000	0.281	0.820	1
8	24.52	0.507	0.537	0.925	0.075	0.463	0.694	3
9	26.28	0.725	0.000	0.804	0.196	1.000	0.526	6

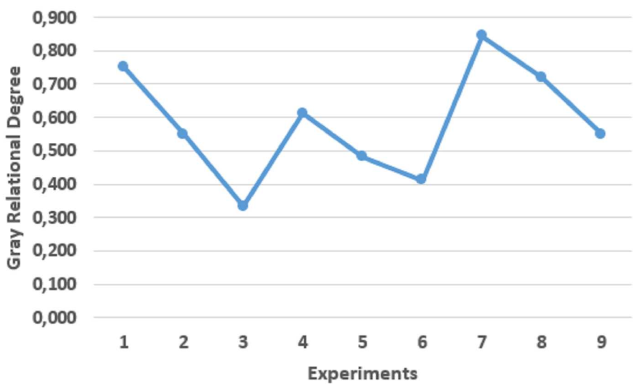

Fig. 1. Grey relational degree for each experiment.

TABLE VI

Grey relational degrees of the factor levels for milling

Levels	(A) Tool path	(B) Feed [mm/min]	(C) Depth of cut [mm]
level 1	0.544	0.735	0.627
level 2	0.501	0.583	0.570
level 3	0.704	0.432	0.552

4. Conclusions

This study of the machinability of Al7075 aluminum alloy with multiple-layer DLC coated end-mills has produced some useful results. Surface roughness and cutting force were used as the criteria for the machinability. Three control factors which were considered to be effective in creating the most suitable conditions for the criteria (feed rate, depth of cut and tool path) were chosen at three different levels and applied in the experimental study. Below is the summary of the results:

- Based on the Grey relational analysis, the optimal cutting parameters for surface roughness and cutting force were A3B1C1, i.e. spiral tool path, feed of 500 mm/min, and depth of cut of 0.25 mm. Taguchi method is beneficial for the experimental design of the machinability of Al7075 aluminum alloy material. Having optimized parameters helps to keep the response values at required levels.

- Test results prove the effectiveness of the wiper inserts in providing excellent surface roughness. The results also suggest that the use of the wiper insert is an effective way to significantly increase cutting efficiency without changing the machined surface roughness in high feed turning operations.

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