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Experimental Investigation and Optimization of Material Removal Rate and Surface Roughness in Centerless Grinding of Magnesium Alloy Using Grey Relational Analysis

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Modern enterprises concentrate on higher production rates with reduced time and admired quality. The surface integrity defines the quality of the product. Several processes like grinding, polishing and buffing have been used to improve the surface texture of the machined products. The most prominent challenge that is faced by an engineer is to manufacture a component with better surface integrity at reduced time, leading to increased production rate and improved profit. It is important to select proper combination of the machining parameters for obtaining the best results. The process called through feed centerless grinding helps in obtaining better surface texture. The main aim of this work is to examine the influence of various machining parameters such as regulating wheel angle, regulating wheel speed and depth of cut over surface roughness and machining time in machining magnesium alloy using silicon carbide grinding wheel. Grey relational analysis method is used for investigating the results. The optimal machining parameters were found with regulating wheel speed, regulating wheel angle and depth of cut being 46 rpm, 2 degree and 0.2 mm.

Keywords: MRR, surface roughness, magnesium alloy, silicon carbide grinding wheel, Grey Relational Analysis.

1. Introduction

Phan Bui Khoi et al [1] carried out the experimentation on centerless grinding with center height angle, longitudinal grinding wheel dressing feed rate, plunge feed rate and control wheel velocity as input parameters on 20 X- infiltration carbon steel. Genetic algorithm (GA) and Response surface methodology (RSM) was adopted to optimize the machining parameters which revealed that GA produced the best optimized result with a minimized roundness error of 0.0001. Kaifei Zhang et al [2] conducted an experimental study on internal cylindrical grinding of bearing steel with electrolytic in-process dressing grinding which revealed that optimal results were as follows: depth of cut 1–2 μm, current duty ratio 50% (5 μs/5 μs), and open circuit voltage 90 V for minimum surface roughness and coarser grit size wheel is often used to achieve high grinding efficiency while the finer one needs to realize fine surface quality. Dapeng Dong et al [3] investigated on the effect of different heat treatment processes on grinding machinability and surface integrity of 9Mn2V which revealed superior grinding integrity with the occurrence of grinding burn and grinding cracks reduced by using this process. Cryogenic and tempering treatment improved the grinding machinability of 9Mn2V greatly, grindability would be further enhanced if the material could be cryogenic and tempering treated in twice. Hairong Wang et al [4] investigate the influence of main grinding parameters on the micro cracks of subsurface damage, relationships among the average abrasive size, grinding force, wheel speed, and grinding depth and characterization parameters of micro cracks are established. The influences of average abrasive size, grinding force, wheel speed, grinding depth, and other grinding process parameters on the length of subsurface micro cracks are consistent with those on the surface roughness of samples, so the information of the micro crack length can be used to estimate the degree of SSD caused during the machining process. Jorge Alvarez et al [5] proposed a simulation method to improve the infeed grinding process by continuously varying the feed rate (CVFR) which studied the influence of variation parameters in process forces, workpiece roughness, roundness and size tolerance, or dynamic behaviour. The analysis proved that CVFR lead to more efficient cycles without the difficulty of defining feed rate and stock removal values. This work concluded that grinding processes can be improved with this method regarding productivity and workpiece geometrical and surface tolerances. W. Brian Rowe [6] suggested a new method of optimization considering the effect of positive grain boundaries and negative up boundaries in dynamic stability charts which helped in understanding the dynamic behaviour of the centerless grinding process and roundness of the workpiece. This helped in selection of grinding parameters such a work speed, set–up and number of lobes. Do Duc Trung et al [7] focused on determining the optimum centerless grinding parameters which included center height angle of the workpiece , longitudinal dressing feed–rate, plunge feed–rate and control wheel velocity over the responses surface roughness (SR) and roundness error. The analysis revealed that all the four parameters had a significant effect on the responses. The minimized average surface roughness of 0.3090 μm and roundness error of 1.3493 μm was obtained. Mondal and mandal [8] proposed an empirical model using Artificial Neural Network (ANN) in terms of wheel speed, depth of cut and coolant flow rate for predicting the surface roughness in centerless grinding process. This model was trained and when tested with the experimental data, it proved to be efficient and depth of cut was the most significant factor.

David Barrenetxea et al [9] introduced a new algorithm for analysis of stability and optimization of infeed centerless grinding process which involved transforming the high level grinding models into a web based simulation to reduce the cycle time. The model was created based on dressing speed, regulating wheel speed, dressing stock and work piece height to analyse cycle time and roundness error.

The simulation resulted in 70% reduction in cycle time and improved the roundness by 6%. Jorge Alvarez et al [10] proposed a semi–discretization method for dynamic stability analysis of the in–feed cylindrical grinding process. The residual flexibility has been included in this method since it has much influence on grinding processes due to the deformations of the grinding wheel and the workpiece at the contact point. A higher residual flexibility leads to a more stable process. A special care has to be taken analysing dynamic instability when grinding at different positions along their length because both equivalent stiffness of the process and dynamic stiffness of workpiece vibration modes change. Contrary to expected, in some cases, chatter frequencies and their amplitudes decrease at positions with higher process equivalent stiffness, as seen in the paper theoretical and experimentally. Garitaonandia et al [11] established an efficient modelling procedure to optimize an active chatter control system and developed a finite element model center height angle and angular velocity of workpiece to study the effect on the roundness. The model developed helped in improved in chatter stability. Uhlman et al et al [12] proposed a simulation method to predict the wear rate of the grinding wheel in centerless grinding process. The model used was developed as a function of grinding wheel speed, feed rate of grinding wheel and regulating wheel speed. Lin et al [13] et al conducted a error analysis and compensation for the precision grinding of large aspheric mirror surface. The results indicated that form accuracy has been further improved after main error separation compensation grinding. This research showed that this compensation process is effective in large aspheric mirror surface grinding.

Alessandro Rascalha et al [14] expressed that use of taguchi method provided better understanding on setup of grinding process. The input parameters were the depth of dressing, the feed rate of dressing, the diameter of the grinding wheel, and the speed of the regulating wheel. The responses were the surface roughness, the roundness error, and the dressing force. The parameters were optimized and results showed that diameter of grinding wheel was the most significant factor for SR and roundness. Dresser feed rate had influence of dressing force which ended up in reduced dressing time. Fukuo Hashomoto et al [15] discussed the recent trends in centerless grinding technologies which included advanced monitoring systems and developments that were made in grinding wheels. Janardhan and Gopala Krishna [16] developed an empirical models for surface roughness and metal removal rate by considering wheel speed, table speed and depth of cut as control factors. It is found that the error in prediction of the optimum conditions is about 3 to 8%. Yao et al [17] tried to study the effect of machining parameters such as surface linear speed, wheel speed, wheel depth and wheel material [vitrified bond single alumina (SA) wheel and a resin cubic boron nitride (CBN)] as input parameters over the temperature distribution and the grinding force developed in centerless grinding process. Microstructure was analysed and residual stresses on various points were plotted to find the effect of parameters over surface integrity which showed that grinding depth had great effect on grinding force and temperature and better surface can be achieved using a SA wheel. Guogiang guo et al [18] described that the heat affected zone was identified and ground surface had a minor changes in micro structure as a effect of varying feed rate and workpiece speed. The maximum undeformed chip thickness increases, it leads to higher specific normal and tangential grinding force but lower specific grinding energy. Grinding force ratio and specific energy decrease with the increasing worktable feed rate when chip formation plays a dominant role in the mechanism of grinding.

Alvarez et al [19] developed a dynamic model based on continuously varying work speed to improve the diametrical tolerance and roundness of workpiece and simulated that helped in predicting the chatter. The developed model on implementation resulted in improved diametrical tolerance, surface roughness and roundness. This proves that continuous variation of work speed has a great influence over the stability of the product. Weixing Xua [20] proposed a simulation method for investigating the through–feed centerless grinding process performed on a surface grinder, where a compact centerless grinding unit, composed of a guide plate, an ultrasonic elliptic–vibration shoe, a blade, and their respective holders, is installed onto the worktable of a surface grinder, and the through–feed centerless grinding operation is performed as the workpiece located on the guide plate is fed into the space between the grinding wheel and ultrasonic shoe. The simulation depicted that higher machining accuracy can be.

2. Experimental set up

Star make model centerless grinding machine is used for the experimental work. The specification of machine tool is shown Tab. 1.

Table 1 Machine tool specification

Abrasive speed	1219 surface m/min (4000 surface ft/min)
Regulating wheel speed	50 rpm
Through – feed rate	3.05 m/min (10 ft/min)
Grinding pressure	0.148 amp/cm (0.375 amp/inch)
Coolant	Water based soluble oil

Figure 1 Centerless grinding machine

2.1. *Work piece material – Magnesium alloy*

Magnesium bars of 20 mm diameter and 75 mm length were used for the experimentation processes.

2.2. *Process variables and their limits*

In the present experimental study, spindle regulating wheel speed, regulating wheel angle and depth of cut have been considered as process variables. The working range of each parameter with their units is listed in Tab. 2.

Table 2 Range of parameters with their units

Parameters		Levels	
	1	2	3
Regulating wheel speed(rpm)	12	25	46
Regulating wheel angle (degree)	2	3	4
Depth of cut: D (mm)	0.1	0.16	0.2

2.3. *Measuring device*

The time was measured using stopwatch; however the machining time is the sum of tool travel time from approach point, machining time and tool relieving. The surface roughness is measured by using MITUTOYO make surface roughness tester. The length and diameter of work piece is measured using Vernier caliper. The surface roughness tester is shown in Fig. 2.

Figure 2 Surface roughness tester

2.4. *Selection of experimental design*

Based on Taguchi's Orthogonal Array (OA) design, the L27array have been selected and is mentioned in the Tab.3.

Table 3 Process variables and their limits

Experiment no.	Regulating wheel speed [rpm]	Regulating wheel angle [degrees]	Depth of cut [mm]
1	12	3	0.04
2	12	3	0.08
3	12	3	0.12
4	12	2	0.04
5	12	2	0.08
6	12	2	0.12
7	12	1	0.04
8	12	1	0.08
9	12	1	0.12
10	25	1	0.04
11	25	1	0.08
12	25	1	0.12
13	25	2	0.04
14	25	2	0.08
15	25	2	0.12
16	25	3	0.04
17	25	3	0.08
18	25	3	0.12
19	46	3	0.04
20	46	3	0.08
21	46	3	0.12
22	46	2	0.04
23	46	2	0.08
24	46	2	0.12
25	46	1	0.04
26	46	1	0.08
27	46	1	0.12

2.5. *Material removal rate*

The material removal rate is a function of weight and machining time that are measured using weighing pan and stopwatch. Following equation is used to calculate the response Material Removal Rate (MRR).

$$\mathrm{MRR} = \frac{\text{Initial weight of workpiece} - \text{Final weight of workpiece}}{\text{Density} \times \text{Machining}}$$

3. Analysis of results

The experiments were conducted to study the effect of process parameters over the output response as designed in the table. The experimental results of Surface Roughness and Material Removal Rate are given in the table 3.

Table 4 Response values from experimental work

Experiment no.	Material removal rate [g/sec]	Surface Roughness $R_a[\mu m]$
1	0.0880	1.53
2	0.0980	1.31
3	0.0381	1.72
4	0.1041	3.62
5	0.0471	1.45
6	0.0483	5.32
7	0.2395	1.83
8	0.3333	3.15
9	0.0689	5.45
10	0.1333	1.80
11	0.2500	1.43
12	0.1639	2.81
13	0.3225	2.96
14	0.1190	5.24
15	0.1886	2.46
16	0.1298	3.80
17	0.1818	4.15
18	0.1851	3.22
19	0.1613	2.03
20	0.1369	4.14
21	0.1123	4.36
22	0.2127	3.13
23	0.1960	3.18
24	0.2500	2.63
25	0.2500	2.05
26	0.5710	2.55
27	0.7890	3.40

3.1. *Grey relational analysis*

Grey relational analysis is a method that is used to predict the approximate sequence among a cluster of sequences using the entity called Grey Relational Grade (GRG). The responses that are measured is normalized between the range of 0 to 1. Thereafter the optimization of multiple characteristics is converted into single optimization of Grey relational grade. The data must be pre–processed to a group

of sequence called "grey relational generation". Normalization is done for converting the raw data into comparable data. This process of transferring is called data processing.
The following formulae's are used in normalization.
If the expectation is "larger the better".

$$xi(k) = \frac{x_1(k) - \min(x_i^0(k))}{\max(x_i^0(k)) - \min(x_i^0(k))}$$

If the expectation is "smaller the better".

$$xi(k) = \frac{\min(x_i^*(k)) - x_1(k)}{\max(x_i^0(k)) - \min(x_i^0(k))}$$

where:
i = 1,...m, k = 1,...n,
m is number of experimental data items,
n is the number of parameters,
$x_i^0(k)$ is the original sequence,
$x_i^*(k)$ is the sequences after data preprocessing,
min $x_i^0(k)$ and max $x_i^0(k)$ are the smallest and the largest value of $x_i^0(k)$.
The relationship between the model and actual normalized experimental values is expressed in terms of grey relational coefficient following data pre–processing. The grey relational coefficient is calculated with the following formulae.

$$\xi(k) = \frac{\Delta\text{min} - \zeta\Delta\text{max}}{\Delta_{\text{i,0}}(k) - \Delta\text{max}}$$

where:
$\xi_i(k)$ is the grey relational coefficient ranging from 0 to 1.
ζ is the identification coefficient which is 0.5 because it offers moderate distinguishing factor.
Δmin and Δmax are the minimum and maximum of the series which is 0 and 1.
$\Delta_{\text{i,0}}(k) = ||x_i(k) - x_0(k)||$ is the difference of absolute value between $x_i(k)$ and $x_0(k)$.
The grey relational codes for the corresponding experiments are tabulated below in Tab. 4. After obtaining the grey relational coefficient, the grey relational coefficient is obtained my taking the average of the grey relational codes. The ranking is done of maximum to minimum value of GRG, as it depicts the order of desirability. The final average GRG value for the individual level of the input parameters is given in Tab. 5. The Fig. 7 depicts the selected level of each input for attaining best machining characteristics based on the average Grey Relation Grade value.

From the above Fig. 3, the optimal machining parameter was found to have the regulating wheel speed of 46 rpm, regulating wheel angle of 2 degree and depth of cut of 0.2 mm.

Table 5 Grey Relational Grades for the responses

S.NO	NOR MRR	NOR SR	DEL MRR	DEL SR	GRC 1	GRC 2	TOTAL GRC
1	0.09135	0.68182	0.90865	0.31818	0.35495	0.61111	0.96606
2	0.19231	0.72727	0.80769	0.27273	0.38235	0.64706	1.02941
3	0.19231	0.00000	0.80769	1.00000	0.38235	0.33333	0.71569
4	0.03571	0.84091	0.96429	0.15909	0.34146	0.75862	1.10008
5	0.10989	0.70455	0.89011	0.29545	0.35968	0.62857	0.98826
6	0.22115	0.79545	0.77885	0.20455	0.39098	0.70968	1.10065
7	0.00148	0.56818	0.99852	0.43182	0.33366	0.53659	0.87025
8	0.00000	0.34091	1.00000	0.65909	0.33333	0.43137	0.76471
9	0.03846	0.79545	0.96154	0.20455	0.34211	0.70968	1.05178
10	0.12130	0.61364	0.87870	0.38636	0.36266	0.56410	0.92676
11	0.04808	0.45455	0.95192	0.54545	0.34437	0.47826	0.82263
12	0.04808	1.00000	0.95192	0.00000	0.34437	1.00000	1.34437
13	0.09135	0.79545	0.90865	0.20455	0.35495	0.70968	1.06463
14	0.13462	0.56818	0.86538	0.43182	0.36620	0.53659	0.90278
15	0.10989	0.38636	0.89011	0.61364	0.35968	0.44898	0.80866
16	0.48077	0.22727	0.51923	0.77273	0.49057	0.39286	0.88342
17	0.16923	0.34091	0.83077	0.65909	0.37572	0.43137	0.80710
18	0.37692	0.56818	0.62308	0.43182	0.44521	0.53659	0.98179
19	0.30769	0.22727	0.69231	0.77273	0.41935	0.39286	0.81221
20	1.00000	0.79545	0.00000	0.20455	1.00000	0.70968	1.70968
21	0.48077	0.20455	0.51923	0.79545	0.49057	0.38596	0.87653
22	0.22115	0.34091	0.77885	0.65909	0.39098	0.43137	0.82235
23	0.65385	0.29545	0.34615	0.70455	0.59091	0.41509	1.00600
24	0.65385	0.22727	0.34615	0.77273	0.59091	0.39286	0.98377
25	0.48077	0.27273	0.51923	0.72727	0.49057	0.40741	0.89797
26	0.10989	0.56818	0.89011	0.43182	0.35968	0.53659	0.89627
27	0.25824	0.79545	0.74176	0.20455	0.40265	0.70968	1.11233

Table 6 Selected machining parameters based on GRG

	Regulating wheel speed	Regulating wheel angle	Depth of cut
Level 1	4.29344	4.34354	4.17187
Level 2	4.27107	**4.38859**	4.46342
Level 3	**4.55856**	3.95268	**4.48779**

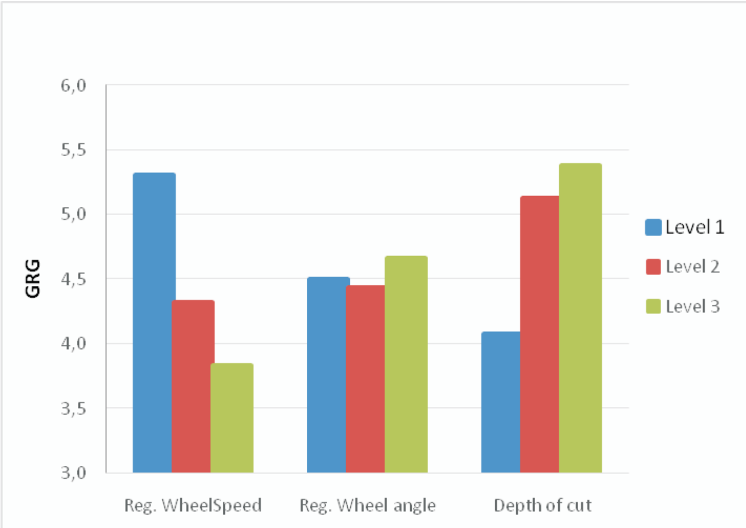

Figure 3 Optimized machining parameters based on GRG

4. Conclusion

The previous works discovered the domination of various parameters for different process which involved the study of MRR, surface roughness and roundness of machined component. In our work, the experimental examination involves centerless grinding of magnesium alloy using silicon carbide grinding wheel. The main aim of the work is to extend an empirical model using Grey relational analysis. Thus, an empirical model for predicting the values of surface roughness and Material Removal Rate was developed successfully to select the optimal machining parameters.

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