Investigating flexible self-sharpening effect and optimal parameters in magnetic finishing with gel abrasive

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Self-sharpening effect creates good abrasive performance in magnetic abrasive finishing (MAF); however, abrasive is easily flown away by the centrifugal force, reducing the finishing efficiency in MAF. Therefore, a novel polishing effect of flexible self-sharpening was demonstrated to reveal the excellent abilities in magnetic finishing with abrasive gel (MFGA), and grey relational method based on Taguchi experimental data was applied to obtain the optimal parameters in MFGA. In this paper, a cylindrical rod was finished with silicone gel to compare the MR and SR to those without this medium, and showed the flexible self-sharpening effect in MFGA. The results displayed that high temperature of the gel abrasive (exceeded 110^{o}C) during polishing effect induced slow motion of the gel in the working area; hence, old abrasives would be pushed outside the working area during the motion of workpiece and flow motion of gel would pull the new abrasives into the polishing area, creating flexible self-sharpening effect in MFGA. Furthermore, from the grey relational analysis, the best experimental combination of the influential factors was presented; additionally, based on the analysis of variance, concentration of steel grit, machining time and kinds of abrasive dominate the behaviors of MFGA process.

NOMENCLATURE

$x_i^*(k)$ = the sequence after data pre-processing,
max $x_i^{(o)}(k)$ = the largest value of $x_i^{(o)}(k)$,
min $x_i^{(o)}(k)$ = the smallest value of $x_i^{(o)}(k)$

1. Introduction

Magnetic abrasive finishing (MAF) is a polishing method that uses a group of magnetic abrasives as cutting tool and assists with the magnetic field to control the abrasion pressures in machining process. Magnetic abrasives in MAF are not fixed in the certain position; tangential forces, produced by the magnetic field, can push these abrasives creating a slow motion on the working surface. Hence, the polishing positions and the cutting angles are changed during the motion, making a self-sharpening effect in MAF [1-3]. The excellent effect of MAF enables it to finish, deburr, clean and remove the recasting layers of metals or advanced materials [4-6]. However, the abrasives are easily flown away from the working area regardless of either unbonded magnetic abrasives or sintering magnetic abrasives used in MAF; this situation will reduce the polished efficiency and induce the pollution problem in the environment.

Application of magnetic finishing with gel abrasive (MFGA) can alleviate the abrasive media problems mentioned above. Wang et al. [3] applied silicone gel to mix steel with grits and silicon carbons as a gel abrasive. This gel abrasive could be closely wrapped around the cylindrical rod without magnetic forces and steel grits and silicon carbons would not fly away by the centrifugal force in MFGA. The results showed that roughness improvement rate still remains at a high level of 90% when the same abrasive medium (35 grams) is used 15 times to finish 15 workpieces; thus this gel abrasive has an excellent ability for recycling. However, the difference between MAF and MFGA and the role of the silicone gel in MFGA were not identified in this research. Therefore, a novel effect of flexible self-sharpening will be demonstrated to elucidate the reasons why MFGA can create high polishing efficiency. Besides, optimal parameters can't easily be obtained in the study because many working conditions must be evaluated in MFGA. Over the last several years, statistic methods have attracted a lot of attention working on this area to discover the optimal parameters in industrial processes. Orthogonal chart of Taguchi method markedly reduces experiment numbers to locate the optimal parameters in MAF and EDM [7-9]. Singh et al. [7] applied L9 orthogonal array to evaluate the working parameters. The results indicate that voltage and working gap are the most significant parameters for a change in surface roughness. Lin et al. [9]

utilized Taguchi-based gray relational analysis to perform the optimal valve in magnetic-force-assisted EDM, showing that peak current, pulse duration and no load voltage are the significant machining parameters in the machining process. Therefore, in this study attempts are focused on demonstrating the finishing mechanism of gel abrasive and determining the optimal parameters in MFGA process.

2. Method

2.1 MFGA set up

Figure 1 shows the MFGA layout. Equipment consists of a magnetic force control system, rotating system, reciprocating system and control panel. A magnetic force control system uses two series of electromagnets to induce the magnetic poles that produce the magnetic field during finishing. A rotating system utilizes a brushless DC motor (M1) to drive the chuck that enables the workpiece to achieve rotational motion. Eccentric cam, induction motor (M2) and frequency converter are combined as the reciprocating system to produce the axial vibration of the workpiece. A control panel is applied to adjust the current and the vibrating frequency in MFGA.

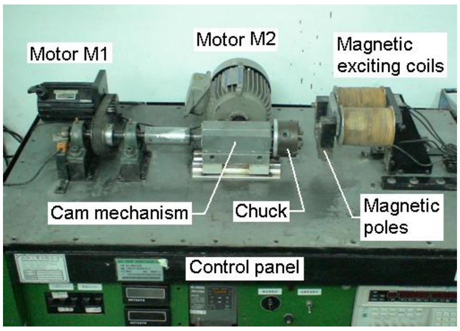


Fig. 1 Layout of the experimental apparatus.

2.2 Materials

In this study, silicone gel was selected as the bonding gel to mix with the ferromagnetic particles and the abrasives. Given to this gel is a semi-solid polymer and has the deformable characteristic, ferromagnetic particles and abrasives can mix with the gel very uniformly. With the flexible property of the gel abrasive, this medium can wrap around the workpiece closely. Ferromagnetic particles and abrasives mixed in the silicone gel are steel grit (SG) and silicon carbon (SiC) or aluminum oxide (Al_2O_3, AO), respectively. The ratio of the gel and abrasive depends on the weights of the silicone gel, SG and SiC or AO. Figure 2 presents the magnetic lines of SG in the silicone gel (no abrasive in the gel). According to this figure, the abrasive brushes of magnetic lines are clearly formed when two magnets are placed on opposite sides of the bottle. Besides, the magnetic brushes will not easily collapse because of the constraint of the magnets and silicone gel. The finishing ability of MFGA will thus be more effective than that of MAF. An attempt was made to determine the polishing effect in the die/mold by choosing the mold steel of SKD-11 as the working material in MFGA. Given that the short working gap can identify the large magnetic force in MAF, the working gap between the cylindrical rod and magnetic poles was set at a small distance of 1mm apart.

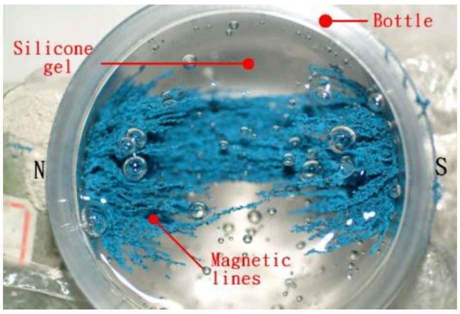


Fig. 2 Magnetic lines of steel grits in the silicone gel

2.3 Gray relational analysis (GRA) in MFGA

Taguchi-based of GRA is a new approach to optimizing the machining parameters of a multi-purpose process; this method can provide an efficient solution to the uncertain model or incomplete information [9]. In this study, L18 orthogonal chart contains eight columns and eighteen rows, so it has seventeen degrees of freedom to treat one parameter with two levels and seven parameters with three levels. Thus, abrasives (A), abrasive meshes (B), rotation rate (C), vibration frequencies (D), currents (E), SG meshes (F), abrasive concentrations (G) and machining time (H) were setting as controllable factors in L18 orthogonal chart; these factors except that A had two levels, others had three levels in GRA. Setting levels of the controllable factors are displayed in Table 1. The details of the factor levels and corresponding results of MRR and SR are shown in Table 2. GRA was performed to evaluate the effects of the machining parameters on the target sequence: material removal (MR) and surface roughness (SR). For data pre-processing (DPP), normally MR is a higher value in the magnetic finishing industry; therefore, the equation of “the higher the better” is list as follows:

$$x_i^*(k) = \frac{x_i^{(o)}(k) - \min x_i^{(o)}(k)}{\max x_i^{(o)}(k) - \min x_i^{(o)}(k)}, \quad (1)$$

As to the SR, the less the non-uniformity of the surface profile, the better quality of the material; hence, the equation of “the smaller the better” is normalized as follows:

$$x_i^*(k) = \frac{\max x_i^{(o)}(k) - x_i^{(o)}(k)}{\max x_i^{(o)}(k) - \min x_i^{(o)}(k)}. \quad (2)$$

After the establishment of data pre-processing in the equation (1) and (2), the grey relational grades can be located in GRA [9].

Table 1 Setting levels of controlling factors

	Level 1	Level 2	Level 3
Abrasives: (A)	Al_2O_3	SiC	
Mesh no. of abrasive: (B)	#4000	#6000	#8000
Rotation rate (rpm): (C)	700	1000	1300
Vibrational frequency (Hz): (D)	4	5	6
Current (A): (E)	1	2	3
Mesh no. of SG: (F)	#45	#70	#100
Concentration of SG (wt%): (G)	0.5:1	1:1	1.5:1
Machining time (min): (H)	10	20	30

Table 2 Orthogonal array L18 ($2^1 \times 3^7$) of the experiments and results

Exp	A	B	C	D	E	F	G	H	MRR(g)	SR (μm_Ra)
1	1	1	1	1	1	1	1	1	0.0266	0.274
2	1	2	1	2	2	2	2	2	0.0391	0.2178
3	1	3	1	3	3	3	3	3	0.0443	0.1122
4	1	2	2	1	1	3	3	2	0.0505	0.1275
5	1	3	2	2	2	1	1	3	0.0294	0.1416

6	1	1	2	3	3	2	2	1	0.0367	0.3163
7	1	3	3	1	2	2	3	1	0.0285	0.2645
8	1	1	3	2	3	3	1	2	0.0457	0.2191
9	1	2	3	3	1	1	2	3	0.0699	0.0769
10	2	2	1	1	3	2	1	3	0.0519	0.075
11	2	3	1	2	1	3	2	1	0.0285	0.2592
12	2	1	1	3	2	1	3	2	0.1199	0.0347
13	2	1	2	1	2	3	2	3	0.1033	0.045
14	2	2	2	2	3	1	3	1	0.0784	0.0479
15	2	3	2	3	1	2	1	2	0.0443	0.1318
16	2	3	3	1	3	1	2	2	0.1190	0.0322
17	2	1	3	2	1	2	3	3	0.1980	0.0369
18	2	2	3	3	2	3	1	1	0.0388	0.2725

2.4 Procedures

In the beginning of the experiments, the cylindrical rod of SKD-11 was clamped by the chuck, and the magnetic gel abrasive was inserted into the working gap and covered over the rod. Additionally, the setting parameters from the control panel were selected to perform the finishing process. In order to investigate the flexible self-sharpening, a mirror was put in the right hand side of the rod to figure out the slow motion of the gel abrasive in MFGA. Moreover, gray relational grades in the experiments were calculated during GRA. At the same time, gray relational grades became quality indexes to show the contribution of the experimental parameters to MR and SR, and the criterion for MR is “the higher the better”, for SR “the smaller the better”. Furthermore, analysis of variance (ANOVA) is identified the significant parameters that contribute effectively in the system responses [9]. Figure 3 shows the workpiece is wrapped by the gel abrasive, as well as the magnetic field in MFGA. According to this figure, the abrasive is not only pressed by the magnetic forces, but also constrained by the viscous forces of the silicone gel; in addition, all of the constrained forces are flexible in MFGA.

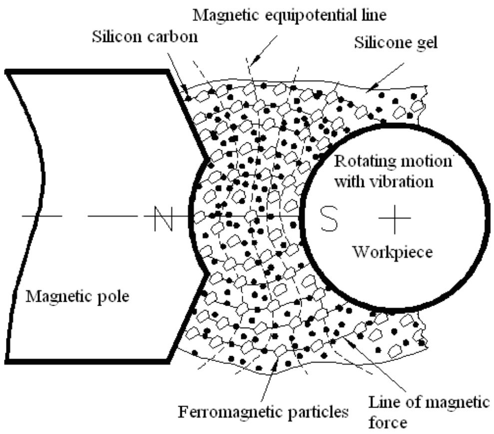


Fig. 3 Schematic diagram of the magnetic field in the gel abrasive

3. Results and discussion

In order to understand the flexible self-sharpening of silicone gel in MFGA, the processes with and without silicone gel were studied in these experiments first, then gray relational grades of MR and SR to locate the optimal parameters in MFGA. Finally, verification of the gray relational grades from GRA and experiment identified the efficiency of MFGA.

3.1 Effects of silicone gel and flexible self-sharpening in MFGA

To understand the difference between MAF and MFGA, this paper employed two kinds of abrasive media to investigate the polishing effect on the magnetic finishing process. MAF utilized unbonded magnetic abrasives to perform the experiment, due to the fact that MFGA process did not add SiC fluid in the finishing stage, hence, MAF did not add SiC fluid in the working area either. Fig. 4 shows the effects of the abrasive media with or without the silicone gel on MR and SR. According to the results, although SR decreases and MR increases with an increasing finishing time in these two experiments, MFGA performs better than MAF during polishing in terms of efficiency. The results also show that MFGA quickly reduces SR within 10 min and MAF produces bad performance in SR and MR. This is largely due to the fact that MAF cannot supply extra abrasives to abrade the workpiece because of lack of SiC fluid in MAF, so that the efficiency of MAF is very poor. However, a flexible self-sharpening is created in the working area to produce high efficiency in MFGA, even though no SiC fluid is added in the abrasive medium.

Fig. 5 indicates the flexible self-sharpening in finishing process. In Fig. 5(a), N pole is the magnetic pole, S pole is the workpiece with rough surface, white particles are ferromagnetic abrasives SG, and A, B, C and D represent SiC abrasives. Magnetic field and silicone gel constrain SG and SiC in the machining process, so workpiece is finished by these abrasives due to rotating and vibrating motions. For the reason that A and B are not pressed tightly by magnetic forces in Fig. 5(b), the motion of the workpiece causes A and B to rotate, but the rotating angles are small because of the viscosity of silicone gel; hence, new cutting edges of abrasives are appear to polish the workpiece after the following process. Furthermore, because SiC A pressed tightly by magnetic forces may crack into two or more small abrasives by large impact forces, e.g., abrasives A and A’ in Fig. 5(c), new cutting edges are produced on these abrasives, and workpiece is finished by these new edges in the following step. Additionally, temperature of silicone gel in the working area increases gradually in the polishing procedure. With the temperature dependent property, silicone gel contacting on the workpiece converts into fluid gel at certain time, and the abrasives in the fluid gel are easily pushed out of working area (the pushed gel abrasives with charcoal gray are showed in the left hand side of Fig. (c) or in the right hand side of Fig. (d)). Thus new abrasives near the workpiece are pulled into the finishing area by flowing silicone gel and continuously polish the working surface in the following process, e.g., abrasives C and D in Fig. 5(d). By virtue of the viscous flow of gel abrasive in Fig. 5, a flexible self-sharpening, inducing high polishing efficiency was defined in this study. Fig. 6 also reveals a change of abrasive medium after finishing 30 minutes continuously. The result indicates that temperature of gel abrasive on the finishing surface reaches 110^{o}C within 30 min, inducing the viscous flow of the gel abrasive in the working area. Then the flowed gel abrasive (black color) was pushed out of the finishing region in Fig. 6 (b) during the vibrated motion, and new abrasives would replace used abrasives in the working area, producing flexible self-sharpening effect on MFGA.

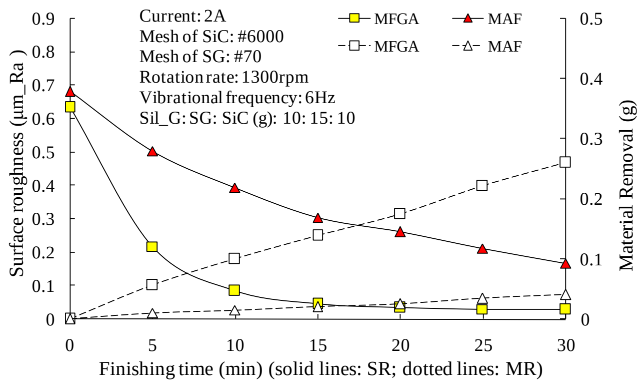
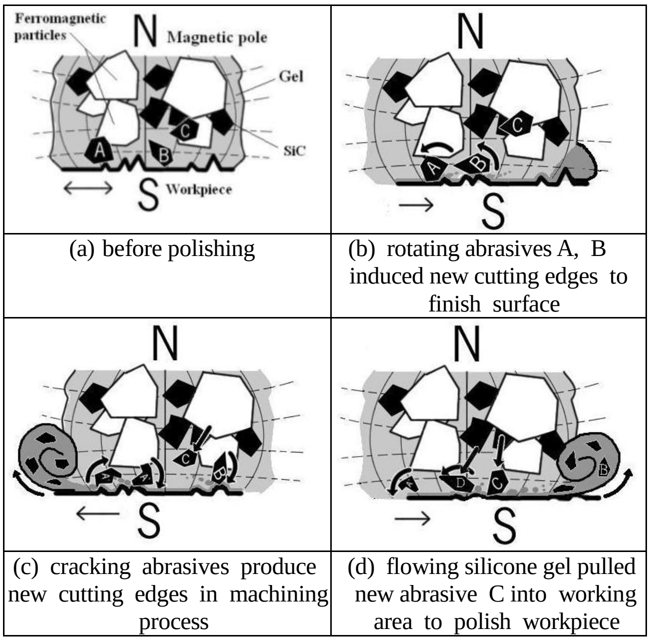


Fig. 4 Effects of MAF and MFGA on the MR and SR



(a) before polishing

(b) rotating abrasives A, B induced new cutting edges to finish surface

(c) cracking abrasives produce new cutting edges in machining process

(d) flowing silicone gel pulled new abrasive C into working area to polish workpiece

Fig. 5 Flexible self-sharpening of gel abrasive in MFGA

(c) Before finishing (MFGA)

(d) 30 minutes finishing (MFGA)

Fig. 6 Change of abrasive medium after finishing 30 minutes

3.2 Grey Relational Analysis for MFGA Process

In this study, the grey relational analysis was performed to evaluate the effects of the machining parameters on the target sequence (MR and SR). For data pre-processing, MR was "the higher the better" and SR was employed for the "the smaller the better". Then the deviation sequences of the pre-processing data were calculated and to obtain the grey relational coefficients from the distinguishing factors. Finally, the grey relational coefficients were averaged in equal weighting 0.5 so as to locate the grey relational grade, as shown in Table 3.

After the grey relational grades have been located, the response of Taguchi method, by averaging grades for the individual factors, can then be calculated. The objective of this procedure is to find the optimal combinational levels of the machining parameters associated with the target sequence (MR and SR). From Table 4, the response after averaged grades for the factors is displayed. Since the grey relational grade stands for the correlative degrees of comparable sequences of data on the preferred reference sequence, the larger value of the grey relational grade means the comparable sequence has a stronger correlation to the reference sequence. Therefore, from Table 4, A2, B1, C3, D2, E1, F1, G3, and H3, have the largest value of the relational grades for the machining parameters A, B, C, D, E, F, G, and H, respectively. As a result, the optimal combination of the machining parameters associated with MR and SR for MFGA process is: abrasives (SiC), mesh no. of abrasive (#4000), rotation rate (1300rpm), vibrational frequency (5Hz), current (1A), mesh no. of SG (#45), concentration of SG (1.5:1, wt%), machining time (30min.).

Table 3 The grades of MRR and SR after grey relational analysis

	MRR	SR	MRR	SR	
Run no.	DPP		GR coeff.		Grade
1	0.0000	0.1490	0.3333	0.3701	0.3517
2	0.0733	0.3469	0.3505	0.4336	0.3920
3	0.1032	0.7184	0.3580	0.6397	0.4988
4	0.1398	0.6646	0.3676	0.5985	0.4831
5	0.0165	0.6149	0.3370	0.5649	0.4510
6	0.0589	0.0000	0.3470	0.3333	0.3401
7	0.0113	0.1820	0.3359	0.3794	0.3576
8	0.1114	0.3423	0.3601	0.4319	0.3960
9	0.2525	0.8429	0.4008	0.7609	0.5809
10	0.1477	0.8494	0.3698	0.7686	0.5692
11	0.0111	0.2009	0.3358	0.3849	0.3603
12	0.5441	0.9912	0.5231	0.9827	0.7529
13	0.4473	0.9552	0.4750	0.9178	0.6964
14	0.3025	0.9450	0.4175	0.9008	0.6592
15	0.1032	0.6497	0.3580	0.5880	0.4730
16	0.5391	1.0000	0.5203	1.0000	0.7602
17	1.0000	0.9836	1.0000	0.9682	0.9841
18	0.0715	0.1544	0.3500	0.3716	0.3608

Table 4 The response table after averaged grades for the factors

Factor	Level 1	Level 2	Level 3
A	0.4279	0.6240	
B	0.5869	0.5075	0.4835
C	0.4875	0.5171	0.5733
D	0.5364	0.5404	0.5011
E	0.5388	0.5018	0.5372
F	0.5926	0.5193	0.4659
G	0.4336	0.5217	0.6226
H	0.4050	0.5429	0.6301

3.3 Results of analysis of variance and confirmation test

Analysis of variance (ANOVA) was conducted in this paper to assess the machining parameters which significantly affect the target sequence. Results of ANOVA based on the grey relational grades are shown in Table 5. From the table, the contribution was calculated, and in accordance with the criterion to identify the machining parameters as significant factors if the values of contribution are greater than 20%, it is clearly observed that the abrasives and the machining time of the parameters significantly influence the performance of MRR and SR in the MFGA process.

After identifying the optimal combination of the machining parameters and most influential factors on the target sequence, the confirmation test by comparing the validation of the optimal combination of the machining parameters to the predicted value is required [9]. Table 6 lists the results of the confirmation test. From this table, the value of MR increases from 0.0519 to 0.2739 g and that of SR decreases from 0.075 to 0.0266 μm when comparing results of the initial levels to the optimal combination levels. It can also be observed that the value of the grey relational grade between the two experiments has greatly been improved from 0.5692 to 0.6887, and the error between predicted value and the value of the optimal combination levels is less than 6%. Hence, the experimental results confirm the feasibility of this approach with grey relational analysis and show a fairly good agreement with the prediction.

Table 5 ANOVA of the grey relational grades

Parameter	Degree	Square Sum	Variance	Contribution (%)
A	1	0.1730	0.1730	47.1019
B	2	0.0351	0.0176	4.7812
C	2	0.0228	0.0114	3.0982
D	2	0.0056	0.0028	0.7647
E	2	0.0053	0.0026	0.7168
F	2	0.0486	0.0243	6.6110
G	2	0.1073	0.0537	14.6095
H	2	0.1546	0.0773	21.0364
Error	2	0.0094	0.0047	1.2802
Total	17	0.5617	0.3674	100

Table 6 Error of grey relational grade between predicted result and experiment

	Initial levels of machining parameters A_2, B_2 $C_1D_1E_3F_2G_1H_3$	Optimal combination of machining parameters $A_2B_1C_3D_2E_1F_1G_3H_3$	
		Predicted value	Experimental value
MRR (g)	0.0519		0.2739
SR (μm)	0.075		0.0266
GR grade	0.5692	0.7281	0.6887
error		5.41%	

4. Conclusions

A flexible self-sharpening was developed to enhance the efficiency of MAF in this study. The results show that with no addition of SiC fluid in the working area, MFGA performs better than MAF during polishing in terms of efficiency. The reason is that abrasives are constrained by gel and magnetic forces in MFGA, but abrasives are only constrained by magnetic forces in MAF; therefore, non-ferromagnetic abrasive (SiC) is easily flown away in MAF. Meanwhile, silicone gel is a temperature dependent material. Temperature of gel abrasive on the working surface reaches 110^{o}C within 30 min in MFGA, resulting in making gel abrasive create a slow motion on the machining surface, and in making new abrasives easily replace old abrasives nearby the workpiece so as to produce flexible self-sharpening on finishing process. However, this effect doesn't happen in MAF, so MFGA functions better than MAF in the polishing efficiency.

Because of the criterion of the maximum MR and minimum SR, grey relational grade used "the higher the better" of MR and "the smaller the better" of SR as the rules to evaluate the characteristics of MFGA. The results demonstrate that machining time, kinds of abrasive and concentration of SG are the most important factors to dominate the behavior of MR and SR in MFGA. Long machining time, high hardness abrasive and high concentration of SG contribute to excellent MR and SR in this study. Results also demonstrate that from the confirmation test, MR increases from 0.0519 to 0.2739 g and that of SR decreases from 0.075 to 0.0266 μm when comparing results of the initial levels to the optimal combination levels. Furthermore, the error between predicted value and the value of the optimal combination levels is less than 6%, so in the investigation, there is a very good agreement between the analytical and experimental results.

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