Int J Adv Manuf Technol (2013) 69:1791–1801
DOI 10.1007/s00170-013-5139-y

ORIGINAL ARTICLE

A study on the magneto-assisted spiral polishing on the inner wall of the bore with magnetic hot melt adhesive particles (MHMA particles)

Wei-Chan Chen · Kun-Ling Wu · Biing-Hwa Yan · Man-Chin Tsao

Received: 24 January 2013 / Accepted: 17 June 2013 / Published online: 6 July 2013

Abstract The spiral polishing mechanism employed a fast turning screw rod to drive the abrasive for workpiece surface polishing. In this study, the powerful ring magnet installed around the workpiece would attract the self-developed magnetic hot melt adhesive particles (MHMA particles) during the process of polishing, driving the SiC particles against the workpiece, the inner wall of the bore. At the same time, the flexibility of MHMA particles helped improve the surface quality of the bore by preventing the SiC particles from heavily scratching it. The effects of magnetic flux density, size and concentration of SiC particles, concentration of MHMA particles, viscosity of silicone oil, revolution speed of the spindle as well as machining time and machining gap on operation temperature, slurry viscosity, surface roughness, and material removal were discussed and the best parameter combination was identified based on the results of the experiment. The effects of each machining parameter on the finished surface topography of the workpiece were also examined. Both analysis of variance and *F*-test indicated that magnetic flux density and the concentration of MHMA particles were the two most important variables affecting the surface roughness. In other words, magnetic force helped improve spiral polishing. Furthermore, the results showed that adding new MHMA particles to the slurry greatly improved the surface quality, at a rate of 90 %, and reduced the workpiece surface roughness from 0.9 μm down to 0.094 μm.

This paper has not been published elsewhere, nor has it been submitted for publication elsewhere.

W.-C. Chen · B.-H. Yan (✉) · M.-C. Tsao
Department of Mechanical Engineering,
National Central University, Jhongli 320, Taiwan
e-mail: bhyen@cc.ncu.edu.tw

K.-L. Wu
Department of Mechanical Engineering, Tungnan University,
New Taipei City 222, Taiwan

Keywords Magneto-assisted spiral polishing · Inner-wall polishing · Magnetic hot melt adhesive particles (MHMA particles) · Analysis of variance · *F*-test

1 Introduction

With the trend towards precision and miniaturization, more and more micro cuttings are required in most production processes. However, surfaces of the thin bore and slots after micro cutting are often left with cutting marks and burrs afterwards. Removing the cutting marks and burrs for better surface quality thus becomes a must. Therefore, the requirements on product precision and surface quality in the precision machining industry make surface polishing commonly employed nowadays. The precision polishing technologies available today include chemical mechanical polishing (CMP) [1, 2] and electro polishing (EP), each with its own constraints. Polishing with flowing abrasive is getting popular as CMP costs a lot on mechanical equipment and as EP is not applied in machining non-conductive materials.

The abrasive flow machining was thought of as a substitution for conventional finishing process for such benefits as deburring, polishing, and honing as well as removing recasting layer generated by electric discharge machining.

Walia et al. [3] used a rotation rod to a generate centrifugal force on the abrasive and explored the effects of profile form, revolution speed of the spindle, squeezing pressure, grain size, and slurry concentration on changes of surface roughness and material removals. An analysis model concerning the angle and the speed of the grains when hitting the workpiece was done in the study.

Sankar et al. [4] designed a drill-bit-guided abrasive flow finishing process. A drill was placed within the machining slot to generate an axial rotational force. With the movement of grains upward and downward, an axial rotation was created, and better material removal rate and surface quality were obtained. An outcome simulation mechanism was designed based on non-linear multivariate regression analysis and artificial neural network

Kar et al. [5] replaced the expensive silicone-based polymer with visco-elastic carrier by mixing natural and butyl rubber with silicon carbide and naphthenic oil. Impacts of different abrasive ingredient ratios on visco-elasticity of the abrasive and the workpiece surface roughness were investigated as well.

Hanada et al. [6] employed the plasma spraying to polish stainless steel plate by magnetic force with the aid of diamond particles adhering onto iron-based composite powder.

Sankar et al. [7, 8] employed the rotational abrasive flow finishing (R-AFF) process. The material removal was increased by rotating the workpiece and increasing the back-and-forth movement of the grains. In the R-AFF process, the grains scrubbed the workpiece directly. The tangential force generated by the friction between the workpiece and the grains drove the grains to move circularly but left spiral lines on the workpiece surface. The radial force pushed the grains to squeeze the workpiece while the axial force removed the materials by turning them into tiny pieces.

Jha and Jain [9] created the magneto-rheological fluid by mixing carbonyl iron powder and SiC particles with visco-elastic fat and mineral oils to get better surface quality by controlling the grains through precisely monitoring the external magnetic field.

Singh and Shan [10] invented a type of magnetic abrasive, a mixture of hydrocarbon gel, SiC polymer, and particles (with a combination of 40 % ferromagnetic particles, 45 % Al_2O_3, and 15 % Si_2O_3). By encircling the workpiece with an electro-magnet to generate a magnetic field, they examined the effects of magnetic flux density, cycle times, and abrasive flow rate on surface roughness and material removal rate.

Wani et al. [11] built up the diagram of magnetic potential distribution of the machining area during the magnetic polishing process. With the finite element method, the magnetic potential distribution in the magnetic abrasive brush formed in the process of polishing was obtained and the machining pressure, surface finishing as well as material removal were evaluated. Besides, the use of abrasive made of iron particles and grains, the effects of iron particle size, grain size, magnetic flux density, and the number of circles on surface roughness and material removal rate were also examined.

All the methods described above employed a linear movement of the piston to drive the abrasive back and forth, which resulted in poor machining quality on complex surfaces, and the abrasive flow was considered too slow. This study developed a magnetic-assisted spiral polish method to improve the surface roughness of the inner wall of the bore, to remove burrs and residuals left on machined surface, and to prevent the generation of the metamorphic layer. In addition, the surface quality was effectively promoted as the machined surface was free from residual stress, heat distortion, and metamorphic layer.

The spiral polishing mechanism, as shown in Fig. 1 [12], utilized a high-speed rotating screw to drive the abrasive in the polishing process. When the rod revolved at a high speed, the slurry, with good fluidity, was driven upward along the groove of the rod and polished the workpiece directly. When flowing along the workpiece surface, the SiC particles in the slurry polished the surface by pressing and squeezing the workpiece surface. After rising above to the top of the mold, the abrasive stopped flowing upward but was pushed aside. The mold was designed in a hollow shape to have the abrasive flow from the bottom to the top, creating a circular movement of the abrasive.

This study invented a new type of magnetic hot melt adhesive particles (MHMA particles) for spiral polishing. MHMA particles were magnetic particles, created by coating steel grit on hot melt particles, presumed to add the effects of machining when added to the slurry. MHMA particles

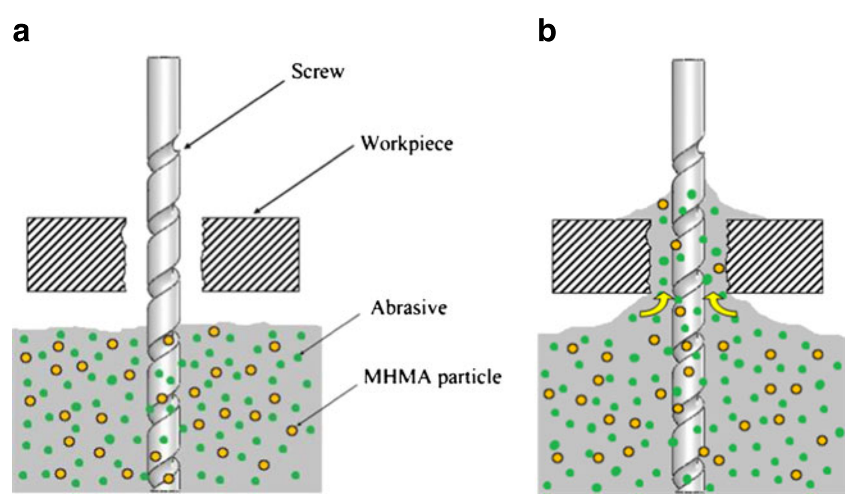

Fig. 1 Mechanism of spiral polishing **a** before polishing, **b** during polishing

contained in the slurry drove the SiC particles toward the workpiece surface to remove the asperities on it at a faster speed with the help of an extra force provided by the external magnetic field. The cushion effect brought about by the elasticity of MHMA particles ensured good surface quality but avoided deep scratches. Abrasive used in this study was operated in repeated cycles, which not only consumed less abrasive and cost less but also removed the burrs and the metamorphic layer faster and more effectively, achieving the purpose of fine polishing.

2 Experimental apparatus and method

2.1 Magnetic hot melt adhesive particles (MHMA particles)

Hot melt adhesive particles of thermal activation temperature ranging from 60 to 180 °C have been extensively used as the adhesive layer for leather, textile, synthetic leather, and shoe materials. The HM-T10 hot melt adhesive particles (as shown in Table 1) employed in this study were transparent and colorless particles of size 2 mm. The first step was to heat it, with a electromagnetic heater, to 86 °C (in between its softening and melting points) until the surface of hot melt adhesive particles looked viscous and semi-molten. Then steel grit of size 125 μm was added into hot melt adhesive particles, heated, and churned until hot melt adhesive particles surface was fully coated with steel grits. Cool the mixture for 15 min and MHMA particles were ready for use. Figure 2 showed the structure of MHMA particles.

2.2 Properties of the magneto-assisted spiral polishing

As the slurry was of good fluidity, the high-speed rotating screw could drive MHMA particles toward the surface of the workpiece. The steel grit coated on MHMA particles would be attracted by the external magnet, pushing the SiC particles to press and squeeze the workpiece surface for the purpose of fine polishing. Abrasive passing through the inner wall of the bore would be blocked when they reached the top of the mold. It was then pushed aside the screw rod. When the abrasive accumulated to a great amount, it flew down to the bottom of the mold because of the gravity and of the weakening of the upward force exerted by the rod. The repeated recycles were thus formed, as shown in Fig. 3a.

Table 1 Physical property of hot melt adhesive particle

Properties	Description
Viscosity (cP)	6,108
Melt index (g/10 min)	17.4
Softening point (°C)	66
Melting point (°C)	96

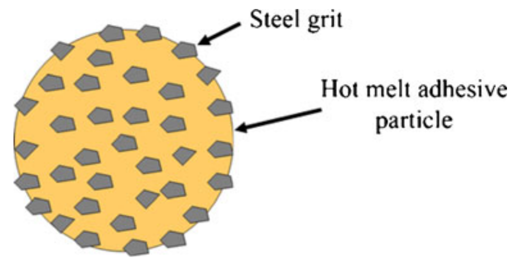

Fig. 2 Structure of MHMA particles

As illustrated in Fig. 3b, SiC particles in the flowing slurry pushed upward along the groove of the rod would polish the asperities on the workpiece. Meanwhile, the polishing effects were enhanced by MHMA particles, being attracted by the ring magnet, and creating stronger pushing and squeezing forces in driving the SiC particles for better material polishing effects.

The self-developed MHMA particles in the slurry in the present study served two functions, as presented in Fig. 4. One was to give an additional squeezing force. MHMA particles coated with steel grit provided an additional squeezing force when exerted by the external magnet, and drove the SiC particles toward the inner wall of the bore for polishing. The other was to serve as a cushion. Elasticity of MHMA particles could soften the impacts brought about by SiC particles when polishing the wall of the bore and shorten the polishing time.

2.3 Slurry

The slurry was the key to spiral polishing quality. The slurry used in this study was a mixture of SiC particles, MHMA particles, and silicone oil in specific portions for the best lubrication and fine machining (as shown in Table 2). The ragged shaped and hard SiC particles promoted the polishing effects, and were taken as suitable materials for fine polishing.

2.4 Experimental apparatus

The apparatus was designed based on the concept of spiral polishing. With a mold set on a CNC machining tool, a rotation rod was motivated by the processing machinery to achieve the purpose of magneto-assisted spiral polishing.

The mold featured a hollow container to empower the abrasive to be used in repetitive cycles and a screw rod connected to a CNC or conventional machining tool (Fig. 5). After placing the workpiece and MHMA particles inside the mold, the rod turned to drive and recycle the abrasive for polishing the workpiece spirally. Such a design not only reduced the required space but also saved the

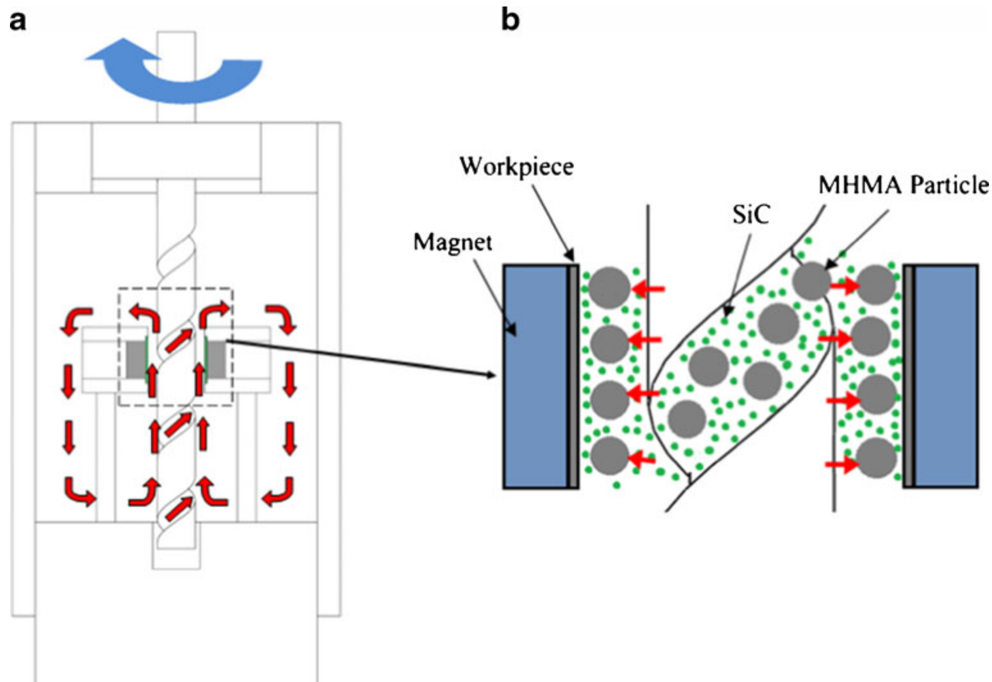

Fig. 3 **a**, **b** Flowing path of abrasive within the mold

consumption of abrasive as it was applied in the mold for continuous and repetitive polishing operation.

The workpiece was a stainless steel tube of 13 mm OD, 9.8 mm ID, and 10 mm in height. Initial surface roughness (Ra) of the inner wall of the bore was 0.90 μm.

2.5 Experiment design

Since Taguchi methods were widely employed on polishing [13–16], and surface roughness was taken as the quality attribute in this experiment. Therefore, Taguchi methods were used to determine the sequence of the orthogonal array adopted by the experiment. The analysis of variance (ANOVA) technique was used to find out the effect significance of various parameters on surface roughness. The responding effects out of the optimum parameter combinations were compared with the estimated values. The verified optimum parameter combinations were then used to explore the relations between the key machining variables and the improvement of the surface.

Experiment parameter combinations designed with Taguchi methods not only reduced the times in conducting the experiment and reducing the costs of the experiment to the least but also facilitated exploring the relative importance among the variables. This study selected six controlled machining variables with each pair of them assigned with respective level values (Table 2). Fixed variables set in this experiment were given in Table 3.

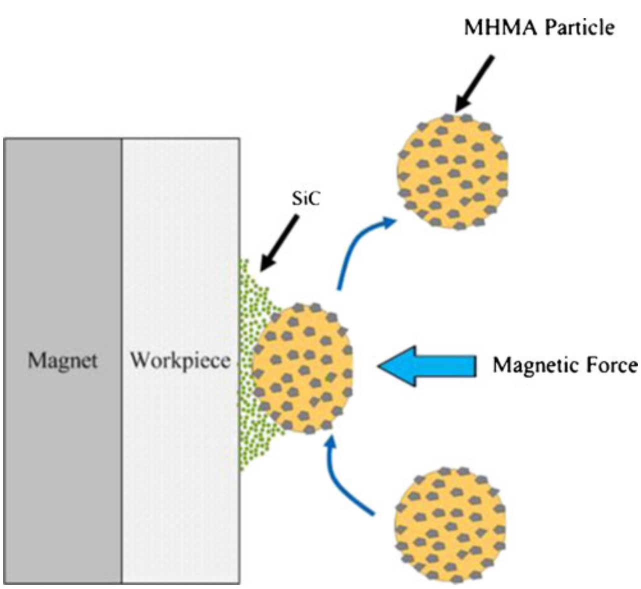

Fig. 4 Polishing mechanism of MHMA particles

Table 2 Ingredients of the slurry

Ingredients	Level 1	Level 2	Level 3
SiC particle (% wt)	44	50	55
MHMA particle (% wt)	33	38	41

Silicone oil, 100 g

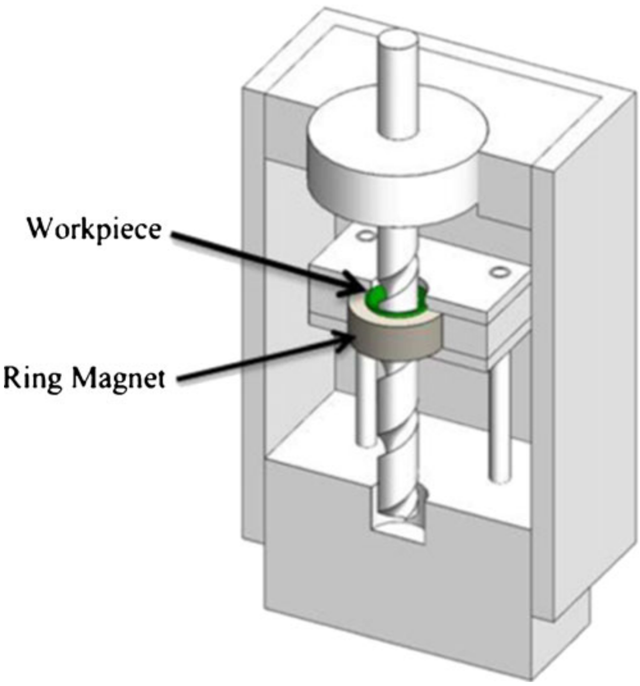

Fig. 5 Illustration of the apparatus

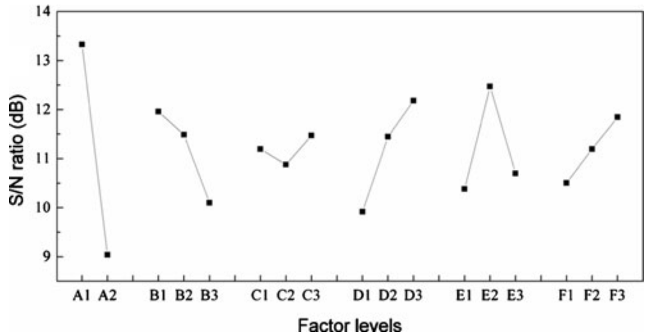

Fig. 6 Signal-to-noise ratios response graph of surface roughness

3 Results and discussion

3.1 Parameter combination for the least surface roughness

This experiment referred to surface roughness as the-smaller-the-better characteristics of machining quality so as to reduce the processing time and improve the surface roughness. The effect strength of parameter variables varied (Fig. 6), indicating that the stronger the variable effect was, the more the variable was related to the surface quality. The best combination of parameter variable levels was the one where each parameter variable had the highest level value. In the present study, the parameter variable level combination was A1B1C3D3E2F3. That was: magnetic flux density of 90 mT, SiC particle size of 22 μm, and SiC particles of 55 % wt, MHMA particle of 41 % wt, silicone oil viscosity of 2,000 mm^2/s, and spindle revolution speed at 4,000 rpm.

The analysis of variance is a crucial analysis method for conventional experiments. It estimates the impacts of experimental variables on quality characteristics by statistical tests. The ANOVA is used to estimate the prominent level of each experiment variable and their interactions on the quality characteristics. The derived optimum values are then used as selecting criteria for estimating the responding effects for the best parameter combination.

When surface roughness became the object value, as demonstrated by the *F*-tests, the effect of magnetic flux density ranked especially significant (*A*), followed by MHMA particle concentration (*D*; Table 4). The relative contribution of each variable was ranked:

Magnetic flux density > MHMA particle concentration > silicone oil viscosity > SiC particle size > spindle revolution speed > SiC particle concentration.

As magnetic flux density and MHMA particle concentration contributed the most to surface quality, increase of the two improved the surface roughness significantly.

To testify the results of the experiment, the parameter combinations were obtained with the aid of Taguchi DOE. From Tables 5 and 6, we could find that the results of this experiment showed little difference from the predictive values. The parameter combination A1B1C3D3E2F3, derived from the present experiment and analysis, was of high credibility in improving the surface roughness. Figure 7 illustrated the SEM photograph of the workpiece surfaces before and after polishing.

Table 3 Controlled variables and level values in the experiment

Parameters	Level 1	Level 2	Level 3
A: magnetic flux density (mT)	90	80	–
B: SiC particle size (μm)	22	12	6.7
C: SiC particle concentration (% wt)	44 %	50 %	55 %
D: MHMA particle concentration (% wt)	33 %	38 %	41 %
E: silicone oil viscosity (mm^2/s)	1,000	2,000	3,000
F: spindle revolution speed (rpm)	3,000	3,500	4,000

Silicone oil, 100 g

Table 4 Fixed variables in the experiment

Fixed variables	Description
Silicone oil weight (g)	100
Workpiece material	SUS304 stainless steel
Magnet	Nd-Fe-B magnets
Machining gap (mm)	0.9
Machining time (min)	30

Table 5 ANOVA and F-test analysis

Factors	DOF	Sum of squares	Mean square	F value	$F_{0.05}$	Contribution (%)
A	1	82.7466	82.7466	91.4848[a]	5.9874	59.5790
B	2	11.1877	5.5938	6.1846[b]	5.1433	8.0553
C	2	1.0724	0.5362	0.5928	5.1433	0.7721
D	2	16.0009	8.0004	8.8453[b]	5.1433	11.5209
E	2	15.2186	7.6093	8.4128[b]	5.1433	10.9576
F	2	5.4235	2.7118	2.9981	5.1433	3.9050
Error	6	7.2359	1.2060			5.2100
Total	17	138.886				100

[a] Very significant factors

[b] Significant factors

3.2 Analysis of the machining parameters

As indicated by the importance ranking of the Taguchi variables, magnetic flux density, MHMA particles concentration, and silicone oil viscosity were the top three important variables. Effects of these three, along with the width of machining gap, on spiral polishing quality were analyzed below.

3.2.1 Effects of magnetic flux density on surface roughness

The newly developed MHMA particles were the main point of this experiment. Figure 8 presented the results that the surface roughness, when compared with conventional spiral polishing without the appliance of magneto-assistance, improved from 64.42 to 84.56 %. The magnetic force was proved to significantly improve the surface roughness in the spiral polishing.

The effects of different magnetic flux density were illustrated in Fig. 9. When magneto-assisted spiral polishing was carried out with magnet flux density controlled at 80 mT, the polishing result looked poor and many irregular potholes were clearly seen, as the magnetic force was too weak to drive MHMA particles to press and squeeze the workpiece. When magnetic flux density was increased to 90 mT, deep potholes on the surface vanished and the surface roughness was rather improved. However, when magnetic flux density was raised to 120 mT, the stronger magnetic force, on the contrary, left deeper scratches on the workpiece surface (Fig. 10). When magnetic flux density boosted to 170 mT, much deeper irregular scratches were found on the workpiece surface. The surface quality was further deteriorated in that MHMA particles squeezed and pressed the workpiece surface with too much pressure due to too strong magnetic force.

For material removal, the least material removal was seen when magnetic flux density was controlled at 80 mT. Poor polishing effects showed that the magnetic force was too weak to effectively drive MHMA particles for workpiece surface polishing. Raising the flux density to 90 mT, according to the results of the experiment, could significantly increase the removal amount but reduced when the density was above 90 mT. The reason was that strong magnetic force gathered too many MHMA particles instead of SiC particles in the slurry to polish the workpiece.

Table 6 Results of the confirmation experiments

Surface roughness, Ra (μm)	
Calculation	Experiment
0.1357	0.1393

3.2.2 Effects of MHMA particle concentration on surface roughness

Effects of different MHMA particle concentrations: 33, 35, 38, 39, 41, and 44 % wt, on surface roughness were shown in Fig. 11. As the concentration of MHMA particles increased, the surface roughness improved, with a peak at 70 g. It suggested that, with the increase of MHMA particles in the slurry, the surface polishing effects got better as there were more chances for MHMA particles to squeeze and press the workpiece surface. However, too many MHMA particles, when attracted by the ring magnet, would cause the abrasive to flow slowly and press each other with the pushing force brought by the high-speed rotating screw, leaving scratches on the workpiece surface and influenced the workpiece surface quality.

The material removal apparently increased when MHMA particle concentration increased from 33 to 41 % grams. When MHMA particles in the slurry increased, the surface polishing effects became better as MHMA particles got more chances to squeeze and press the workpiece surface. Nevertheless, when there were too many MHMA particles but less SiC particles on the workpiece surface ,the MHMA particles would easily be attracted by the magnet, and poorer machining effect could be obtained.

3.2.3 Effects of silicone oil viscosity on surface roughness

Effects of different silicone oil viscosity, 1,000, 2,000, 3,000, and 5,000 mm^2/s, on surface roughness are shown in Fig. 12. Viscosity of 2,000 mm^2/s brought about the best polishing results. Slurry made of silicone oil at 1,000 mm^2/s viscosity improved the workpiece surface less effectively because the low viscosity of the slurry would create higher fluidity and less friction forces between the workpiece surface and the abrasive. However, slurry made of 3,000 and 5,000 mm^2/s silicone oils resulted in worse surface quality than expected.

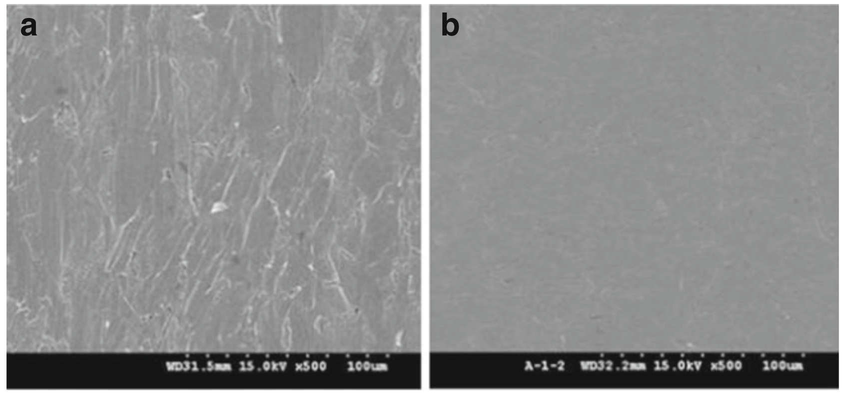

Fig. 7 SEM photograph of the workpiece surface **a** before polishing (Ra=0.9 μm), **b** after polishing (Ra=0.1393 μm)

In case like this, the slurry was hard to be driven by the screw rod for its high viscosity and low fluidity. In addition, if the slurry became more viscous, the SiC particles polish the workpiece surface less on account of thicker lubrication and protection layer on the slurry. Meanwhile, it was more difficult for SiC particles to break through the Silicone oil layer, and less ideal polishing effects were created.

With regard to material removal, the experiment indicated that the slurry made of silicone oil at 1,000 mm^2/s viscosity removed less amount of material as less friction forces were generated between the workpiece surface and the abrasive because the fluidity became higher when the silicone oil was less viscous. Slurry made of 3,000 and 5,000 mm^2/s silicone oils viscosity also led to worse machining effects in that the slurry was hard to be driven by the screw rod with its high viscosity and low fluidity; besides, SiC particles were of fewer chances to break through the silicone oil layer to polish the workpiece surface. The reason was that their natural viscous quality would make them to adhere to the workpiece surface, forming a layer of silicone oil. The higher the viscosity was, the thicker the layer was. Meanwhile, the chance for the SiC particles to polish the workpiece lowered, and poorer machining effect was obtained.

3.2.4 Effects of machining gap on surface roughness

This study reduced the machining gap by enlarging the diameter of the screw rod. For the bore of inner diameter of 9.8 mm, two rods, of diameter 8 and 8.6 mm, were used and generated a machining gap of 0.9 and 0.6 mm, respectively. As shown in Fig. 13, better machining effects, with surface roughness reduced down to 0.094 μm at an improvement rate of 89.56 %, could be achieved when machining gap was maintained at 0.6 mm. This might be explained by the fact that when machining gap was smaller, the abrasive could be driven by the screw rod to the workpiece surface more steadily and effectively when higher centrifugal force was created. This, in turn, led to greater polishing force and better surface quality. When the machining gap was larger, the abrasive polished the workpiece surface less effectively and contributed to weaker polishing force and poorer surface quality. In addition, larger gap also caused uneven and

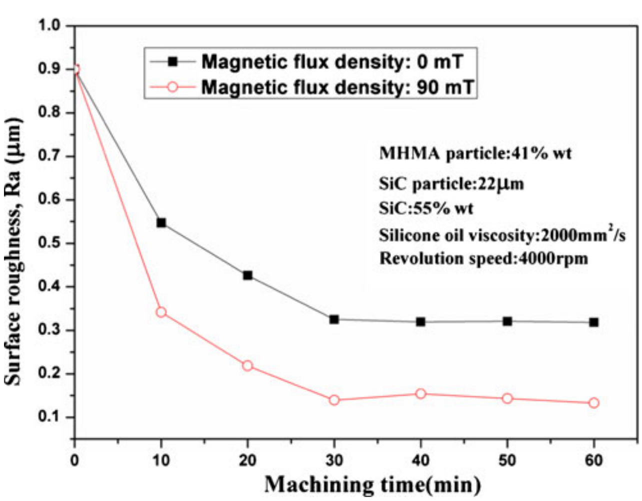

Fig. 8 Effects of magnetic flux density on surface roughness

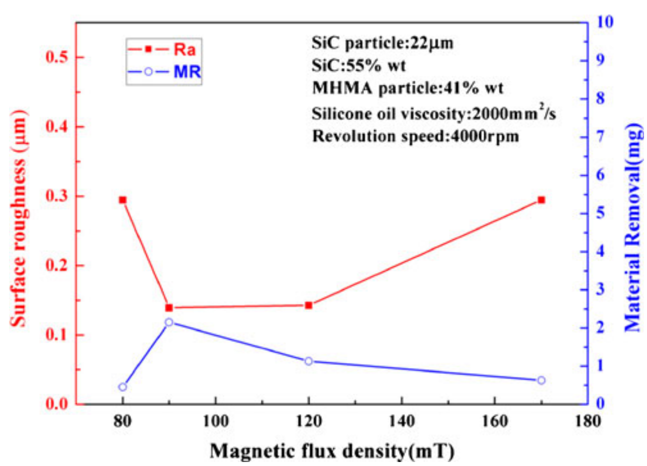

Fig. 9 Effects of magnetic flux density on surface roughness and material removal

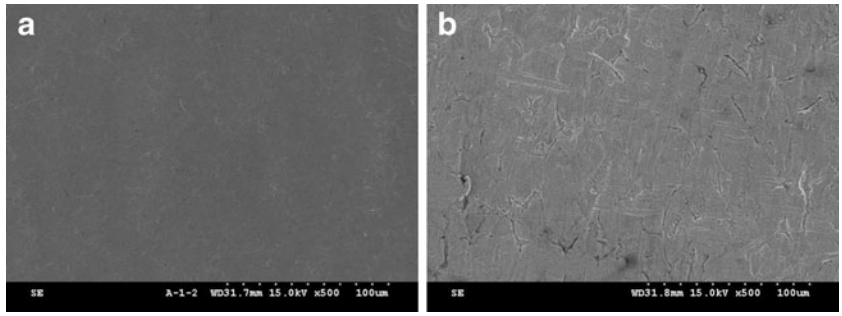

Fig. 10 Workpiece surfaces of varied magnetic flux density **a** 90 mT, **b** 120 mT

unstable flow of the slurry. 3D photos of the workpiece surfaces, before and after polishing, were shown in Fig. 14 respectively. It was clear that after 30 min of machining, the workpiece surface became very smooth, which suggested that the effects of magneto-assisted spiral polishing on surface roughness were evident.

3.3 Effects of slurry viscosity on surface roughness

The slurry viscosity was of prominent influence on the slurry fluidity in the mold and the friction between the abrasive and the workpiece surface. Slurry of higher viscosity would increase the friction between the abrasive and the workpiece surface and remove the asperities. Nevertheless, too much friction lessened the fluidity of the slurry and caused poor polishing quality. That was, though less viscous slurry generated less friction between the abrasive and the workpiece surface, making it difficult to remove the surface asperities, higher slurry fluidity helped achieve finer polishing effects for an ideal surface.

The viscosity of the slurry was measured by a viscometer by putting a probe at the center of the slurry.

3.3.1 Effects of SiC particle size on slurry viscosity

Effects of SiC particle size on slurry viscosity were demonstrated in Fig. 15. According to the results of the experiment, when the size of SiC particles was smaller, more SiC particles could be used to polish compared with larger size of SiC particles with the same concentration. Therefore, when the silicone oil viscosity and the SiC particle concentration were controlled, we tried to compare the concentration of the slurry with different sizes of SiC particles. We found that the concentration, though the same, the viscosity differed. The slurry containing smaller SiC particles had higher viscosity but lower fluidity. However, slurry composed of larger SiC particles would have lower viscosity

3.3.2 Effects of SiC particle concentration on slurry viscosity

Figure 16 showed the effects of SiC particle concentration on slurry viscosity. The results of the experiment suggested that when silicone oil concentration, silicone oil viscosity, and SiC particle size were controlled, slurry that contained heavier SiC particles would be of higher concentration and with more SiC particles. The fact helped the removal of asperities

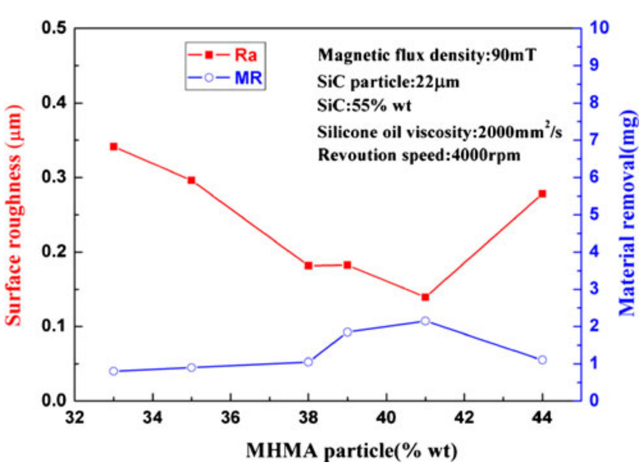

Fig. 11 Effects of MHMA particles concentration on surface roughness and material removal

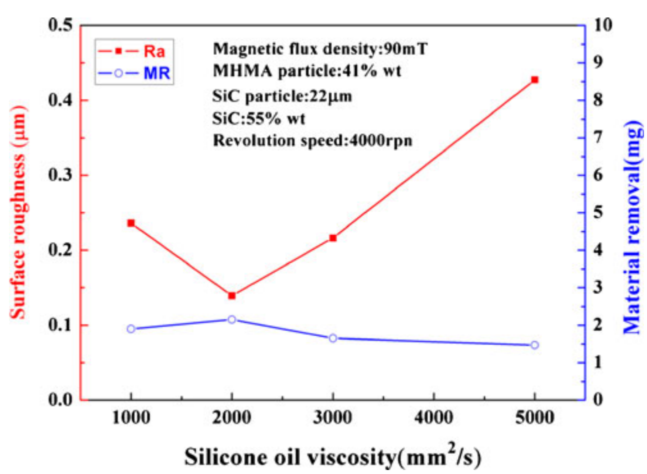

Fig. 12 Effects of silicon oil viscosity on surface roughness and material removal

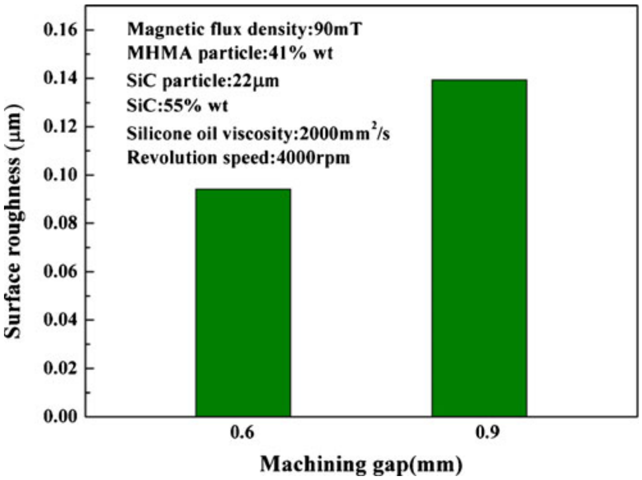

Fig. 13 Effects of machining gap on surface roughness

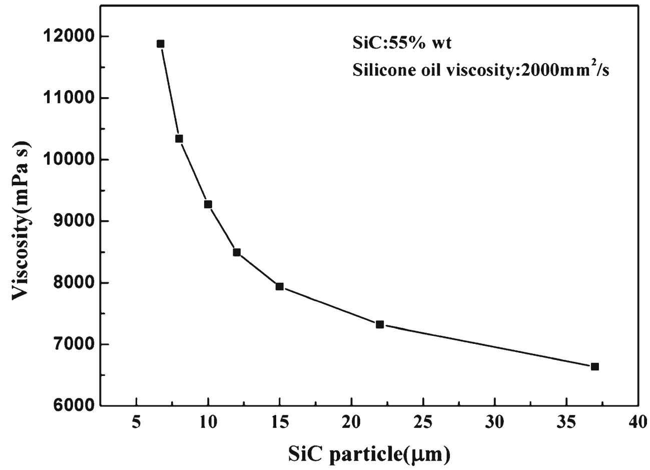

Fig. 15 Effects of SiC particle size on slurry viscosity

on the workpiece surface. However, too many SiC particles might also increase the slurry viscosity but decrease the fluidity, which brought about poorer polishing quality.

3.3.3 Effects of polishing time on slurry viscosity

Effects of polishing time on slurry viscosity, with other machining variables remaining intact, were shown in

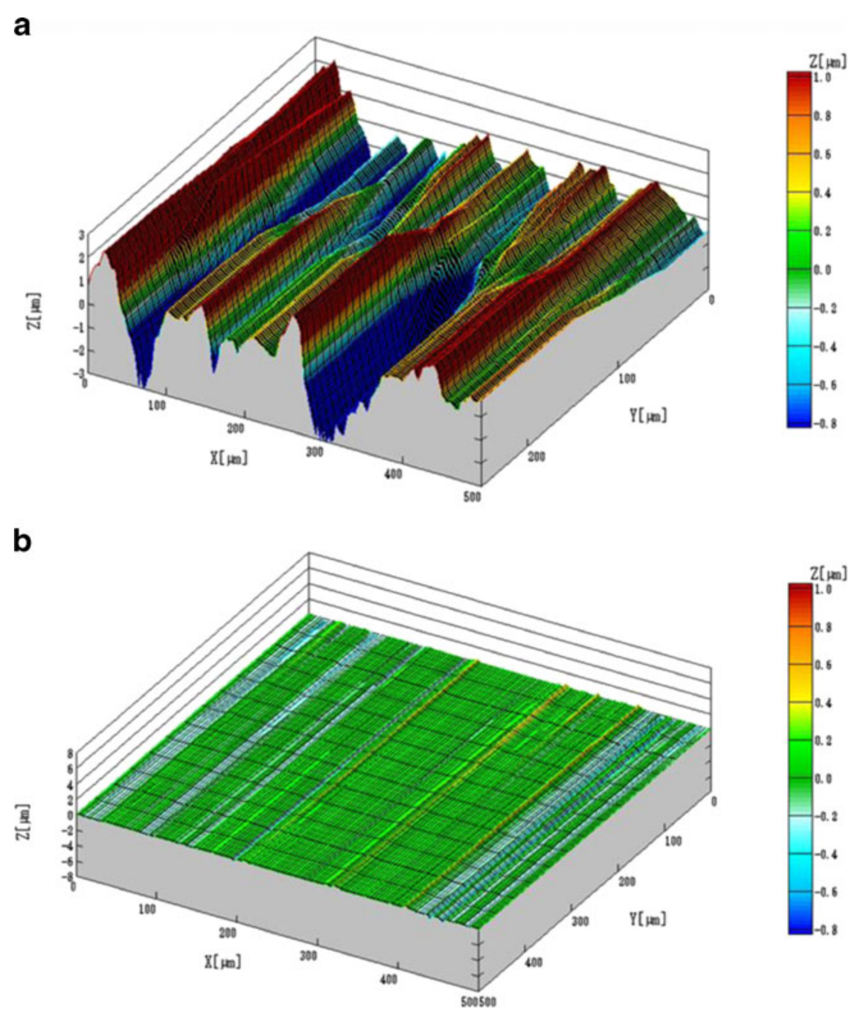

Fig. 14 3D photographs of the workpiece surfaces. **a** Before polishing, **b** after polishing (at a gap of 0.6 mm)

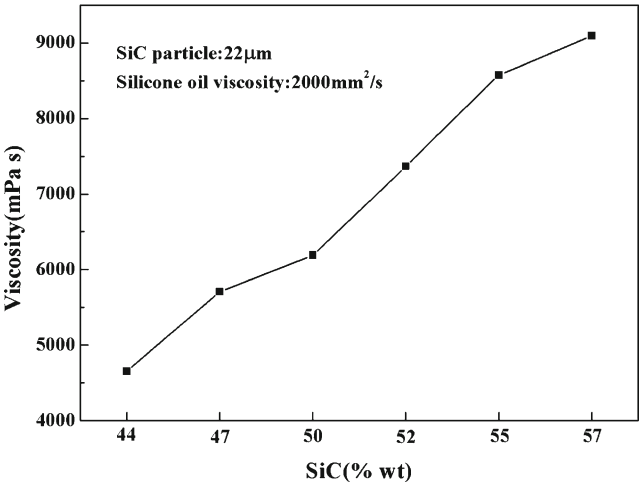

Fig. 16 Effects of SiC particle concentration on slurry viscosity

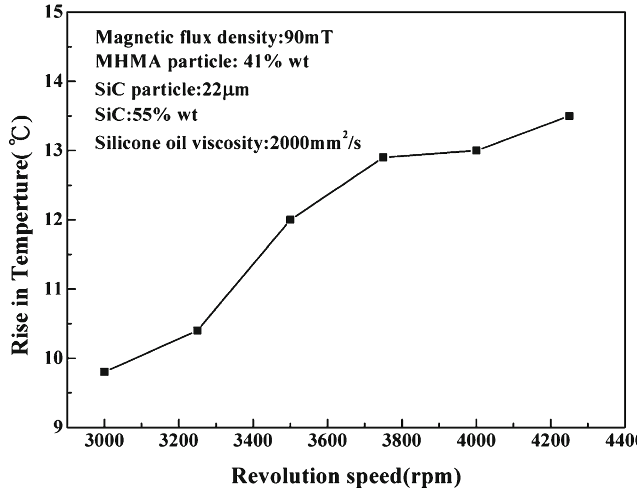

Fig. 18 Effects of spindle revolution speed on slurry temperature

Fig. 17. The slurry viscosity got lower with the progress of polishing time. The rapid temperature rise was testified to be able to lower down the viscosity, but at the same time, to add up the fluidity. At the initial stage, the workpiece surface was quite rough. Greater viscosity, with increased friction between the abrasive and the workpiece surface, was helpful in removing the higher asperities from the workpiece surface. Nevertheless, higher slurry fluidity at the later stage could help conduct fine polishing on the workpiece surface, achieving better polishing results.

3.4 Relations between polishing parameters and slurry temperature

Based on machining parameters employed in this experiment, the spindle revolution speed contributed the most to the rise of the temperature. The temperatural changes of the slurry was measured by a thermocouple fixed at the center of the slurry.

In accordance with the results of the experiment, the greatest changes of the slurry temperature was as high as 14 °C. Therefore it was safe to conclude that the mold designed featured a good cooling effect. Influences on the stainless steel workpiece could be reduced to a minimum if the temperature was controlled within an ideal variation range. With magneto-assisted spiral polishing, this also ensured the stability of the abrasive so as to reach the desired polishing effects.

3.4.1 Effects of spindle revolution speed on slurry temperature

See Fig. 18 for effects of spindle revolution speed on slurry temperature. The faster the spindle turned, the higher the slurry temperature rose. This was because that when the spindle turned faster, the slurry flew faster in that the driving forces got stronger. This increased the frictions between the abrasive and the workpiece surface and, in turn, the slurry temperature rose as a result of the heat generated from the friction.

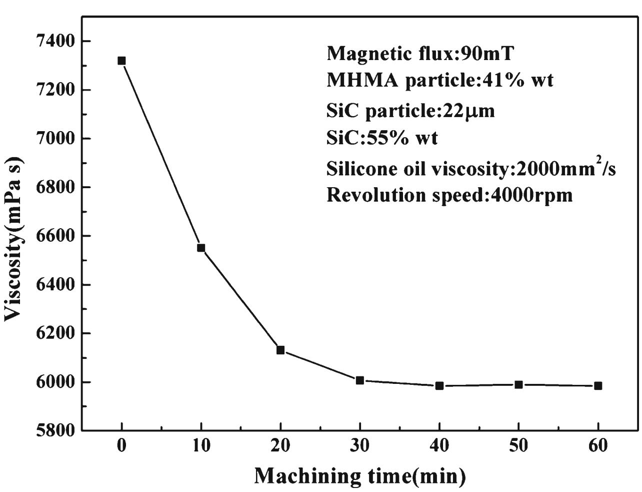

Fig. 17 Effects of polishing time on slurry viscosity

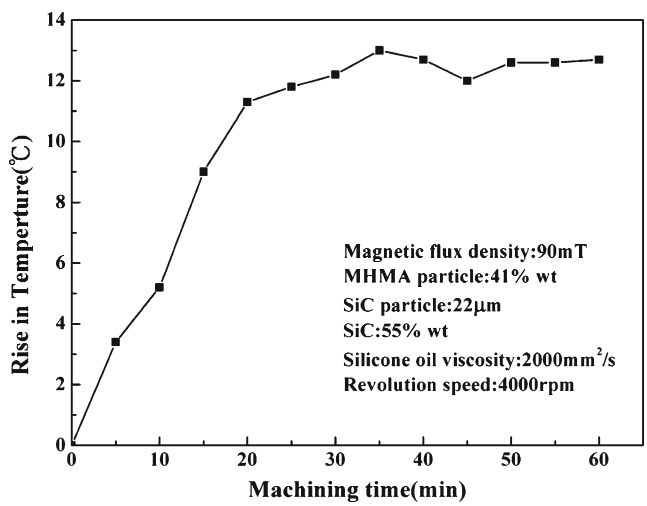

Fig. 19 Effects of machining time on slurry temperature

3.4.2 Effects of machining time on slurry temperature

The slurry temperature rose with the lengthening of the polishing time, as shown in Fig. 19. After 30 min of machining, the abrasive temperature became stable. At the initial stage of polishing, the slurry was of high viscosity and the workpiece surface was rather rough. More heat was generated as both the frictions among the abrasive particles and between the abrasive and the workpiece surface were greater. As the polishing proceeded, the abrasive flew more easily as the slurry got less viscous and the workpiece surface got smoother, both of which stabilized the polishing temperature.

4 Conclusions

According to the results obtained, the following conclusions can be made.

1. The addition of magnetic force greatly improved the surface roughness as indicated by the ANOVA and F-test.
2. This experiment added a ring magnet around the workpiece to polish the inner wall of the bore. The results of the experiment indicated that the surface roughness was improved from 0.9 to 0.094 μm. The improvement rate was up to 90 %.
3. Magnetic flux density of 90 mT was proved to result in better surface polishing quality. When magnetic flux density was higher than 90 m, the workpiece surface might be scratched and poorer polishing quality was obtained.
4. In the initial stage of polishing, the high viscosity of the abrasive was helpful for removing the asperities on the rough workpiece surface. At the later stage, a finer polishing could be carried out as the abrasive was of lower viscosity but of higher fluidity.
5. According to the result of the experiment, the rise of the slurry temperature was measured under 14 °C in the whole polishing period; therefore, we inferred that it would cause little deformation of the stainless steel workpiece.

References

1. Zhang ZY, Meng YW, Guo DM, Wu LL, Tian YJ, Liu RP (2010) Material removal mechanism of precision grinding of soft-brittle CdZnTe wafers. Int J Adv Manuf Technol 46:563–569
2. Zhong ZW, Tian YB, Ang YJ, Wu H (2012) Optimization of the chemical mechanical polishing process for optical silicon substrates. Int J Adv Manuf Technol 60:1197–1206
3. Walia RS, Shan HS, Kumar P (2006) Abrasive flow machining with additional centrifugal force applied to the media. Mach Sci Technol 10:341–354
4. Sankar MR, Mondal S, Ramkumar J, Jain VK (2008) Experimental investigations and modeling of drill bit-guided abrasive flow finishing (DBG-AFF) process. Int J Adv Manuf Technol 42:678–688
5. Kar KK, Ravikumar NL, Tailon PB, Ramkumar J, Sathiyamoorthy D (2009) Performance evaluation and rheological characterization of newly developed butyl rubber based media for abrasive flow machining process. J Mater Process Tech 209:2212–2221
6. Hanada K, Yamaguchi H, Zhou H (2008) New spherical magnetic abrasives with carried diamond particles for internal finishing of capillary tubes. Diam Relat Mater 17:1434–1437
7. Sankar MR, Jain VK, Ramkumar J (2010) Rotational abrasive flow finishing (R-AFF) process and its effects on finished surface topography. Int J Mach Tool Manuf 50:637–650
8. Sankar MR, Jain VK, Ramkumar J (2009) Experimental investigations into rotating workpiece abrasive flow finishing. Wear 267:43–51
9. Jha S, Jain VK (2004) Design and development of the magnetorheological abrasive flow finishing (MRAFF) process. Int J Mach Tool Manuf 44:1019–1029
10. Singh S, Shan HS (2002) Development of magneto abrasive flow machining process. Int J Mach Tool Manuf 42:953–959
11. Wani AM, Yadava V, Khatri A (2007) Simulation for the prediction of surface roughness in magnetic abrasive flow finishing (MAFF). J Mater Process Tech 190:282–290
12. Yang B, Tzeng H, Huang F, Lin Y, Chow H (2007) Finishing effects of spiral polishing method on micro lapping surface. Int J Mach Tool Manuf 47:920–926
13. Liao HT, Shie JR, Yang YK (2008) Applications of Taguchi and design of experiments methods in optimization of chemical mechanical polishing process parameters. Int J Adv Manuf Technol 38:674–682
14. Yang LD, Lin CT, Chow HM (2009) Optimization in MAF operations using Taguchi parameter design for AISI304 stainless steel. Int J Adv Manuf Technol 42:595–605
15. Mali HS, Manna A (2012) Simulation of surface generated during abrasive flow finishing of Al/SiCp-MMC using neural networks. Int J Adv Manuf Technol 61:1263–1268
16. Prabhu S, Vinayagam B (2012) AFM investigation in grinding process with nanofluids using Taguchi analysis. Int J Adv Manuf Technol 60:149–160