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Automated surface finishing of plastic injection mold steel with spherical grinding and ball burnishing processes

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Abstract This study investigates the possibilities of automated spherical grinding and ball burnishing surface finishing processes in a freeform surface plastic injection mold steel PDS5 on a CNC machining center. The design and manufacture of a grinding tool holder has been accomplished in this study. The optimal surface grinding parameters were determined using Taguchi's orthogonal array method for plastic injection molding steel PDS5 on a machining center. The optimal surface grinding parameters for the plastic injection mold steel PDS5 were the combination of an abrasive material of PA Al₂O₃, a grinding speed of 18 000 rpm, a grinding depth of 20 μm, and a feed of 50 mm/min. The surface roughness R_a of the specimen can be improved from about 1.60 μm to 0.35 μm by using the optimal parameters for surface grinding. Surface roughness R_a can be further improved from about 0.343 μm to 0.06 μm by using the ball burnishing process with the optimal burnishing parameters. Applying the optimal surface grinding and burnishing parameters sequentially to a fine-milled freeform surface mold insert, the surface roughness R_a of freeform surface region on the tested part can be improved from about 2.15 μm to 0.07 μm.

Keywords Automated surface finishing · Ball burnishing process · Grinding process · Surface roughness · Taguchi's method

1 Introduction

Plastics are important engineering materials due to their specific characteristics, such as corrosion resistance, resistance to chemicals, low density, and ease of manufacture, and have increasingly

replaced metallic components in industrial applications. Injection molding is one of the important forming processes for plastic products. The surface finish quality of the plastic injection mold is an essential requirement due to its direct effects on the appearance of the plastic product. Finishing processes such as grinding, polishing and lapping are commonly used to improve the surface finish.

The mounted grinding tools (wheels) have been widely used in conventional mold and die finishing industries. The geometric model of mounted grinding tools for automated surface finishing processes was introduced in [1]. A finishing process model of spherical grinding tools for automated surface finishing systems was developed in [2]. Grinding speed, depth of cut, feed rate, and wheel properties such as abrasive material and abrasive grain size, are the dominant parameters for the spherical grinding process, as shown in Fig. 1. The optimal spherical grinding parameters for the injection mold steel have not yet been investigated based in the literature.

In recent years, some research has been carried out in determining the optimal parameters of the ball burnishing process (Fig. 2). For instance, it has been found that plastic deformation on the workpiece surface can be reduced by using a tungsten carbide ball or a roller, thus improving the surface roughness, surface hardness, and fatigue resistance [3–6]. The burnishing process is accomplished by machining centers [3, 4] and lathes [5, 6]. The main burnishing parameters having significant effects on the surface roughness are ball or roller material, burnishing force, feed rate, burnishing speed, lubrication, and number of burnishing passes, among others [3]. The optimal surface burnishing parameters for the plastic injection mold steel PDS5 were a combination of grease lubricant, the tungsten carbide ball, a burnishing speed of 200 mm/min, a burnishing force of 300 N, and a feed of 40 μm [7]. The depth of penetration of the burnished surface using the optimal ball burnishing parameters was about 2.5 microns. The improvement of the surface roughness through burnishing process generally ranged between 40% and 90% [3–7].

The aim of this study was to develop spherical grinding and ball burnishing surface finish processes of a freeform surface

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plastic injection mold on a machining center. The flowchart of automated surface finish using spherical grinding and ball burnishing processes is shown in Fig. 3. We began by designing and manufacturing the spherical grinding tool and its alignment device for use on a machining center. The optimal surface spherical grinding parameters were determined by utilizing a Taguchi's orthogonal array method. Four factors and three corresponding levels were then chosen for the Taguchi's L_{18} matrix experiment. The optimal mounted spherical grinding parameters for surface grinding were then applied to the surface finish of a freeform surface carrier. To improve the surface roughness, the ground surface was further burnished, using the optimal ball burnishing parameters.

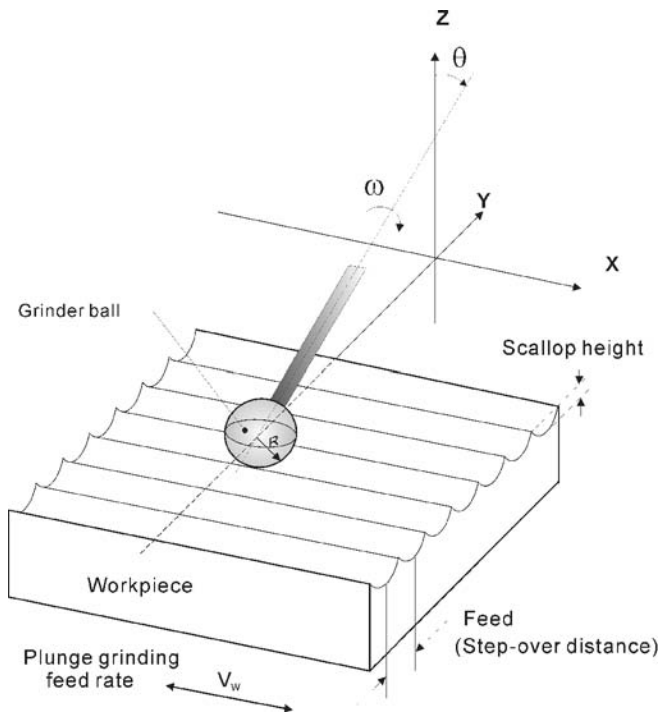


Fig. 1. Schematic diagram of the spherical grinding process

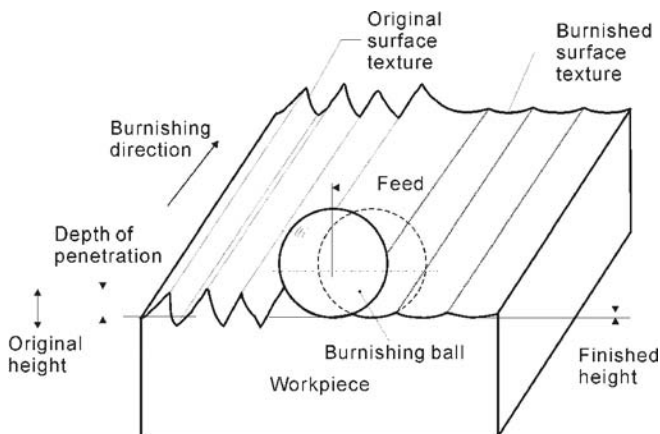


Fig. 2. Schematic diagram of the ball-burnishing process

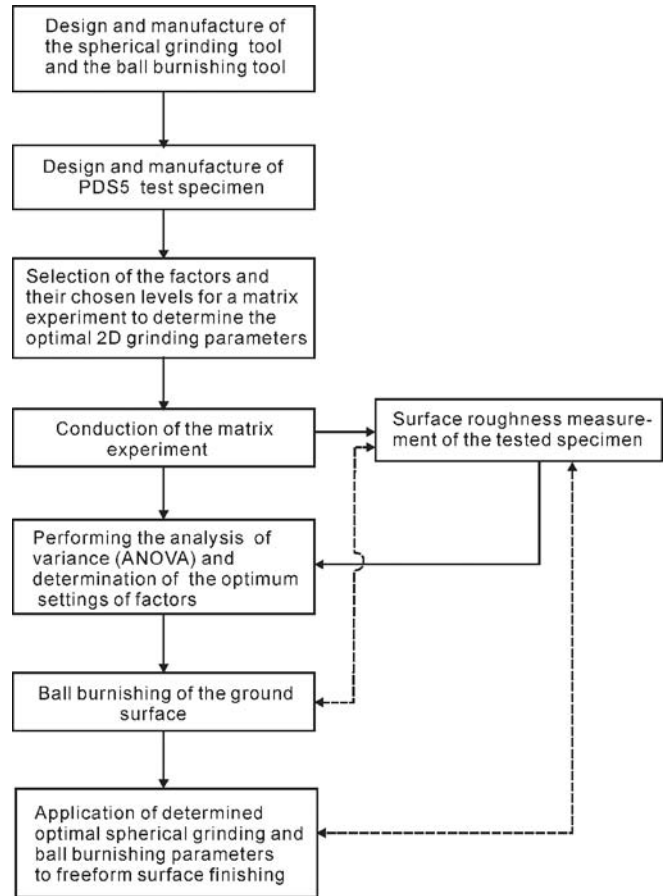


Fig. 3. Flowchart of automated surface finish using spherical grinding and ball burnishing processes

2 Design of the spherical grinding tool and its alignment device

To carry out the possible spherical grinding process of a freeform surface, the center of the ball grinder should coincide with the z-axis of the machining center. The mounted spherical grinding tool and its adjustment device was designed, as shown in Fig. 4. The electric grinder was mounted in a tool holder with two adjustable pivot screws. The center of the grinder ball was well aligned with the help of the conic groove of the alignment components. Having aligned the grinder ball, two adjustable pivot screws were tightened; after which, the alignment components could be removed. The deviation between the center coordinates of the ball grinder and that of the shank was about $5\ \mu\text{m}$, which was measured by a CNC coordinate measuring machine. The force induced by the vibration of the machine bed is absorbed by a helical spring. The manufactured spherical grinding tool and ball-burnishing tool were mounted, as shown in Fig. 5. The spindle was locked for both the spherical grinding process and the ball burnishing process by a spindle-locking mechanism.

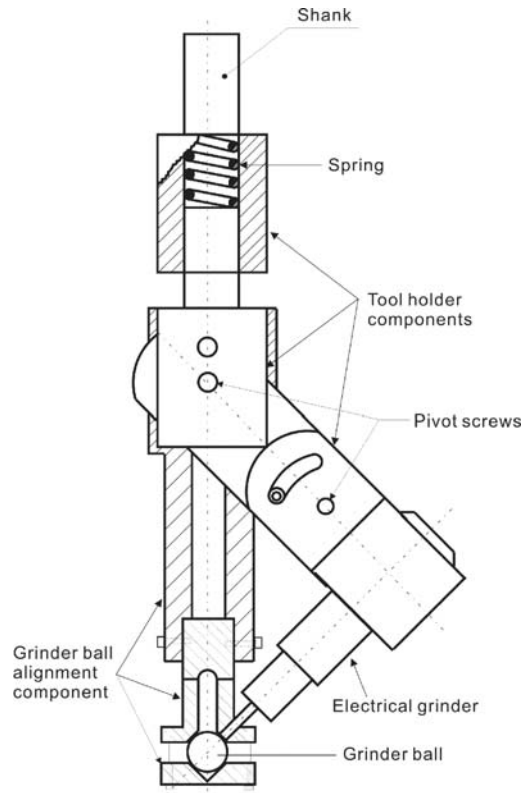


Fig. 4. Schematic illustration of the spherical grinding tool and its adjustment device

3 Planning of the matrix experiment

3.1 Configuration of Taguchi's orthogonal array

The effects of several parameters can be determined efficiently by conducting matrix experiments using Taguchi's orthogonal array [8]. To match the aforementioned spherical grinding parameters, the abrasive material of the grinder ball (with the diameter of 10 mm), the feed rate, the depth of grinding, and the revolution of the electric grinder were selected as the four experimental factors (parameters) and designated as factor A to D (see Table 1) in this research. Three levels (settings) for each factor were configured to cover the range of interest, and were identi-

Table 1. The experimental factors and their levels

Factor	1	Level 2	3
A. Abrasive material	SiC	Al ₂ O ₃ , WA	Al ₂ O ₃ , PA
B. Feed (mm/min)	50	100	200
C. Depth of grinding (μm)	20	50	80
D. Revolution (rpm)	12000	18000	24000

fied by the digits 1, 2, and 3. Three types of abrasive materials, namely silicon carbide (SiC), white aluminum oxide (Al₂O₃, WA), and pink aluminum oxide (Al₂O₃, PA), were selected and studied. Three numerical values of each factor were determined based on the pre-study results. The L₁₈ orthogonal array was selected to conduct the matrix experiment for four 3-level factors of the spherical grinding process.

3.2 Definition of the data analysis

Engineering design problems can be divided into smaller-the-better types, nominal-the-best types, larger-the-better types, signed-target types, among others [8]. The signal-to-noise (S/N) ratio is used as the objective function for optimizing a product or process design. The surface roughness value of the ground surface via an adequate combination of grinding parameters should be smaller than that of the original surface. Consequently, the spherical grinding process is an example of a smaller-the-better type problem. The S/N ratio, η , is defined by the following equation [8]:

$$\eta = -10 \log_{10}(\text{mean square quality characteristic})$$

$$= -10 \log_{10} \left[\frac{1}{n} \sum_{i=1}^n y_i^2 \right]. \quad (1)$$

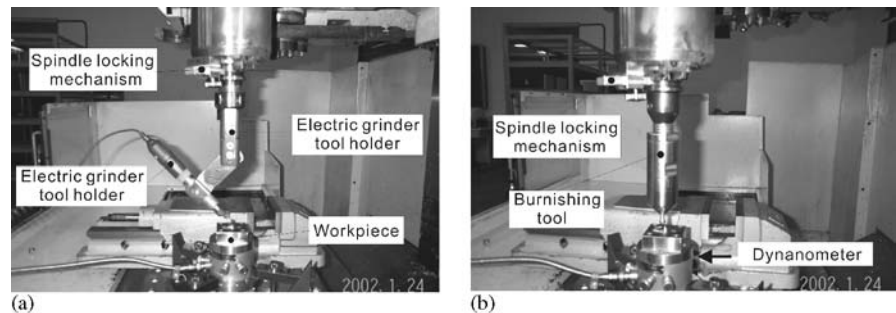
where:

y_i : observations of the quality characteristic under different noise conditions

n : number of experiment

After the S/N ratio from the experimental data of each L₁₈ orthogonal array is calculated, the main effect of each factor was determined by using an analysis of variance (ANOVA) technique and an F-ratio test [8]. The optimization strategy of the

Fig. 5. a Photo of the spherical grinding tool **b** Photo of the ball burnishing tool



smaller-the-better problem is to maximize η , as defined by Eq. 1. Levels that maximize η will be selected for the factors that have a significant effect on η . The optimal conditions for spherical grinding can then be determined.

4 Experimental work and results

The material used in this study was PDS5 tool steel (equivalent to AISI P20) [9], which is commonly used for the molds of large plastic injection products in the field of automobile components and domestic appliances. The hardness of this material is about HRC33 (HS46) [9]. One specific advantage of this material is that after machining, the mold can be directly used for further finishing processes without heat treatment due to its special pre-treatment. The specimens were designed and manufactured so that they could be mounted on a dynamometer to measure the reaction force. The PDS5 specimen was roughly machined and then mounted on the dynamometer to carry out the fine milling on a three-axis machining center made by Yang-Iron Company (type MV-3A), equipped with a FUNUC Company NC-controller (type 0M) [10]. The pre-machined surface roughness was measured, using Hommelwerke T4000 equipment, to be about $1.6\mu\text{m}$. Figure 6 shows the experimental set-up of the spherical grinding process. A MP10 touch-trigger probe made by the Renishaw Company was also integrated with the machining center tool magazine to measure and determine the coordinated origin of the specimen to be ground. The NC codes needed for the ball-burnishing path were generated by PowerMILL CAM software. These codes can be transmitted to the CNC controller of the machining center via RS232 serial interface.

Table 2 summarizes the measured ground surface roughness value R_a and the calculated S/N ratio of each L_{18} orthogonal array using Eq. 1, after having executed the 18 matrix experiments. The average S/N ratio for each level of the four factors can be obtained, as listed in Table 3, by taking the numerical values provided in Table 2. The average S/N ratio for each level of the four factors is shown graphically in Fig. 7.

Table 2. Ground surface roughness of PDS5 specimen

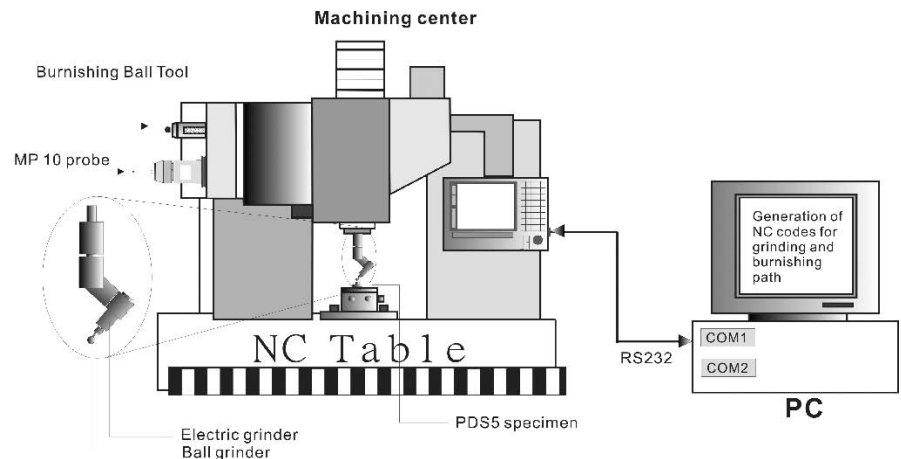
Exp. no.	Inner array (control factors)				Measured surface roughness value (R_a)			Response	
	A	B	C	D	y_1 (μm)	y_2 (μm)	y_3 (μm)	S/N ratio η (dB)	Mean \bar{y} (μm)
1	1	1	1	1	0.35	0.35	0.35	9.119	0.350
2	1	2	2	2	0.37	0.36	0.38	8.634	0.370
3	1	3	3	3	0.41	0.44	0.40	7.597	0.417
4	2	1	2	3	0.63	0.65	0.64	3.876	0.640
5	2	2	3	1	0.73	0.77	0.78	2.380	0.760
6	2	3	1	2	0.45	0.42	0.39	7.520	0.420
7	3	1	3	2	0.34	0.31	0.32	9.801	0.323
8	3	2	1	3	0.27	0.25	0.28	11.471	0.267
9	3	3	2	1	0.32	0.32	0.32	9.897	0.320
10	1	1	2	2	0.35	0.39	0.40	8.390	0.380
11	1	2	3	3	0.41	0.50	0.43	6.968	0.447
12	1	3	1	1	0.40	0.39	0.42	7.883	0.403
13	2	1	1	3	0.33	0.34	0.31	9.712	0.327
14	2	2	2	1	0.48	0.50	0.47	6.312	0.483
15	2	3	3	2	0.57	0.61	0.53	4.868	0.570
16	3	1	3	1	0.59	0.55	0.54	5.030	0.560
17	3	2	1	2	0.36	0.36	0.35	8.954	0.357
18	3	3	2	3	0.57	0.53	0.53	5.293	0.543

Table 3. Average S/N ratios by factor levels (dB)

Factor	A	B	C	D
Level 1	8.099	7.655	9.110	6.770
Level 2	5.778	7.453	7.067	8.028
Level 3	8.408	7.176	6.107	7.486
Effect	2.630	0.479	3.003	1.258
Rank	2	4	1	3
Mean			7.428	

The goal in the spherical grinding process is to minimize the surface roughness value of the ground specimen by determining the optimal level of each factor. Since $-\log$ is a monotone decreasing function, we should maximize the S/N ratio. Consequently, we can determine the optimal level for each factor as being the level that has the highest value of η . Therefore, based

Fig. 6. Experimental set-up to determine the optimal spherical grinding parameters



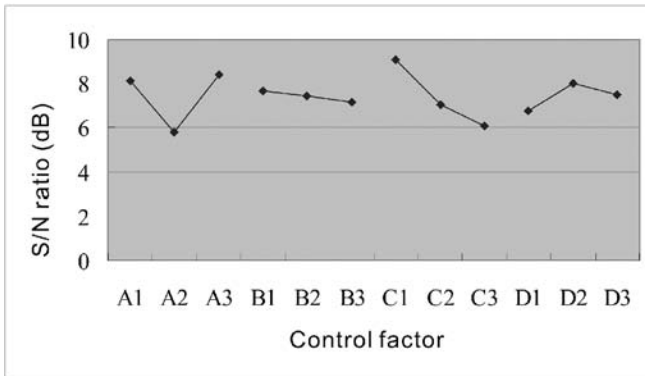


Fig. 7. Plots of control factor effects

on the matrix experiment, the optimal abrasive material was pink aluminum oxide; the optimal feed was 50 mm/min; the optimal depth of grinding was 20 μm ; and the optimal revolution was 18000 rpm, as shown in Table 4.

The main effect of each factor was further determined by using an analysis of variance (ANOVA) technique and an F ratio test in order to determine their significance (see Table 5). The $F_{0.10,2,13}$ is 2.76 for a level of significance equal to 0.10 (or 90% confidence level); the factor's degree of freedom is 2 and the degree of freedom for the pooled error is 13, according to F-distribution table [11]. An F ratio value greater than 2.76 can be concluded as having a significant effect on surface roughness and is identified by an asterisk. As a result, the feed and the depth of grinding have a significant effect on surface roughness.

Five verification experiments were carried out to observe the repeatability of using the optimal combination of grinding parameters, as shown in Table 6. The obtainable surface roughness value R_a of such specimen was measured to be about 0.35 μm . Surface roughness was improved by about 78% in using the op-

Table 4. Optimal combination of spherical grinding parameters

Factor	Level
Abrasive	Al_2O_3 , PA
Feed	50 mm/min
Depth of grinding	20 μm
Revolution	18000 rpm

Table 5. ANOVA table for S/N ratio of surface roughness

Factor	Degrees of freedom	Sum of squares	Mean squares	F ratio
A	2	24.791	12.396	3.620*
B	2	0.692	0.346	
C	2	28.218	14.109	4.121*
D	2	4.776	2.388	
Error	9	39.043		
Total	17	97.520		
Pooled to error	13	44.511	3.424	

* F ratio value > 2.76 has significant effect on surface roughness

Table 6. Surface roughness value of the tested specimen after verification experiment

Exp. no.	Measured value R_a (μm)			Mean \bar{y} (μm)	S/N ratio
	y_1	y_2	y_3		
1	0.30	0.31	0.33	0.313	10.073
2	0.36	0.37	0.36	0.363	8.802
3	0.36	0.37	0.37	0.367	8.714
4	0.35	0.37	0.34	0.353	9.031
5	0.33	0.36	0.35	0.347	9.163
Mean			0.349		9.163

timal combination of spherical grinding parameters. The ground surface was further burnished using the optimal ball burnishing parameters. A surface roughness value of $R_a = 0.06 \mu\text{m}$ was obtainable after ball burnishing. Improvement of the burnished surface roughness observed with a 30 \times optical microscope is shown in Fig. 8. The improvement of pre-machined surfaces roughness was about 95% after the burnishing process.

The optimal parameters for surface spherical grinding obtained from the Taguchi's matrix experiments were applied to the surface finish of the freeform surface mold insert to evaluate the surface roughness improvement. A perfume bottle was selected as the tested carrier. The CNC machining of the mold insert for the tested object was simulated with PowerMILL CAM software. After fine milling, the mold insert was further ground with the optimal spherical grinding parameters obtained from the Taguchi's matrix experiment. Shortly afterwards, the ground surface was burnished with the optimal ball burnishing parameters to further improve the surface roughness of the tested object (see Fig. 9). The surface roughness of the mold insert was measured with Hommelwerke T4000 equipment. The average surface roughness value R_a on a fine-milled surface of the mold insert was 2.15 μm on average; that on the ground surface was 0.45 μm

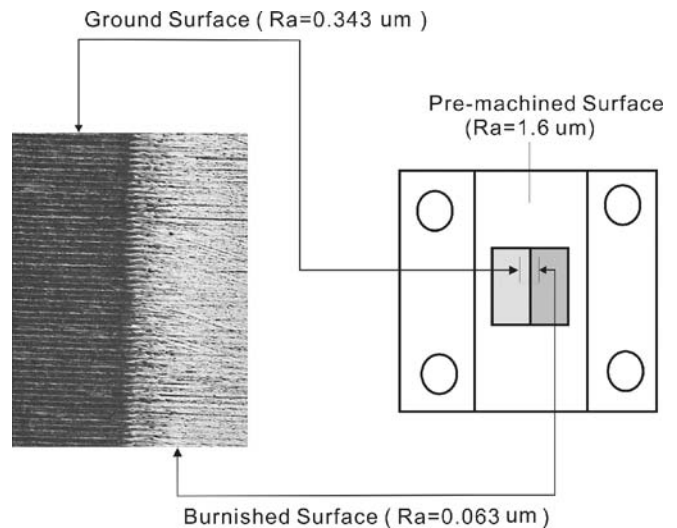


Fig. 8. Comparison between the pre-machined surface, ground surface and the burnished surface of the tested specimen observed with a toolmaker microscope (30 \times)

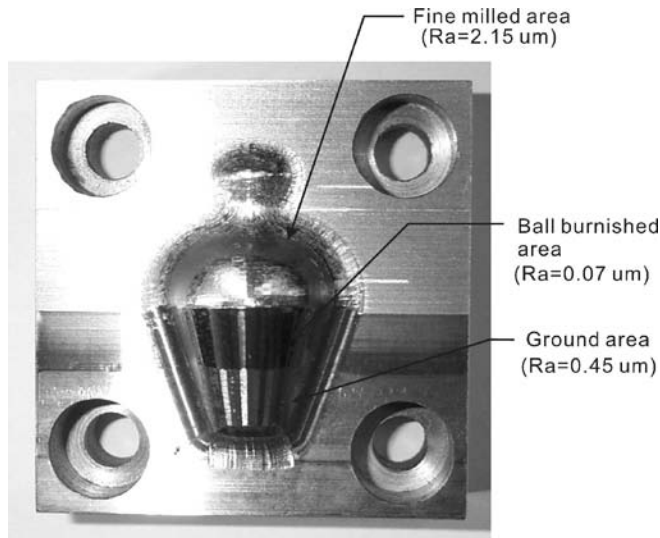


Fig. 9. Fine-milled, ground and burnished mold insert of a perfume bottle

on average; and that on burnished surface was $0.07 \mu\text{m}$ on average. The surface roughness improvement of the tested object on ground surface was about $(2.15 - 0.45)/2.15 = 79.1\%$, and that on the burnished surface was about $(2.15 - 0.07)/2.15 = 96.7\%$.

5 Conclusion

In this work, the optimal parameters of automated spherical grinding and ball-burnishing surface finishing processes in a freeform surface plastic injection mold were developed successfully on a machining center. The mounted spherical grinding tool (and its alignment components) was designed and manufactured. The optimal spherical grinding parameters for surface grinding were determined by conducting a Taguchi L_{18} matrix experiments. The optimal spherical grinding parameters for the plastic injection mold steel PDS5 were the combination of the abrasive material of pink aluminum oxide (Al_2O_3 , PA), a feed of 50 mm/min , a depth of grinding $20 \mu\text{m}$, and a revolution of

18000 rpm . The surface roughness R_a of the specimen can be improved from about $1.6 \mu\text{m}$ to $0.35 \mu\text{m}$ by using the optimal spherical grinding conditions for surface grinding. By applying the optimal surface grinding and burnishing parameters to the surface finish of the freeform surface mold insert, the surface roughness improvements were measured to be ground surface was about 79.1% in terms of ground surfaces, and about 96.7% in terms of burnished surfaces.

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