Abrasive Jet Polishing on Bulk Metallic Glass

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Abstract - This study investigates the optimal abrasive jet polishing parameters for bulk metallic glass (BMG) material by using the Taguchi method. An abrasive jet polishing (AJP) system is newly designed and mounted on a machining center. In order to determine the optimal polishing parameters for the BMG sample, six polishing parameters, namely the hydraulic pressure, the impact angle, the standoff distance, the abrasive material, the abrasive concentration and the polishing time are chosen as the control factors of experiments. The optimal AJP parameters are determined after carrying out the experiments based on the Taguchi's L_{18} orthogonal array experimental results. These optimal parameters are the combination of the hydraulic pressure of 2 kg/cm^2, the impact angle of 30^o, the standoff distance of 15 mm, the abrasive material of SiC, the abrasive concentration of 1:5 and the polishing time of 60 minutes. The surface roughness is improved from an initial value of R_a = 0.675μm to a final value of R_a =0.016μm by using the AJP optimal parameters.

Key words: Abrasive jet polishing, Bulk metallic glass, Taguchi method, orthogonal array.

I. INTRODUCTION

The development of new bulk metallic glass (BMG) from 1980s has opened the door for many applications in engineering materials [2]. In recent years, the new type of BMG with the excellent mechanical properties including its superior strength, hardness, corrosion and wear resistance, was developed. A number of studies investigated on the difference aspects of BMG such as the glass-forming ability, physical properties. BMG has strange properties. It has the randomly arranged atoms and the most other metals have the crystalline structure. Trexler and Thadhani (2010) [3] reviewed the mechanical properties of BMG material. Other properties of the BMG, such as the glass-forming ability, physical properties, mechanical behavior, magnetic properties, were introduced by Suryanarayana and Inoue (2011) [1] and Miller and Liaw (2008) [2]. However, there were no researches considered the relation between the polishing conditions and the surface quality after polishing of the BMG material. Consequently, this study aims to investigate the deeper knowledge about the polishing ability of the BMG materials.

Polishing has been commonly used to improve the surface quality of machine parts and components in the final step of machining. AJP is a method of polishing using a flow of abrasive combined with air, water, or water with oil or polymer addictive [4]. The AJP process was applied to machining the material such as alumina ceramic and stainless steel by F. Li (1996) [5]. The effects of AJP process parameters on the surface quality were examined. It demonstrated that the particles size and the jet impact angle was the significant variable in the polishing process. In 2003, Booji [6] inspected possibilities and limitations of the fluid jet polishing technique in BK7 optical glass material. The influence of the polishing process parameters such as particle type and size, particle velocity, nozzle type and impact angle on the removal rate and final surface roughness was examined.

The abrasive jet polishing technique has a lower abrasive consumption and recycled abrasive particles. In this study, the surface quality of the BMG materials after the processing of grinding and abrasive jet polishing is investigated. The optimal surface polishing parameter for the BMG are determined, after having executed the Taguchi's L_{18} experiments, analysis of variance (ANOVA) and confirmed experiments on a machine center. The AJP process is used to polishing BMG specimen using SiC particles with grit sizes of #2000 and Al_2O_3 particles with grit sizes of #4000 with a compound additive of water and machining oil.

II. EXPERIMENTAL WORK AND RESULTS

A. Material of the Test Specimens

Bulk metallic glass is used in this study. The BMG specimen has the size of width x length 30 mm x 35 mm and the thickness of 2.5 mm. The specimen is shown in Fig. 1. Table I introduces the mechanical properties and the chemical formula of the BMG specimen. Since the size of BMG workpiece is quite small, a fixture is designed and fabricated to clamp this sample. The surface to be polishing is divided into nine zones, so that the average polishing surface roughness value is calculated from that of the nine zones. The surface roughness of the test specimens is measured by the Taylor Hobson Form Talysurf PGI 1240 instrument. The grinded surface of the BMG specimen has the surface roughness of R_a = 0.675μm.

B. Experimental Setup

The experimental setup of the AJP process is shown in Fig. 2. The BMG specimen is mounted on the fixture. This fixture is clamped on a container. The polishing force is measured with a load cell system. The tank is used to contain slurry during the AJP process. The slurry including an additive (water and hydraulic oil) and abrasive particles is stirred in the tank to keep homogeneous concentration.

TABLE I
THE CHEMICAL AND MECHANICAL PROPERTIES OF
BMG WORKPIECE [7]

Properties	Value
Chemical composition	$(Zr_{53}Cu_{30}Ni_{9}Al_{8})_{99}Si_{1}$
Class	Zr-based BMG
Yield strength	1750 MPa
Hardness	580 HV (54 HRC)

The hydraulic oil is added in the mixture in order to decrease the depth of penetration of the abrasives into the workpiece surface [8]. Moreover, the hydraulic oil also gives ability to reduce the amount of the bubbles appearing during the AJP process.

Pump is used to carry out the slurry. The mixed slurry is pumped through the hose to the nozzle. The polishing experiments of the grinded specimens are carried out on the three axis machining center with the NC-controller of FANUC Co. The NC code is simulated and generated by Pro-ENGINEERING software. These codes are transmitted to the CNC controller of the machining center via RS322 serial interface.

C. Experimental Method

The effect of polishing parameters could be determined by conducting matrix experiments using Taguchi's orthogonal array [9]. Parameters for the AJP processes, having significant effects on surface roughness, are investigated by Taguchi's method. The L_{18} orthogonal array is selected to perform the matrix experiments in order to determine the optimal polishing process parameters. The fixed AJP parameters and Taguchi control factors are summarized in Table II and III, respectively. As show Table III, the six control factors are assigned three different level settings. The size of each AJP trial is the width x length 3 mm x 5mm.

Engineering design for problem can be divided into the-smaller-the-better type, nominal-the best type, the larger-the-better-type, etc. [10]. The signal-to-noise (S/N) ratio is used as objective function for optimizing process design. The surface roughness value of polished surface should be smaller than that of the original surface. Consequently, the polishing process is an example of the-smaller-the-better type problem. The S/N ratio, η, is defined by the following equation [10]:

$$\eta = -10\log_{10}\left[\frac{1}{n}\sum_{i=1}^{n} y_i^2\right] \tag{1}$$

where n is the number of test in a trial and y_i represent observations of the quality characteristics under different noise conditions.

The optimization strategy of the-smaller-the-better problem was to maximize η defined by Eq. (1). Levels that maximize η would be selected for the factors that had a significant effect on η. The optimal conditions for polishing

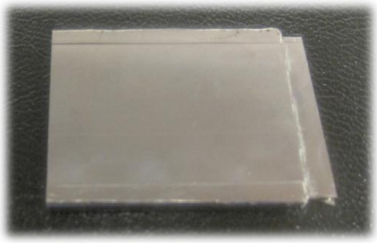


Fig. 1 The BMG specimen.

TABLE II
FIXED FACTORS IN TAGUCHI DESIGN EXPERIMENTS

Fixed factors	Value
Aperture of nozzle (material: Aluminum)	1.5 mm
ANSI mesh of abrasive particles	#2000 SiC (diameter: 6.7μm) #4000 Al_20_3 (diameter: 2.7μm)
Additives	Water and machining oil
Workpiece	BMG
Stirring velocity	100 rpm
Revolution of the workpiece	0 rpm

TABLE III
THE CONTROL FACTORS AND THEIR LEVELS IN
AJP EXPERIMENTS

Control factors	Level		
	1	2	3
A. Abrasive material	SiC	Al_2O_3	-
B. Abrasive concentration (Abrasive : water)	1:5	1:8	1:10
C. Impact angle (^{o})	30	40	50
D. Standoff distance (mm)	5	10	15
E. Pressure (kg/cm^2)	2	3	4
F. Polishing time (min)	30	60	90

could be determined.

D. Experimental Results

Table IV summarizes the measured polished surface roughness value R_a and calculated S/N ratio of each L_{18} orthogonal array using Eq. (1). The average S/N ratio for each level of the six factors is shown in Fig. 3.

E. Combination of the Optimal Level for Each Factor and Confirmation Test

Based on the S/N ratio value, we can determine the optimal level for each factor as being the level that has the highest value of η. According to the plots of the control factor effects in Fig. 3, the combination of the optimal level for each factor is A_1 B_1 C_1 D_3 E_1 F_2. As the results, the optimal parameters for abrasive jet polishing are as follows: abrasive material of SiC particles with diameter of 6.7 μm, the abrasive concentration of 1:5, the impact angle of 30^0, the standoff distance of 15 mm, the pressure of 2 kg/cm^2, the

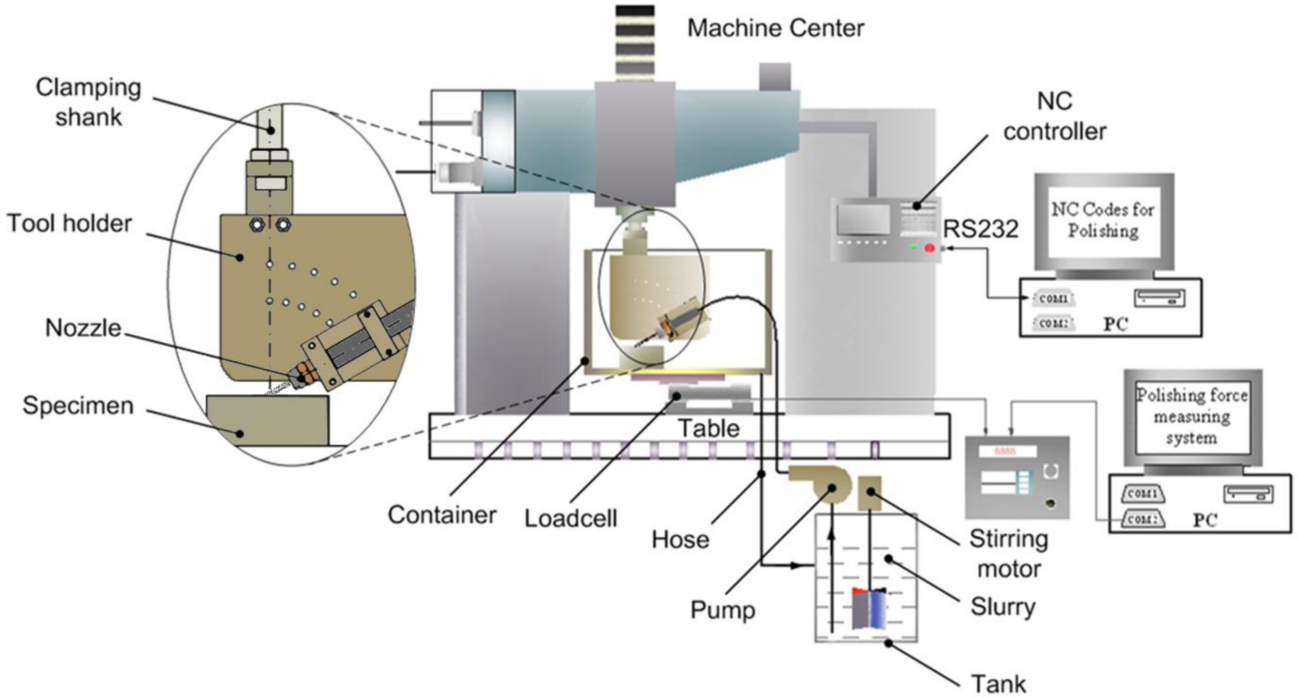


Fig. 2 Experimental setup to determine the optimal polishing parameters.

TABLE IV
EXPERIMENTAL RESULTS OF THE POLISHED SURFACE ROUGHNESS OF BMG SPECIMENS

Experiment. no.	Control factor						Measured R_a value (μm)			S/N ratio	Mean
	A	B	C	D	E	F	1	2	3		
1	1	1	1	1	1	1	0.047	0.024	0.036	28.644	0.036
2	1	1	2	2	2	2	0.030	0.032	0.029	30.290	0.031
3	1	1	3	3	3	3	0.059	0.037	0.045	26.414	0.047
4	1	2	1	1	2	2	0.047	0.037	0.047	27.200	0.043
5	1	2	2	2	3	3	0.157	0.126	0.158	16.615	0.147
6	1	2	3	3	1	1	0.016	0.019	0.017	35.405	0.017
7	1	3	1	2	1	3	0.068	0.065	0.073	23.269	0.069
8	1	3	2	3	2	1	0.065	0.079	0.082	22.403	0.075
9	1	3	3	1	3	2	0.043	0.035	0.059	26.579	0.046
10	2	1	1	3	3	2	0.025	0.026	0.020	32.468	0.024
11	2	1	2	1	1	3	0.117	0.134	0.128	17.974	0.126
12	2	1	3	2	2	1	0.051	0.074	0.081	23.130	0.069
13	2	2	1	2	3	1	0.066	0.099	0.073	21.892	0.079
14	2	2	2	3	1	2	0.049	0.064	0.058	24.845	0.057
15	2	2	3	1	2	3	0.090	0.096	0.142	19.058	0.109
16	2	3	1	3	2	3	0.037	0.055	0.073	24.859	0.055
17	2	3	2	1	3	1	0.051	0.076	0.083	22.953	0.070
18	2	3	3	2	1	2	0.101	0.112	0.098	19.675	0.104

polishing time of 60 min, as shown in Table V. Three verification experiments are performed by using the optimal parameters. The mean surface roughness value on polished surface is R_a = 0.016μm, as shown in Fig. 4. The surface roughness improvement of polished surface is about 97%.

F. Analysis of Variance (ANOVA)

The main effect of AJP parameters on the polished surface roughness is determined by using ANOVA technique and F ratio test.

The factor's degree of freedom is 2 and the degree of freedom for the pooled error is 8. According to the *F*-distribution table, the value of $F_{0.1,\ 2,\ 8}$ is 3.11 (or 90% confidence level) [10]. The *F* ratio value that is greater than

3.11 can be concluded as having a significant effect on surface roughness. Table VI shows that the polishing time, the abrasive material and the standoff distance have the most significant effect on the surface roughness in the AJP process.

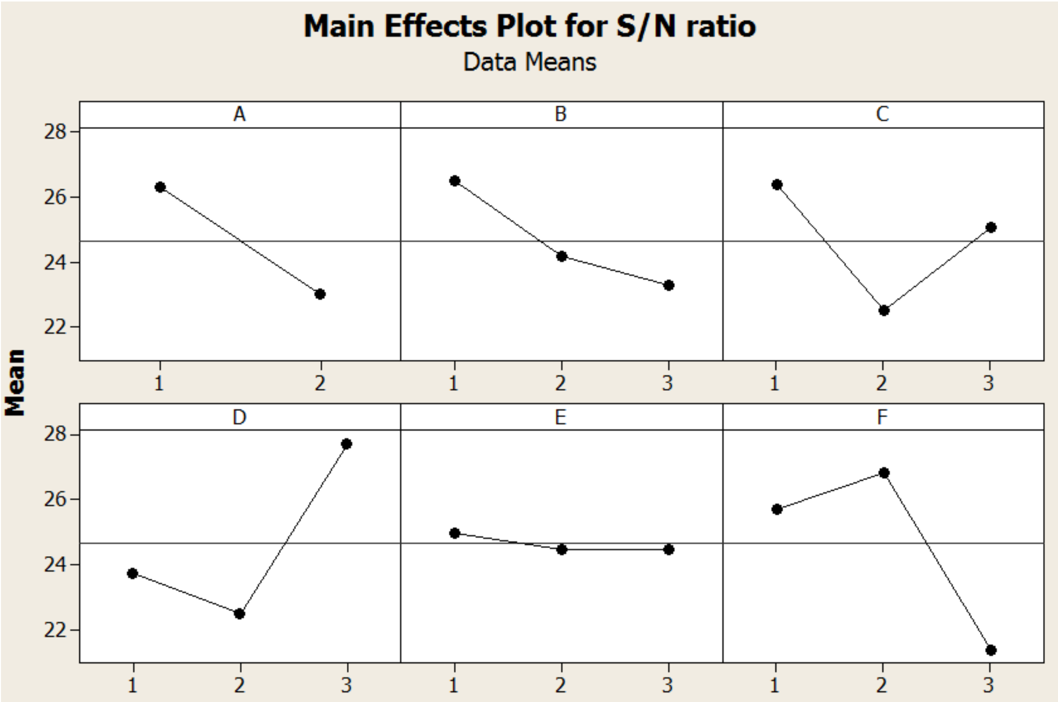


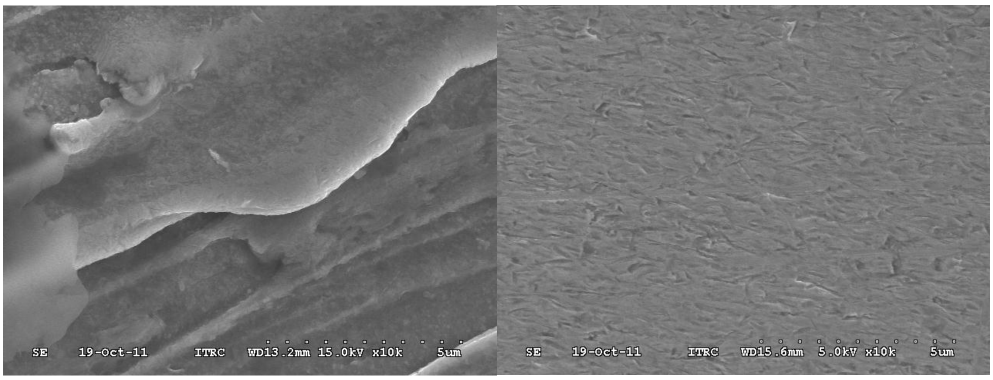
Fig. 3 The plots of the control factor effects.

TABLE V
OPTIMAL COMBINATION OF AJP PARAMETERS

Factor	Value
A. Abrasive material	SiC
B. Abrasive concentration	1:5
C. Impact angle (^{o})	30
D. Standoff distance (mm)	15
E. Pressure (kg/cm^2)	2
F. Polishing time (min)	60

TABLE VI
ANOVA TABLE FOR S/N RATIO OF POLISHED SURFACE ROUGHNESS

Factor	d.f.	S.S.	M.S.	F value	$F_{0.1,2,8}$
A	1	49.88	49.88	3.88	3.11
B	2	32.73	16.37	1.27	3.11
C	2	46.45	23.23	1.81	3.11
D	2	90.33	45.17	3.52	3.11
E	2	0.92	-	-	3.11
F	2	100.71	50.36	3.92	3.11
Error	6	101.85			
Total	17	422.87			
Pooled to error	8	102.77	12.84		



(a) (b)

Fig. 4 SEM images of: (a) grinded surface (b) polishing surface after using optimal AJP parameters.

III. CONCLUSION

This study conducted a series of experiments to establish the optimal parameters for the surface finishing of AJP process on the BMG material. The experimental results showed that the abrasive jet polishing on a machining center improved the grinded surface roughness of BMG material. In addition, based on the results of the Taguchi's L_{18} matrix experiments, the optimal AJP processing parameters for BMG material are the combination of the pressure of 2 kg/cm^2, the impact angle of 30^o, the standoff distance of 15 mm, abrasive material of SiC, the abrasive concentration of 1:5 and the polishing time of 60 minutes. The surface roughness was improved from the initial value of R_a= 0.675μm to the final value of R_a =0.016μm. Furthermore, the pre-grinded layers were almost removed. The polishing time, the abrasive material and the standoff distance affect significantly on the polished surface roughness.

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