Analysis of Process Factors for Material Removal Rate in MR Fluid Polishing Using Design of Experiment

Byung- Chan Kim, Myeong-Woo Cho, Ki-Hyeok Song, Ki-Beom Kim

Abstract**—**Surface flaws such as crack or chipping is generated in fabricating material like glass for optics, because of brittleness. The surface flaws have a large bad effect to transmittance and strength of optics, so it is very important of eliminate surface flaws. However, in process of manufacturing glass, the glass is polished and ground by direct contact of tools and the vibration of tools generates the surface flaws. Therefore it needs to polish glass in a different way. MR(magnetorheological) fluid polishing is being magnified to solve the problem of surface flaws. MR fluid has a characteristic that the viscosity of fluid is changed in the presence of a magnetic field. MR fluid polishing has a great advantage of less micro crack and SSD(subsurface damage). However the material removal rate is small and the polishing time is long. In this study, to increase the material removal rate in case of glass, process factors are analyzed in MR fluid polishing.

Index Terms**—**Design of experiment, Material removal rate, MR fluid polishing, Optical glass

I. Introduction

Optical device is an equipment for controlling a source of light to serve purpose and it is used widely in industry. Especially, the glass is a mainly used as optical device of material due to refraction or penetration of optical devices that regarded as important properties. As ultraprecise measurement is demanded for small and high performing electronic devices, and the optical measurement that has a high resolution is widely used. Therefore, research about manufacturing process of glass optical device is being studied.

Generally, polishing or grinding glass optical device such as lens is a final process step of finishing shape and dimensions of goods. In polishing process, surface roughness of glass increases, and surface flaws such as micro crack or chipping occurred during grinding process are eliminated. Subsurface damage(SSD) like micro crack is generated by removing mechanism in mechanical manufacturing brittle materials [1]. Also, according to condition or kinds of process, the depth of SSD is varied. In mechanical manufacturing process, polishing or grinding is occurred by direct contact of tools and this can generate SSD, deformed layer and residual stress [2]. SSD that occurred during mechanical manufacturing process can decrease strength of optical device. The transmittance at specific wavelength of light diminishes and this allows optical characteristic to destroy [3]. In this reason, minimum SSD is the most important in manufacturing optical device.

Recently, a new polishing process using MR (magnetorheological) fluid is magnified to solve the problems generated by direct contact of tools in mechanical manufacturing. MR fluid is a material which of viscosity is controlled in the presence of a magnetic field and MR fluid polishing is a polishing process using MR fluid polishing. However, MR fluid polishing has a disadvantage that the material removal rate is low. In this reason, MR fluid polishing needs much time to polish glass and it is important to study increasing material removal in MR fluid polishing [4]-[6]. In this study, material removal in MR fluid polishing glass which is widely used as optical device is analyzed using design of experiment.

II. MR Fluid Polishing

MR fluid is a complex fluids which of rheological characteristics change significantly in the presence of a magnetic field and it is a suspension of magnetizable micro particles dispersed [7], [8]. In other words, MR fluid is a smart material whose flow characteristic can be controlled in real time with change of magnetic field. As Fig. 1, particles of MR fluid form the chain shape in magnetic field and MR fluid can changes from liquid to semisolid state in the presence of a magnetic field [7]. In this case, shear force is generated on the polishing surface by relative velocity between MR fluid and workpiece, and the shear force leads to polishing workpiece. MR fluid in the presence of a magnetic field acts as a smooth polishing pad in MR fluid polishing and abrasive slurry is supplied with MR fluid for effective polishing.

Preston calculated material removal rate in conventional polishing by Preston Equation [10]. To calculate material removal rate in MR fluid polishing, pressure toward workpiece is departmentalized as normal stress and characteristics are substituted to Preston equation. Equation (1) shows the Preston equation in MR fluid polishing [11].

$$MRR_{MRF} = C_{P,MRF(\tau,FOM)} \frac{E}{K_C H_V^2} \cdot \tau \cdot V \quad (1)$$

Where $C_{P,MRF(\tau,FOM)}$ is a new Preston constant toward

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shear force, E is a Young’s modulus, H_V is a Vickers hardness, K_C is a fracture toughness and τ is a shear force.

Eq. 1 shows that material removal rate can increase with the decline of H_V or K_C, but these are characteristics of material. Therefore, τ or V must increase in MR fluid polishing to increase material removal rate. With the incline of magnetic field, viscosity of MR fluid increases and it means that τ at MR polishing spot increases. With the incline of the velocity of polishing wheel, material removal rate also can increase.

Fig. 2 shows the schematic diagram of MR fluid polishing system and 3 dimension modeling of electromagnet module. MR fluid is conveyed along the rotating wheel and MR fluid is contacted to workpiece. With coiled core of electromagnet, magnetic field is generated and the rotating wheel is between the pole pieces. At the same time, MR fluid changes from liquid to semisolid.

Fig. 3 shows the system of MR fluid polishing used in this study and it consists of electromagnet module and transport module. Electromagnet can control intensity of magnetic field, unlike a permanent magnet. It means that the viscosity of MR fluid is controlled by electromagnet and the material removal rate can increase viscosity of MR fluid with controlling intensity of magnetic field. Abrasive slurry is supplied on the MR fluid in the presence of the magnetic field separately. Fig. 4 shows the difference of mixed and separated abrasive slurry with MR fluid. At mixed type, MR fluid in the presence of magnetic field is formed semisolid and the abrasive particle is on the MR fluid layer. But abrasive particle is mixed with MR fluid and it is positioned between MR fluid and abrasive slurry layer. In the presence of magnetic field, CI particle is formed chain shape and it can obstruct the abrasive slurry to position on the MR fluid layer. In separated type, MR fluid is already semisolid and the abrasive slurry is supplied on the MR fluid layer. The abrasive slurry cannot penetrate to MR fluid and it can float on the MR fluid layer. Then MR fluid polishing can be more effective through the abrasive slurry without mixed layer.

Magnetostatic analysis is performed to analyze intensity of electromagnet module used in MR fluid polishing system. Magnetostatic analysis is performed using ANSYS WORKBENCH 16.1 and FEM(Finite element method) model and boundary condition are set up as Table 1 and Table 2. Fig. 5 shows the result of magnetostatic analysis of electromagnet. The intensity of magnetic field is the highest at the air gap (with no rotating wheel) where MR fluid polishing is carried out in reality. Therefore, MR fluid polishing is predicted to carry out effectively at the rotating wheel. Through these results, electromagnet is manufactured and the magnetic field is measured to confirm the intensity using Gaussmeter. Fig. 6 shows the graph of measured magnetic field of electromagnet at the rotating wheel. Magnetic field is changed nonlinearly with the incline of the current because permeability of core is affected by magnetic field [12].

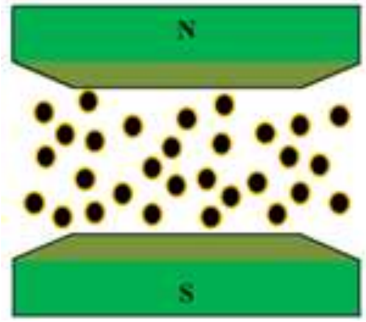

Fig. 1 (a) Without magnetic field

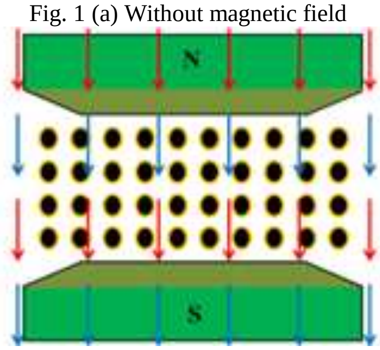

Fig. 1 (b) With magnetic field

Fig. 1. Schematic diagram of chain shape of MR fluid

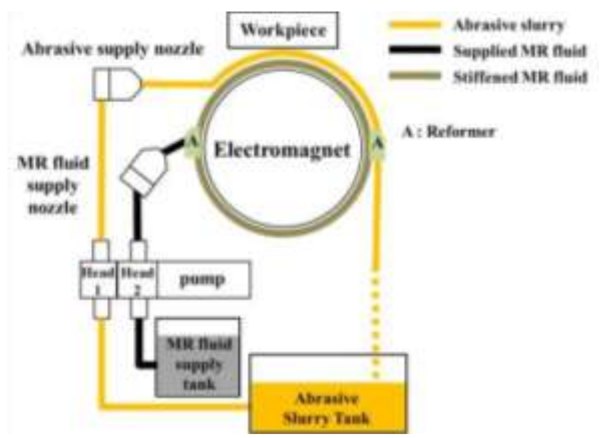

Fig. 2 (a) Schematic diagram of MR fluid polishing

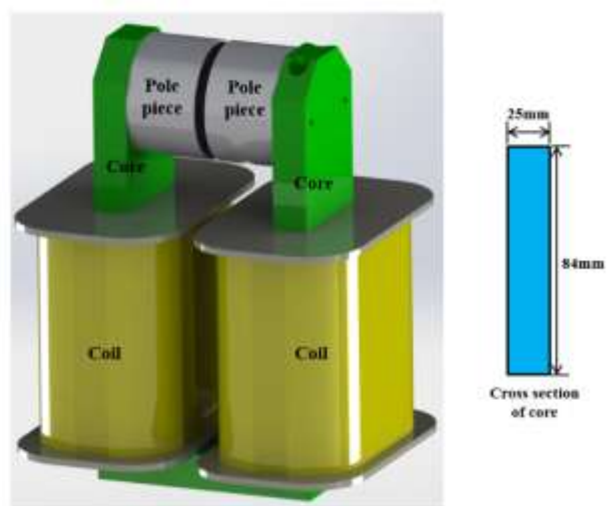

Fig. 2 (b) 3 dimension modeling of electromagnet

Fig. 2. Principle of MR fluid polishing

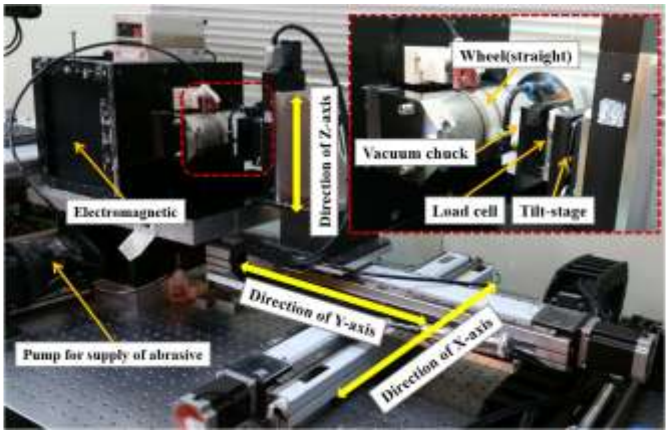

Fig. 3. System of wheel type MR fluid polishing

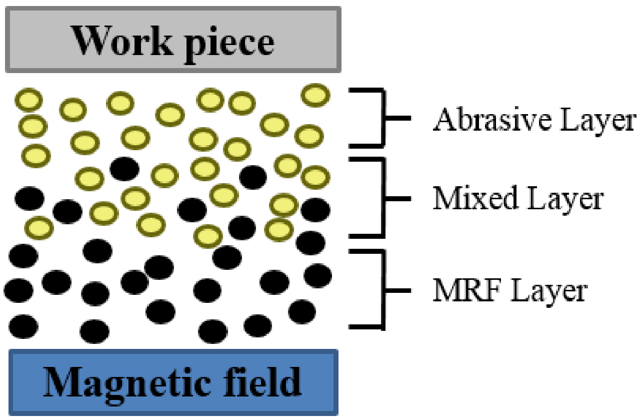

Fig. 4 (a) Mixed supply type

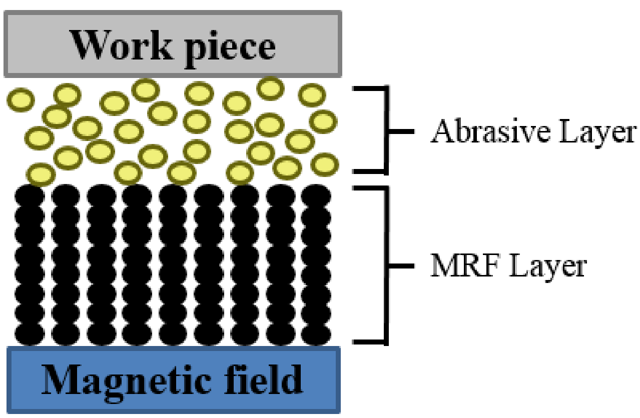

Fig. 4 (b) Separated supply type

Fig. 4. Image of MR fluid according to supply system of abrasive slurry

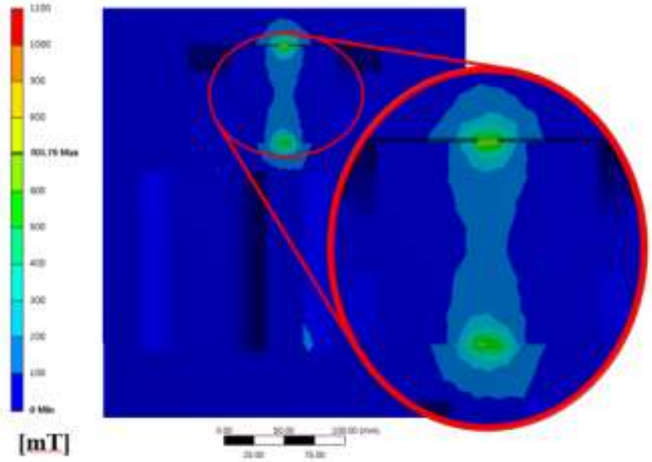

Fig. 5. Result of magnetostatic analysis

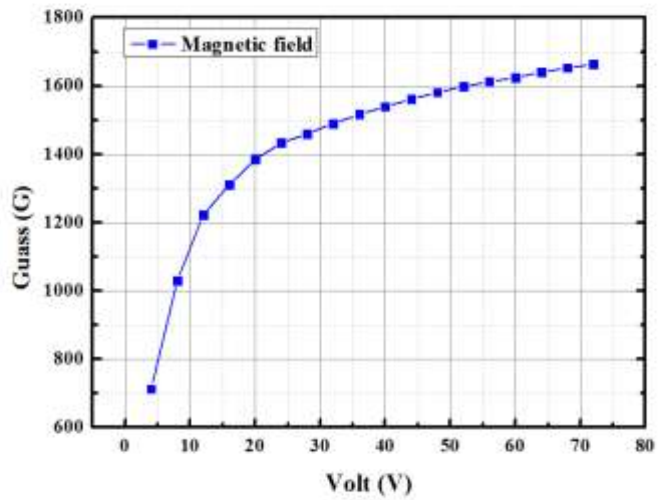

Fig. 6. Graph of the measured magnetic field

TABLE I: CONDITION OF FEM MODEL FOR ELECTROMAGNET

Items	Specification
Mesh type	Tetrahedrons
Mesh size	5mm
Nodes	210379
Elements	147192

TABLE Ⅱ : SPECIFICATION OF ELECTROMAGNET FOR MAGNETSTATIC ANALYSIS

Items	Specification
Material of core and pole piece	Structure steel
Coil diameter	Ø 1.5 mm
Material of coil	Copper
Turns of coil	2440
Current	1A

III. SPOT EXPERIMENT USING DESIGN OF EXPERIMENT

It is difficult for most engineering problem to deduct optimum process condition of real experiment based on theoretical information. It is necessary to experiment with changing size and kinds of variable, but the number of experiments increases geometrically. Therefore, using design of experiment, it is important to understand variable affects the result.

Design of experiment is a method to analyze whether manufacturing factor affects results based on maximum information with minimum number of experiment. It is possible to recognize how much variable affects results and determine optimum process condition satisfying optimum result. Generally, design of experiment is designed based on principle of randomization, principle of blocking, principle of confounding, principle of replication and principle of orthogonality.

Taguchi was the first researcher to suggest Taguchi method that can design uniform quality product and evaluate how much noise factor affects result quantitatively. Taguchi suggested that this method can improve quality with a few cost using S/N ratio (signal to noise ratio). In typical method, cost is not considered, but Taguchi demonstrated quality of product using loss from manufacturing and it is called 'Loss function' [13], [14]. Quality property of loss function is divided into three type; normal-is-best characteristics, smaller-the-better characteristics and larger-the-better characteristics.

In this study, Taguchi method among the design of experiments is used to deduce optimum polishing condition for increasing material removal rate of MR fluid polishing. Material removal rate after MR fluid polishing spot is selected as objective function. τ and V that affected to material removal rate is regarded to manufacturing factor.

Table 3 shows the factor affected to material removal rate of MR fluid polishing; the intensity of magnetic field, speed of polishing wheel, polishing gap, polishing time and composition of CI powder of MR fluid. Soda lime glass(20mm×40mm×1.1mm) is used to analyze easily the shape of MR fluid polishing spot for MR fluid polishing spot experiment.

After finishing experiment according to the order of design of experiment, image processing is performed to calculate material removal rate. To calculate the volume of MR fluid polishing spot, image of workpiece before and after polishing is obtained and mapping algorithm among the image processing method is used. Each workpiece before and after polishing is measured using Newview 7300(Zygo, USA). All images are converted to gray scale like Fig. 7 and the material removal rate is calculated by volume per pixel through mapping algorithm. Fig. 8 shows the he program that calculate the material removal rate through gray scale image and this program is made using vision module of NI Labview 2013. Each material removal rate is calculated using gray scale image and the relation between factor and material removal rate is analyzed through Taguchi method.

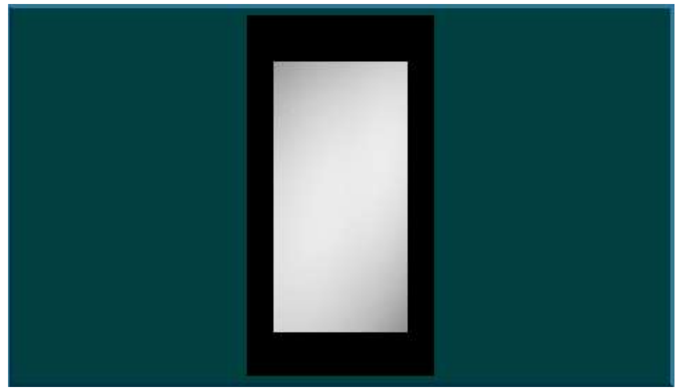

Fig. 7 (a) Image of glass surface before MR fluid polishing

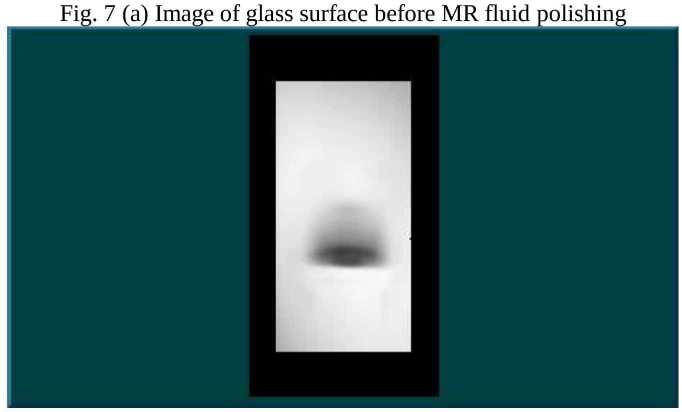

Fig. 7 (b) Image of glass surface after MR fluid polishing

Fig. 7. Gray scale image of glass surface

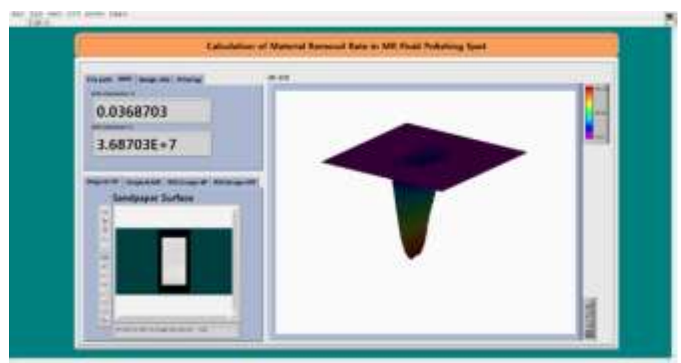

Fig. 8. Calculation program of material removal rate

TABLE III: FACTORS OF DESIGN OF EXPERIMENT

Factors	Minimum	Maximum
Magnetic field intensity (G)	1300	1600
Wheel speed (rpm)	300	400
Polishing gap (mm)	0.6	1.2
Polishing time (min)	2	4
Content of CI powder (Vol. %)	30	40

IV. RESULT

Table 4 and Fig. 9 each shows response table of S/N ratio with larger-the-better and graph of main effect according to S/N ratio. The effect on the material removal rate which is an objective function is high as the delta is larger. Therefore, polishing gap, polishing time and magnetic field has a high effect to the material removal rate in order. Whereas, wheel speed and content of CI powder have a little effect versus the other factors. This is because the intensity of magnetic field has a higher relation to the viscosity of MR fluid in the presence of magnetic field than the content of CI powder [15]. Table 5 shows the optimum polishing condition for maximum material removal rate in MR fluid polishing like Table 5.

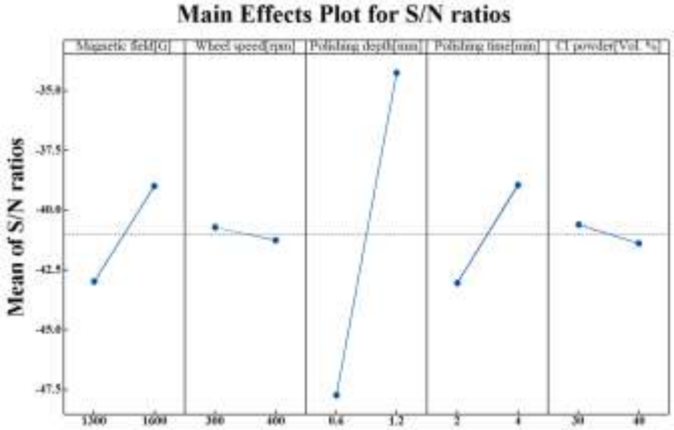

Fig. 9. Result of the main effect according to the S/N ratios

TABLE IV: RESPONSE TABLE FOR MEAN S/N RATIO

Level	Magnetic field intensity	Wheel speed	Polishing gap	Polishing time	Content of CI powder
1	0.0100	0.0125	0.0044	0.0094	0.0128
2	0.0154	0.0129	0.0210	0.0161	0.0126
Delta	0.0054	0.0003	0.0166	0.0067	0.0002
Rank	3	4	1	2	5

TABLE V: OPTIMUM POLISHING CONDITION FOR MAXIMUM MATERTIAL REMOVAL RATE

Factor	Magnetic field intensity	Wheel speed	Polishing gap	Polishing time	Content of CI powder
Specifica tion	1600G	300rpm	1.2mm	4min	30vol. %

V. CONCLUSION

In this study polishing factor is analyzed to solve the problem that the material removal rate of glass used as optical devices is low in MR fluid polishing. To set up the MR fluid polishing system, electromagnet module is designed and the intensity of magnetic field is analyzed using magnetostatic analysis. The position of highest intensity of magnetic field is on the polishing wheel in analysis. To obtain the optimum polishing condition that the material removal rate in MR fluid polishing is highest, the 5 factors affected to the material removal rate are selected and the analysis is performed using Taguchi method among the design of experiment. MR fluid polishing spot experiment is performed through each polishing condition and the material removal rate is calculated with gray scale image of workpiece using mapping algorithm, one of the image processing. As a result, the factors affected to material removal rate in MR fluid polishing are polishing depth, polishing time and the intensity of magnetic field in order. And the other factors have little effect to the material removal rate. In other words, 3 factors that have high relation to the material removal rate need to be controlled to solve the low material removal rate in MR fluid polishing.

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