Chapter

Precision Polishing Techniques for Metal Molding Dies and Glass Forming Technology "Slumping Method"

Akira Shinozaki and Junpei Kinoshita

Abstract

Precision manufacturing techniques are required for the fabrication of small and large optical components in various fields. To prepare molding dies with highly precise geometric shapes and surface roughness that are used in certain molding processes, polishing techniques have been investigated for many materials. In this research, the polishing techniques used for a SUS310S stainless steel molding die for the glass forming technology "slumping method" were investigated. The surface roughness of the polished SUS310S molding die surface was below Rz = 120 nm (P–V), Ra = 20 nm after 35 h of polishing with 0.5% alumina polishing liquid under a pressure of 1.7 kPa. In addition, the centerless polishing machine was designed and manufactured to polish cylindrical molding die surfaces with same polishing conditions. As the result of using cylindrical molding dies that made by this centerless polishing machine, the surface roughness of the glass plate formed using the slumping method with the polished molding die was below Ra = 20 nm. These results indicate that the surface roughness of the molding die had a small effect on the glass plate surface formed using the slumping method.

Keywords: precision polishing, molding die, glass forming, surface roughness, slumping method, manufacturing

1. Introduction

The X-ray astronomical satellite "ASTRO-H" was launched in February 2016 and carried hard and soft X-ray telescopes. However, an accident that occurred during adjustment caused the satellite to break up, and the project was canceled. For the launch of the successor by the Japan Aerospace Exploration Agency (JAXA) in 2020, an X-ray telescope needs to be rapidly fabricated at a lower cost than the ASTRO-H project. The X-ray astronomical satellite consists of over 1,200 super mirror pieces in a telescope with a diameter of 600 mm [1–3]. These mirrors are prepared using the "replica method" that presses and transcribes the mirror material on the surface into thin aluminum plates [4–7]. These techniques using precision molding dies [8–11] have also recently been applied not only for X-ray telescopes but also for various other optical components that require rapid and low-cost manufacturing.

Authors previously proposed the use of the "slumping method" as a thermo glass forming method to achieve rapid and low-cost manufacturing of optical components [12]. The slumping method can be used to manufacture next-generation X-ray telescope; in addition, it can be used for shape forming of glass super mirrors and other optical components. In our previous studies, a SUS304 stainless-steel molding die with nanoscale surface roughness was successfully prepared using the slumping method [13].

In this study, the precision polishing process for a SUS310S stainless-steel molding die as a heat-resisting metal was investigated using various polishing pressures, polishing times, and surface roughnesses. This technology was developed to manufacture super mirrors of space telescopes used in the field of aerospace. Therefore, the accuracy required for these products are so high levels such as "some nano meters or sub nanometers". By considering these results, it may be possible to open up new using fields of application with precision manufacturing and designing technology in the future.

2. Structure of X-ray telescope

Figure 1 shows a structure of the X-ray telescope structure [1]. The diameter of the X-ray telescope cylinder used in ASTRO-H is approximately 600 mm and consists of more than 1,200 super mirror pieces. The X-ray wavelength is below 1 nm, and the X-rays enter at an angle of less than 1° and are reflected twice by the interior surface of the mirror. The reflected X-rays are then focused on a detector positioned 8 m away. The super mirrors with a multi-layer film of "platinum carbon" used to reflect the X-rays by "Bragg reflection [1]"are approximately 0.2 mm thick and very smooth. The super mirrors are the main components of the X-ray telescope; however, their manufacture is difficult because of their arc-line shape and the highly precise surface roughness needed to enable detection of the X-rays. To meet these specifications, high-precision techniques are required to prepare the molding dies used to fabricate the super mirrors.

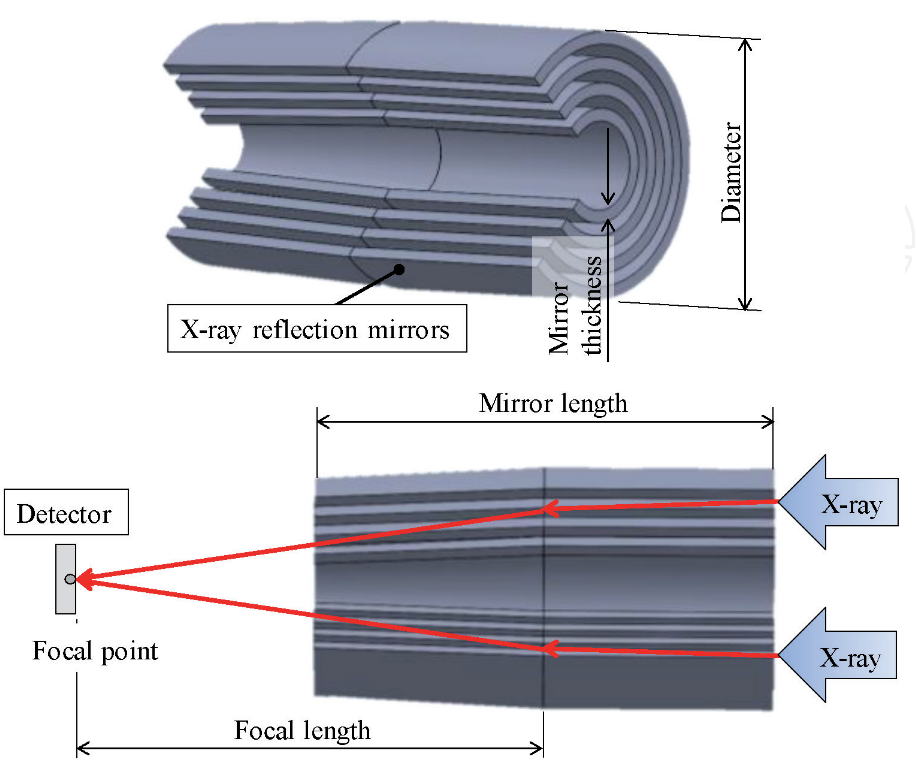


Figure 1.
Structure of the X-ray telescope structure [1].

3. Mechanism of "slumping method"

The "slumping method" was proposed for the manufacture of the base shape of super mirrors and other optical components. The slumping method is a glass forming process with heating at the glass softening point [12]. **Figure 2** presents an overview of the "slumping method". A glass plate is placed on a molding die that has the shape of the optical component. The glass plate is then heated and thermoformed along the molding die. The surface roughness of the molding die is critical because it may be transcribed to the glass surface if it is rough. Therefore, high-precision polishing of the molding die should be performed to achieve a highly precise surface roughness. In addition, the molding die must also exhibit good heat resistance to enable its exposure to repeated heating processes.

4. Precision polishing of SUS310S molding die

In the slumping process, the use of stainless steel SUS310S as the molding die material is proposed because of its good heat resistance. In our previous study, a SUS304 stainless-steel molding die with nanoscale surface roughness was successfully prepared [13]. However, intergranular corrosions occurred at about 600°C on its surface after the slumping process, therefore, in this work, stainless steel SUS310S was selected because of its improved heat resistance [14, 15]. The temperature of 600°C is a softening one used to transform glass plates, in the case of using SUS304, these temperatures almost accords. Therefore, the SUS310S material that intergranular corrosion temperature is over 750°C was selected as an improvement research [16]. By this background, precision polishing experiments were conducted using various polishing pressures, polishing times, and surface roughnesses.

4.1 Precision polishing experimental procedure

Table 1 summarizes the conditions used for the precision polishing experiments, and **Figure 3** presents an overview of the precision polishing experiment. The precision polishing was performed using a bench-type polishing machine (MA-200, Musashino Denshi). The end surfaces of the stainless steel SUS310S workpieces

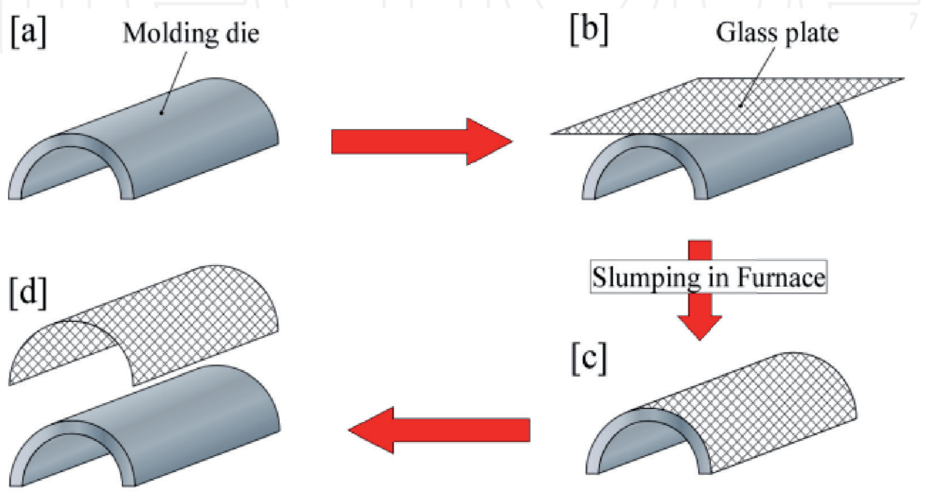


Figure 2.
Outline of the glass forming techniques "slumping method". (a) Preparation of molding die. (b) Processing set up. (c) Demolding process. (d) Deformation process.

Polishing machine	Bench type polishing machine MA-200, Musashino denshi, Co., Ltd
Workpiece material	Stainless steel SUS310S in JIS
Polishing pad	Suede type
Polishing liquid	0.5% – alumina polishing liquid (Abrasive grain size = 5 μm)
Polishing condition	Polishing pressure 1.7 [kPa]

Table 1.
Experiment conditions.

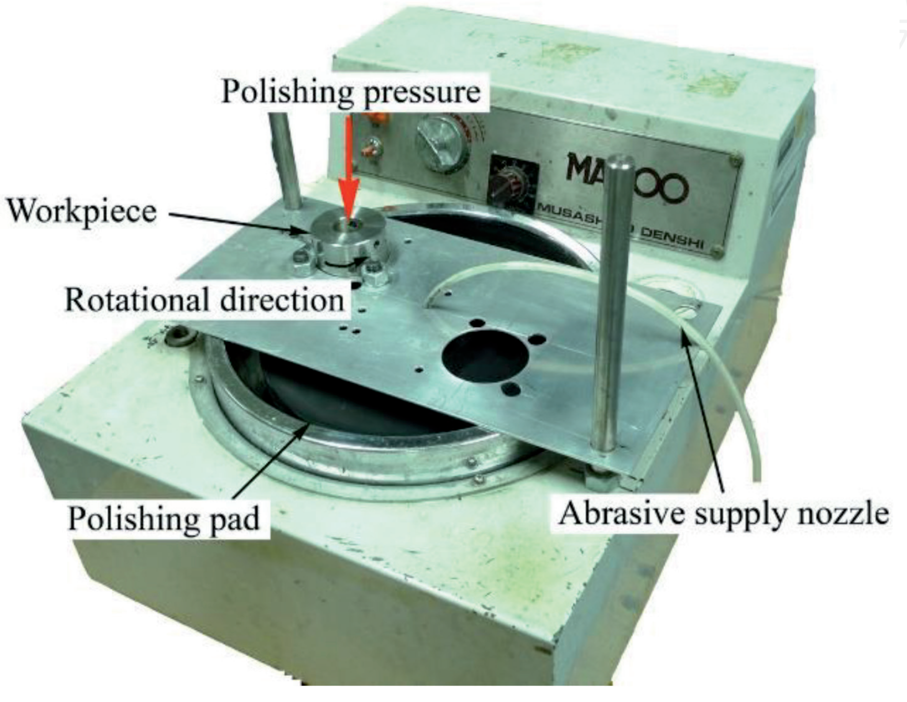


Figure 3.
Overview of precision polishing machine and experiment.

(50 mm diameter, 10 mm thickness) were polished, as shown in **Figure 4**. The polishing pad was a suede-type pad, and the polishing liquid was a 0.5% alumina (# 3000) mixture dispensed at a rate of 50 ml/h by a tube pump (PST110, Iwaki). The surface roughness of the workpieces and formed glass plates were measured using a surface roughness tester (SJ-201, Mitsutoyo) and 3D optical surface profiler (NewView7100, ZYGO). Measurements were taken approximately 5, 12, and 20 mm from the center of the workpiece for the "inside", "center", and "outside" positions, respectively.

4.2 Results of precision polishing for SUS310S

Figure 4 shows the workpieces before and after polishing. Cutting grooves were apparent on the workpiece surface before polishing, as shown in **Figure 4(a)**; these grooves were formed over the entire surface by the previous cutting process. Generally, it has been found that a machining for stainless steels called "hard to cut materials" is difficult to make smooth surface, because diamond bites cannot be used in ultra-precision cutting process [17, 18]. However, after 37 h of polishing, the workpiece had a mirror surface with the grid pattern of the under sheet, as observed in **Figure 4(b)**. Comparison of the surfaces reveals that the precision polishing process reduced the surface roughness.

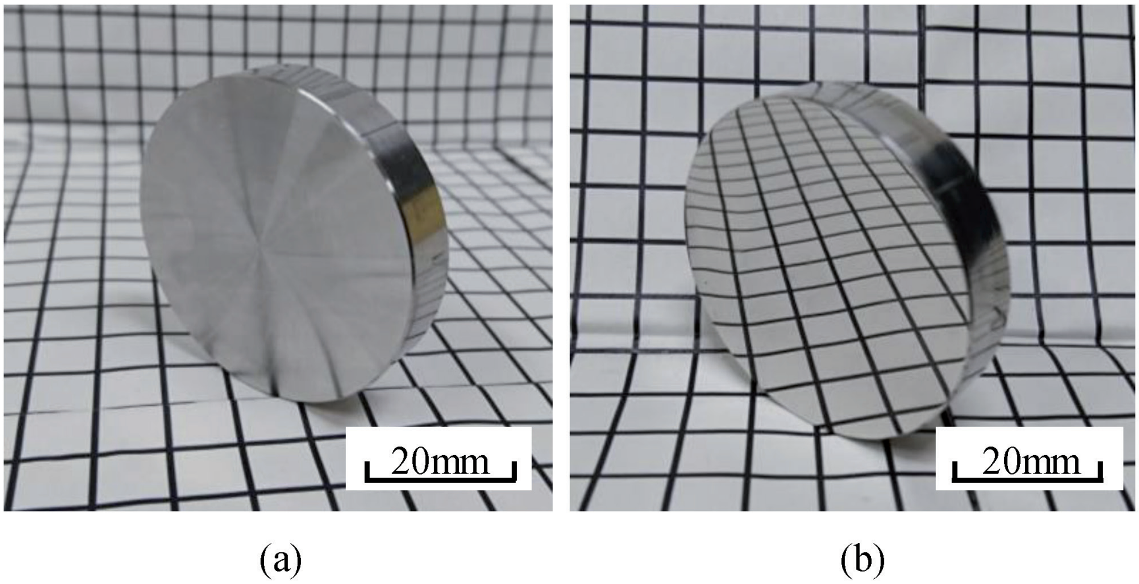


Figure 4.
Comparison of before and after polishing workpieces. [SUS310S, 0.5%-Al_2O_3 polishing liquid, 1.7 kPa]. (a) before polishing. (b) after polishing.

Figure 5 presents shows the relationship between the surface roughness *Rz* of the polished SUS310S surface and polishing time for a polishing pressure of 1.7 kPa. When the precision polishing process was performed for 1 hr., the surface roughness of the outside region was the smallest of all the regions with *Ra* = 0.07 μm and *Rz* = 0.64 μm, as shown in **Figure 5(b)**. After more than 2 hrs of polishing, repeated small variations in the surface roughness were observed and the surface roughness was reduced equally over the entire surface. After approximately 15 hrs of precision polishing, the surface roughness was almost constant at *Ra* = 0.03 μm and *Rz* = 0.25 μm. After that, the surface roughness gradually decreased, and finally, a surface roughness of *Ra* = 0.02 μm and *Rz* = 0.16 μm was achieved after 37 hrs of precision polishing.

In our previous study on precision polishing with a polishing pressure of 0.7 kPa (only the pressure of the die weights without additional pressure), the surface roughness of the outside region was less than 1.0 μm after 5 hrs of polishing [12, 13]. However, in the current study using a pressure of 1.7 kPa, the surface roughness was smaller than *Rz* = 1.0 μm after less than 2 hrs; these results indicate that the polishing efficiency was improved with higher polishing pressure.

Figure 6 compares the surface roughness (a) before polishing, (b) after 1 h polishing, and (c) after 37 hrs polishing for a polishing pressure of 1.7 kPa. **Figure 6(a)** confirms that the tool feed interval roughness resulted in the cutting grooves observed in **Figure 4(a)**, for which the surface roughness was *Ra* = 0.4 μm and *Rz* = 2.7 μm. After 1 h polishing, the surface roughness decreased (*Ra* = 0.07 μm, *Rz* = 0.66 μm), as observed in **Figure 6(b)**. Finally, after 37 h polishing, the cutting grooves were no longer observed, as shown in **Figure 6(b)**, and the surface roughness was *Ra* = 0.01 μm and *Rz* = 0.10 μm.

To examine the precision polished surface more closely and precisely, the precision polished workpiece in **Figure 6(c)** was characterized using an optical surface profiler. The polished surface had an arithmetic mean roughness of *Sa* = 1.8 nm and a maximum height roughness *Sz* = 20.4 nm in the 3D area. The surface roughness in the 2D measurement is *Ra* = 1.7 nm and *Rz* = 9.1 nm, with some small undulations observed. The objective of this study was to achieve a surface

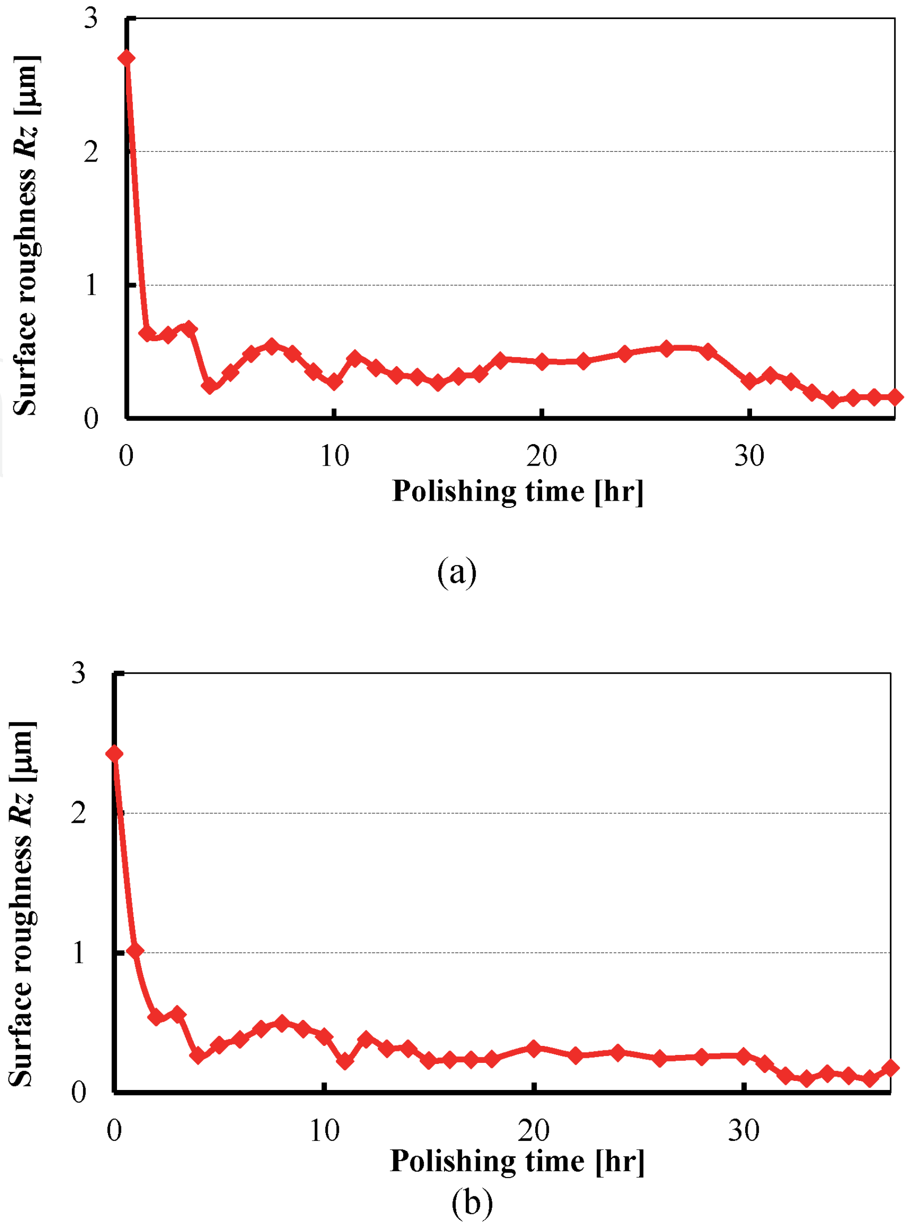


Figure 5.
Surface roughness of polished SUS310S surface. [SUS310S, 0.5%-Al_2O_3 polishing liquid, 1.7 kPa]. (a) inside of workpiece (r = 5 mm). (b) outside of workpiece (r = 20 mm).

roughness of less than *Ra* = 2 nm, which would enable the use of the SUS310S stainless steel molding die.

Our previous polishing experiments on stainless steels with a polishing pressure of 1.7 kPa used SUS310S. Therefore, the SUS304 and SUS310S molding die polishing results are compared for a polishing pressure of 1.2 kPa [12]. The final polished surface roughness was in the same range of *Rz* = 10 nm. The times required to reduce the surface roughness *Rz* from 4 to 1 µm for SUS304 and SUS310S were 7 and 2 h, respectively; for a polishing pressure of 0.7 kPa, these values were 18 and 5 hrs, respectively. These results indicate that the SUS310S molding die may be easier to polish than the SUS304 molding die.

4.3 Designing and manufacturing "centerless polishing machine" for cylindrical molding dies

Figure 7 shows the designed and manufactured centerless polishing machine images to polish cylindrical molding dies. This molding die polishing system will be

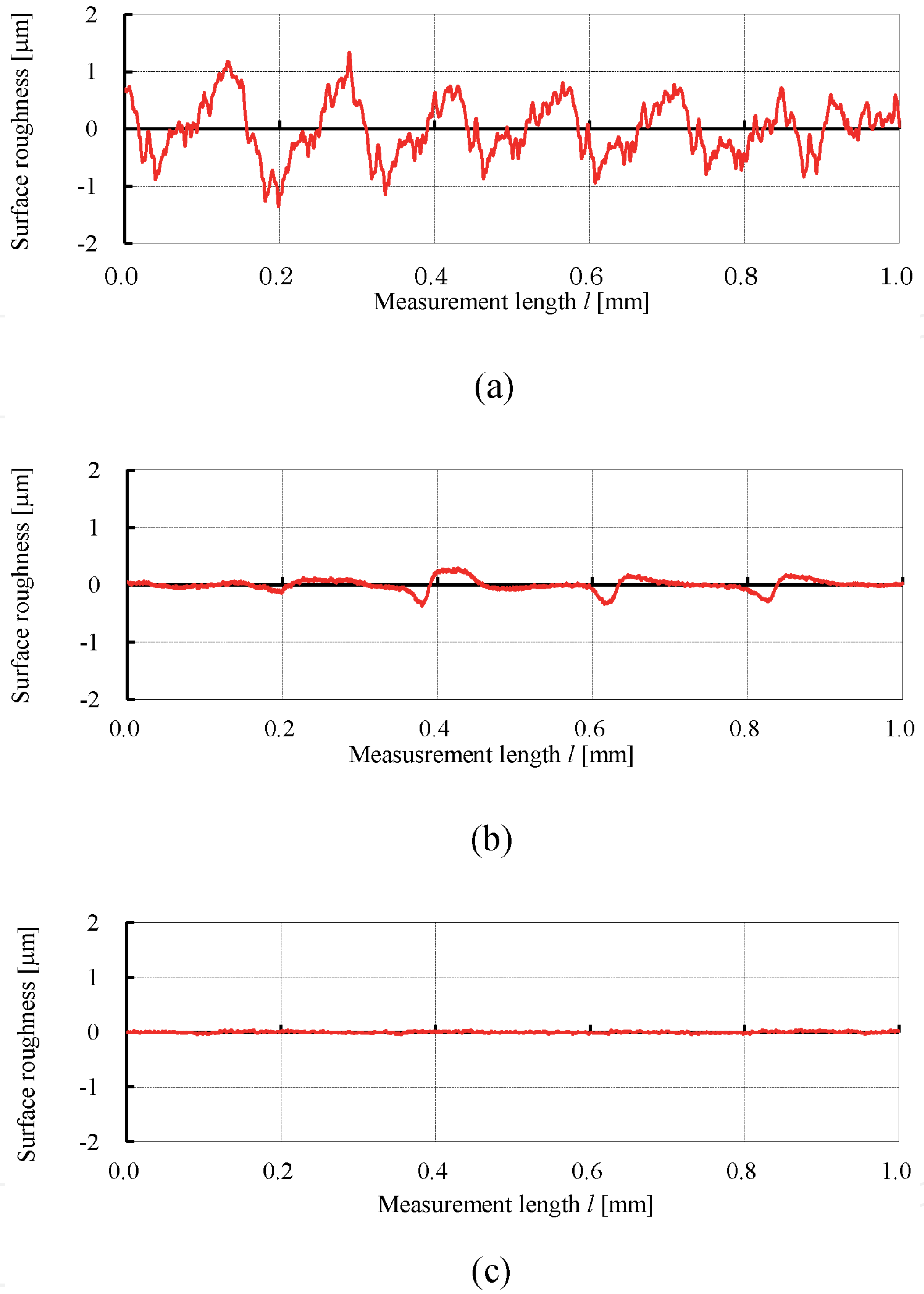


Figure 6.
Surface roughness of polished SUS310S surface. (a) before polishing [Ra = 0.40 µm, Rz = 2.70 µm]. (b) after 1 hour polishing [Ra = 0.07 µm, Rz = 0.66 µm]. (c) after 37 hours polishing [Ra = 0.02 µm, Rz = 0.15 µm].

used for making large scale glass mirrors that are over 600 mm diameter in X-ray telescope field. Therefore large size molding dies have to be manufactured with very small surface roughness. From these background, "centerless polishing machine" was designed. The direction of set-up and polishing of workpieces are lateral direction as shown in **Figure 7(a)**, because it is easy to support and rotate without center fix system of heavy workpieces. In addition, to polish cylindrical molding die surface, polishing pressure that shown in follow polishing examinations for edge surface acts uniformly by using polishing parts self-weight and gravity as shown in **Figure 7(b)**. In these images, a workpiece size is 50 mm diameter and 60 mm length, however the

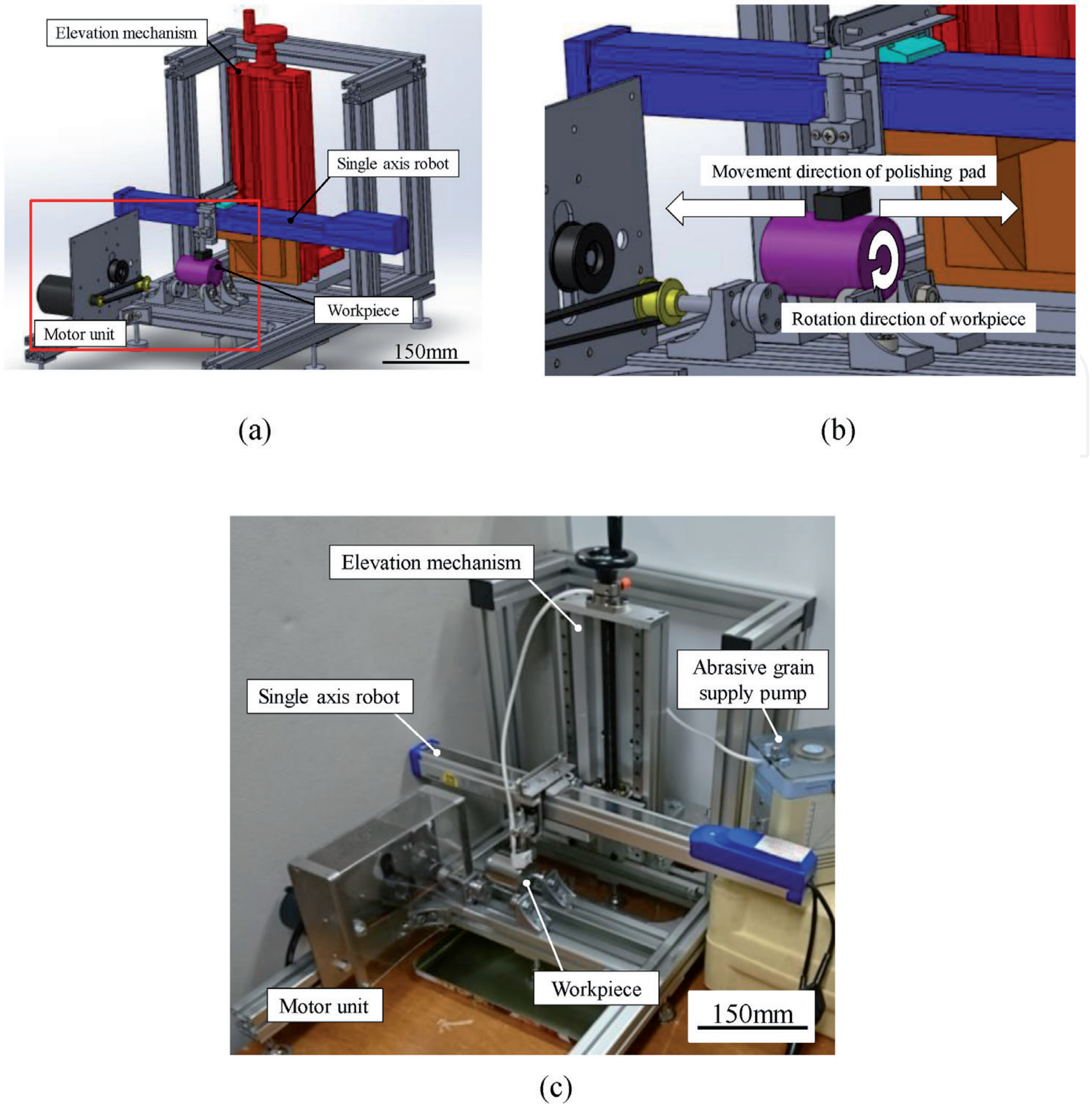


Figure 7.
Centerless polishing machine to polish cylindrical SUS310 molding die surfaces. (a) 3D model of Centerless polishing machine. (b) Polishng method on the machine. (c) Overview of Centerless polishing machine.

designed maximum size for this machine is 200 mm diameter and 200 mm length. By using lifting system and 1 axis robot set up at behind and upside of workpieces, height of polishing parts are able to adjust for each size molding dies.

The centerless polishing machine was manufactured with aluminum pipe frames, as shown in **Figure 7(c)**. Sizes of this machine are 700 x 450 x 500 mm, workpiece rotary drive motor is designed for over 25 kg weight workpieces. The SUS310S molding dies of 50 mm diameter used in slumping process were manufactured by this machine.

5. Glass forming process with "slumping method"

5.1 Effect of molding die surface roughness on formed glass plate surface

A polished SUS310S precision molding die surface with nanoscale surface roughness cannot be easily obtained. Understanding the relationship between the surface roughness of molding dies and formed glass plates will be effective for cost reduction and manufacturing time reduction. In our previous research, the surface roughness of formed glass plates was smaller than that of the polished molding die surface. Therefore, in this work, the effect of the molding die surface on the glass plate surface formed using the slumping process was investigated.

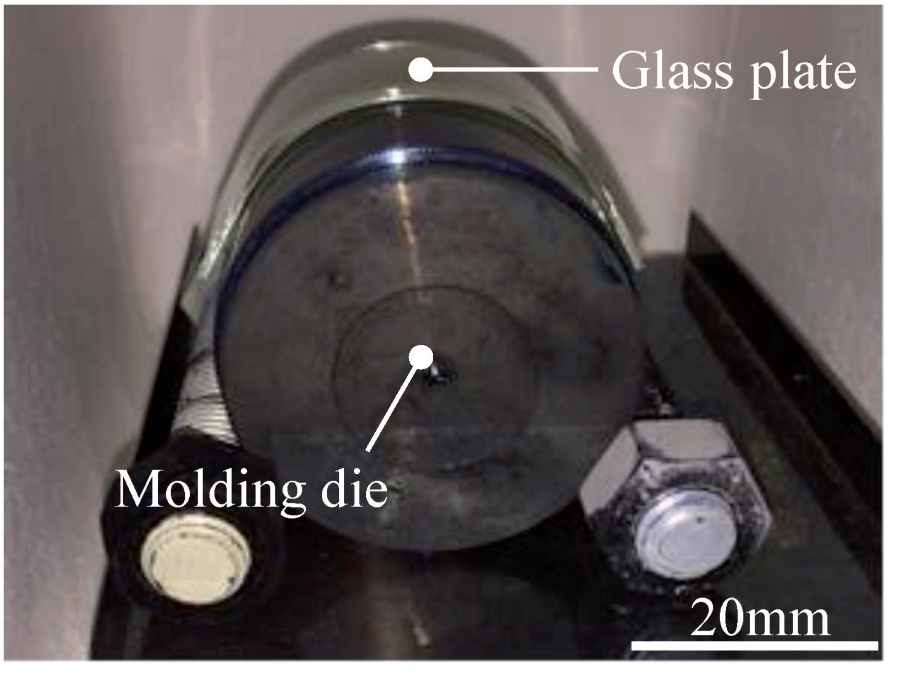
The slumping process was used to form a glass plate using polished SUS310S molding dies with surface roughness of 0.28, 0.13, 0.10, and 0.08 μm. The experimental conditions for the glass forming process were as follows:

1. Glass plate: Soda-lime glass (20 mm x 50 mm x t 2 mm)

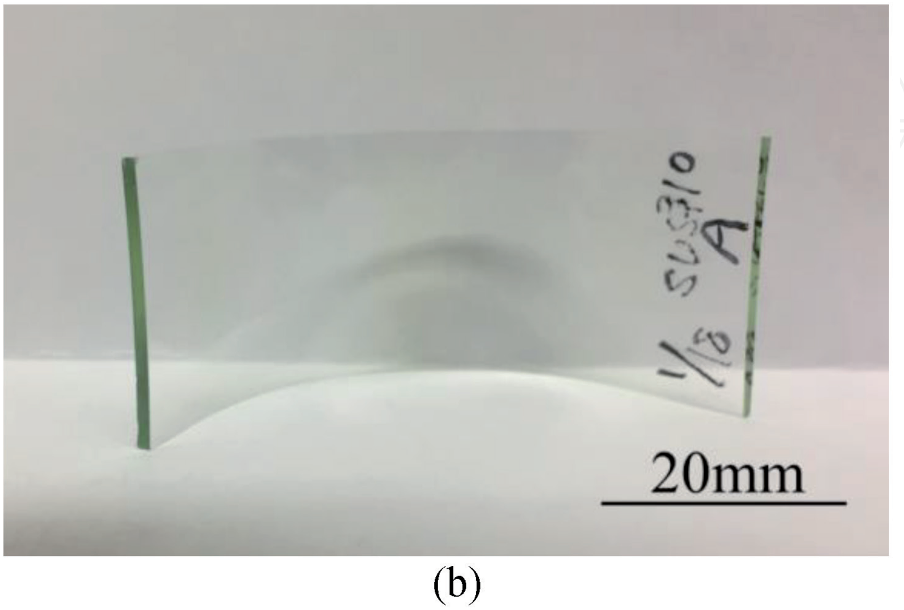
2. Furnace: Small type electric furnace (NHK120-H)

3. Temperature: 670°C (Softening temperature of glass)

4. Heating time: 120 min.



(a)



(b)

Figure 8.
Slumping method with SUS310S molding die for glass. [NHK120-H, 120 min at 670°C in electric furnace]. (a) Overview of glass forming in the electric furnace. (b) Formed glass plate with SUS310S molding die.

Figure 8 presents an overview of the glass-forming process in the electric furnace and shows a formed glass plate prepared using the slumping method. As observed in **Figure 8(a)**, one glass plate was placed on a polished molding die surface and then heated to 670°C for 120 min in an electric furnace. The glass plate must be released from the molding die surface with enough cooling time to prevent breakout caused by rapid cooling, as shown in **Figure 8(b)**.

Figure 9 shows the relationship between the surface roughness of the polished molding die surface and that of the formed glass plate prepared using the slumping method. The surface roughness of the molding dies heated in the electric furnace to form glass plates changed to *Ra* of 0.26, 0.14, 0.11, and 0.13 μm, respectively. After the slumping process, the surfaces of the SUS310S molding die were heated at 670°C, and the metallic mirror surface changed to a blue–black surface, as shown in **Figure 10**. The surface roughness of the glass plate before heating was approximately 0.02 μm in *Ra*; this glass plate had a very smooth surface even though it is a commercial product. The surface roughness before and after heating of the glass plates was almost the same (0.02, 0.02, 0.03, and 0.04 μm in *Ra*, respectively). Each glass plate could be molded by the molding dies with different surface roughness, as

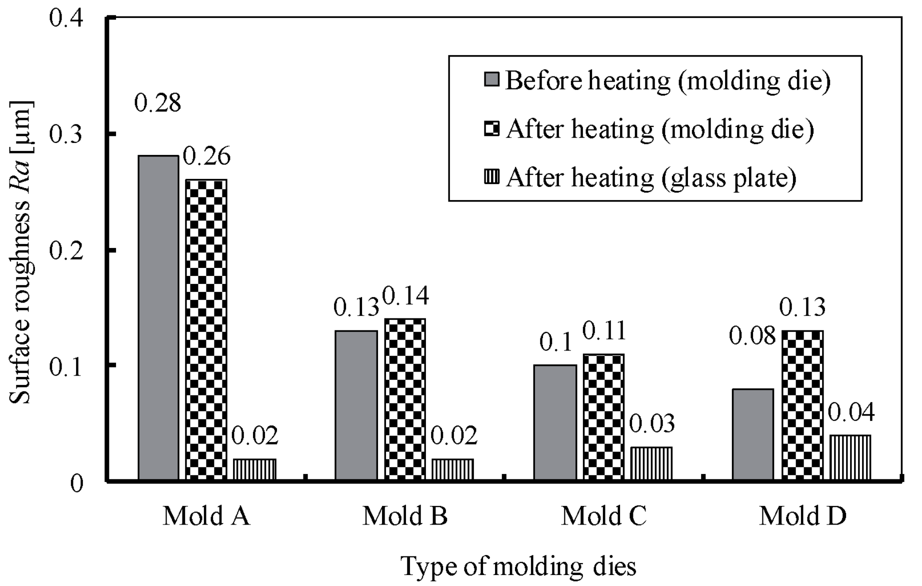


Figure 9.
Relationship between molding die surface and formed glass plate surface with slumping method. [NHK120-H, 120 min at 670°C in electric furnace].

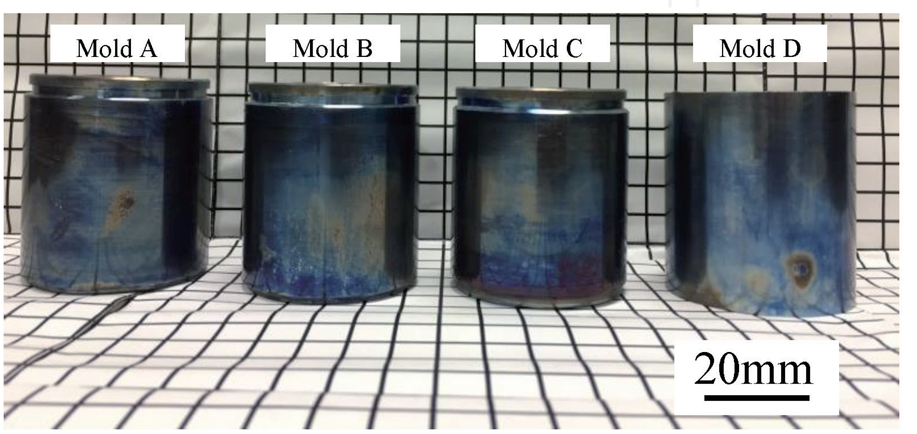


Figure 10.
Used molding die surface at slumping method process. [NHK120-H, 120 min at 670°C in electric furnace].

shown in **Figure 9**. These results indicate that the surface roughness of the molding die had a minor effect on the surface of the formed glass plates.

Generally, it is thought that the surface roughness of manufactured products cannot be smaller than the surface roughness of the molding dies. This principle is applied in molding technology in which melted materials are injected into molding dies. However, in the slumping method, a softened glass plate just remolds along the molding die shape. Therefore, it is thought that the surface roughness of the glass plate is not affected by the roughness of the molding die.

5.2 Analysis of surface roughness copying mechanism

Figure 11 shows schematic view of "slumping method" mechanisms and problems for formed glass plates. The set-up of this process is shown in **Figure 11(a)**, polished molding die have some surface roughness and glass plate of before forming has very smooth surface roughness that is below *Rz* = 10 nm [13]. Glass plate transforms along molding die surface shape by heating at softening temperature. Then transformation of glass plate occurs by only self-weight in this method.

The glass plate deforms at softening temperature, therefore that surface roughness is keep before smooth roughness at a center of deformed glass plate, as shown

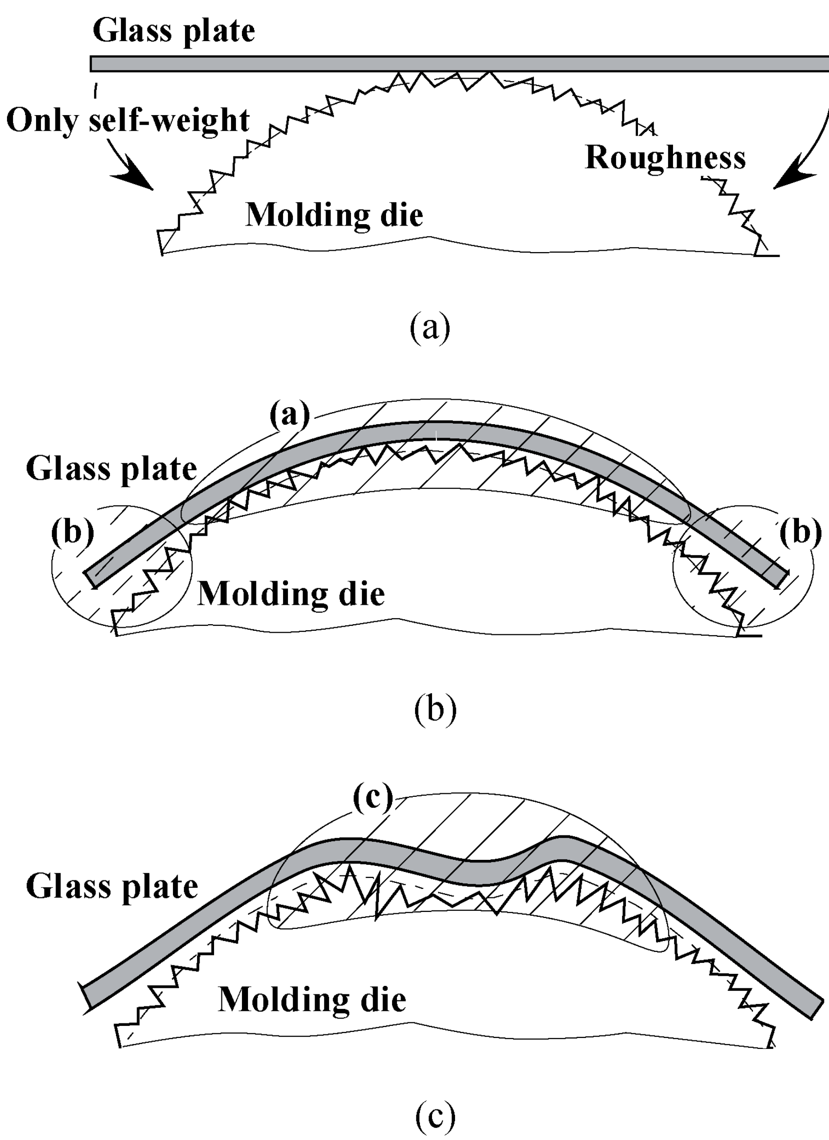


Figure 11.
Schematic of "slumping method" mechanisms and problems for formed glass plates. (a) Set up of slumping method. (b) Analysis of glass forming phenomenon. (c) Effect of molding die shape error for formed glass plate.

in (a) area of **Figure 11(b)**. On the other hand, edge areas of glass plate do not transform along molding die surface shape, because self-weight of glass plate is small in that area as shown in (b) area of **Figure 11(b)** [19, 20]. In this research, real formed glass plate edge areas are almost straight like as a before forming glass plate edge, though that shape is not measured actually.

It was found that the influence of surface roughness of molding die for formed glass plate is considerably small in "slumping method" of this research. However, if molding dies have shape errors, glass plates transform along molding die shape with its errors, as shown in (c) area of **Figure 11(c)**. In this method, shape errors of molding die greatly affects to shape errors of formed glass plate [21–23]. The shape errors and edge transformation of glass plate will be examined as the future works.

6. Discussions

In these trials of molding dies and glass product manufacturing, we were able to obtain research results for a specific aerospace field. The surface roughness of polished molding dies accuracy is below 0.02 μm in *Ra*, if the required accuracy is more than it, this polishing techniques for stainless steels will be used in other manufacturing fields. On the other hand, the surface roughness accuracy of formed glass plates is kept with original glass plate one. This result means that the surface roughness accuracy of the formed glass plate does not depend on the surface accuracy of the base molding die, so it is expected to be a useful result in the conventional manufacturing of optical products.

In recent, molding dies with high precision surface roughness and very small shape error are required in real glass product, such as super mirrors used in X-ray telescopes. If we consider that these techniques will become a molding dies and glass products manufacturing method, the manufacturing cost and manufacturing period of optical products will be shortened, and continuous manufacturing efficiency can be expected in the future. However, optical components used in aerospace field are one of kinds of items and are not produced in large quantities and continuously. When this technology is applied as a manufacturing technology for other products, it will be useful in the industrial field not only as a specific manufacturing technology but also as a sustainable manufacturing technology.

7. Conclusions

In this research, SUS310S precision polishing technology was investigated. The polishing pressure, polishing time, and surface roughness were changed and measured. The following conclusions can be drawn:

1. The precision polishing process transformed the surface of a stainless-steel SUS310S molding die from a surface with many cutting grooves to a finished mirror surface.

2. During the initial polishing process, the surface with a surface roughness of Rz = 2,700 nm was rapidly polished to achieve a surface roughness of approximately 500 nm after less than 5 h. The finished surface roughness after 37 hrs of precision polishing became Ra = 1.7 nm and Rz = 9.1 nm.

3. The precision polishing efficiency was improved by increasing the polishing pressure from 0.7 to 1.7 kPa. The polishing time required to achieve a surface

roughness of Rz = 0.5 μm was reduced from 10 to 4 hrs for the SUS310S polishing process.

4. The centerless polishing machine was designed and manufactured to polish cylindrical molding dies. By using this machine, SUS310S molding die surfaces are polished, then it could be used to form glass plates in slumping method.

5. In the slumping process with the polished SUS310S molding die, the surface roughness of the polished molding die was observed to have a minor effect on the surface roughness of the formed glass plates. However, the surface color of the used SUS310S molding die changed from a metallic mirror surface to blue–black after heating at 670°C. This result indicates that the re-polishing process of the heated molding die must be considered when it is used as a slumping molding die again.

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