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A Study on the Aspheric Glass Lens Forming Analysis in the Progressive GMP Process

Sung-Ho Chang*, Young-Min Lee, Kwang-Ho Shin, and Young-Moo Heo

Precision Molds and Dies Technology Team, Korea Institute of Industrial Technology, Incheon 406-800, Korea

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In the past, precision optical glass lenses were produced through multiple processes such as grinding and polishing, but mass production of aspheric glass lenses requiring high accuracy and having complex profile was rather difficult. In such a background, the high-precision optical glass molding pressing (GMP) process was developed with an eye to mass production of precision optical glass parts by molding press. In this paper, as a fundamental research to develop the multi-cavity mold for higher productivity of a progressive GMP process used in the fabrication of an aspheric glass lens, an aspheric glass lens forming simulation was carried out.

OCIS codes : 000.4430, 160.4670, 222.1250

I. INTRODUCTION

In the past, grinding and polishing were mainly used to produce an aspheric glass lens, but GMP method such as direct forming method has been used to produce an aspheric glass lens recently. The GMP process can be classified into the progressive and the batch type by the method of production. In the case of the progressive type, three heating steps, one forming step and three cooling steps are successively performed on each platform while many glass molds, more than 15, are conveyed such as Figure 1, but all processes are performed on one platform in batch type. So, while cycle time to produce is determined by the process that takes the longest time among heating, forming and cooling in the progressive type, that in the batch type is the total time of each process time. As these reasons, the progressive type is more productive than the batch type. Also, when problems arise in the glass mold, repair/retouch is easier in the progressive type than in the batch type. So, the progressive GMP process is generally used to produce aspheric glass lenses these days [1,2].

In the progressive GMP process, because a glass gob is heated at a high temperature greater than transformation temperature (T_g) and cooled to room-temperature, a birefringence that deteriorates the quality of a glass lens can be generated by the residual stresses in the cooling stage. So, research for forming and cooling stages in the GMP process are very important.

In this study, the glass lens forming simulations for theforming stage were carried out. Figure 2 shows the

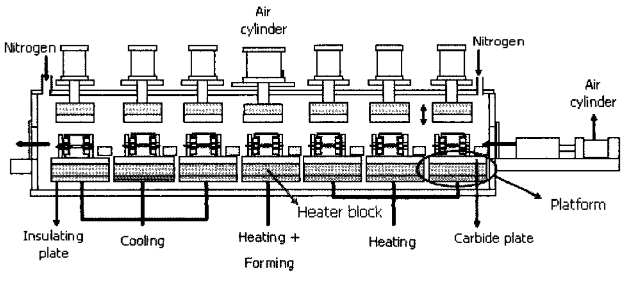


FIG. 1. Schematic diagram of a progressive GMP process.

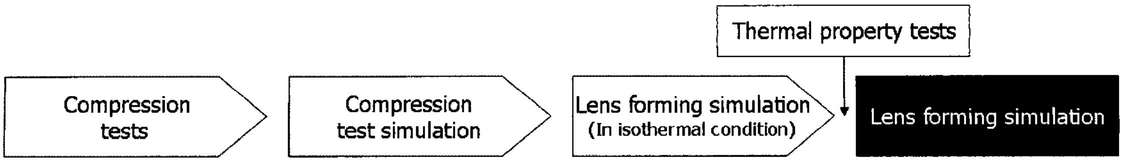


FIG. 2. Research process of a lens forming simulation.

lens forming simulation process. To obtain mechanical properties of glass material, compression tests were conducted and compression forming simulation that traces compression tests was carried out using compression test results. Also, to obtain thermal properties of glass material, thermal property tests were conducted. Finally, lens forming simulation is carried out using material tests and compression forming simulation results.

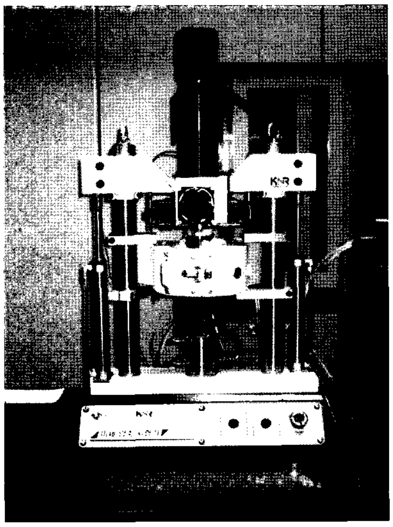


FIG. 3. Micro compress tester.

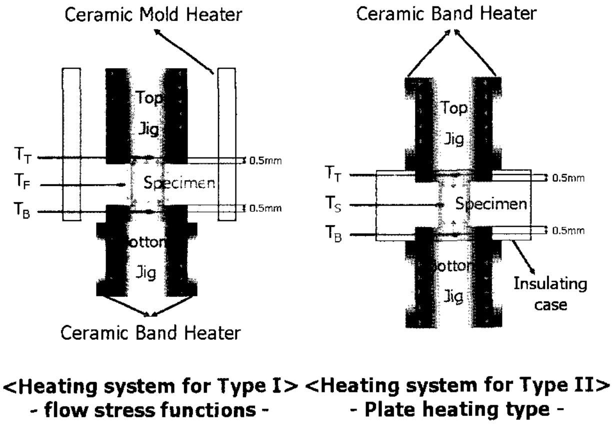


FIG. 4. Heating systems for compression tests.

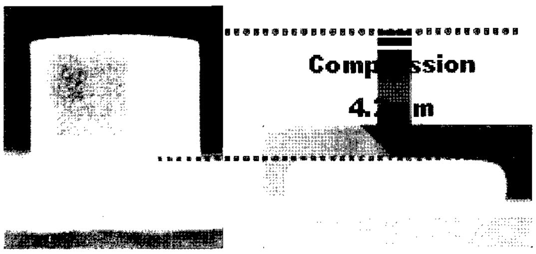


FIG. 5. Test specimen and forming rate.

II. COMPRESSION TESTS

Configurations and specifications of micro compress tester using in this study are shown in Figure 3 and Table 1. According to two major purposes, obtaining flow stress functions (experiment type I) and observing the variation of forming load in forming stage of progressive GMP process (experiment type II), compression tests were carried out using two different heating systems. Two different heating systems are shown in Figure 4. Test conditions are shown in Table 2 (a) and Table 2 (b). To consider that glass gob is heated above 570℃ and forming speed (strain rate) is from 0.01 [1/s] to 0.02 [1/s] in the forming of progressive GMP process, test temperature and strain rate were determined as Table 2 (a) and Table 2 (b). Specimens were compressed to about 60% (4.3 mm) of height of specimen as Figure 5.

Figure 6 shows the results of experiment type I. If it is assumed that deformation history behavior of glass material is neglected and forming of glass material is conducted in isothermal condition, flow stress function is expressed as

TABLE 1. Specifications of micro compress tester

Load capacity	2200N Max.
Load accuracy	±0.5% of indicated load
Stroke	10 mm
Test speed	1 mm/sec
Test temperature	700℃ Max.
Test mode	Compression/Compression creep/ Lens forming
Position accuracy	1.1 μm
Control	Load & Position

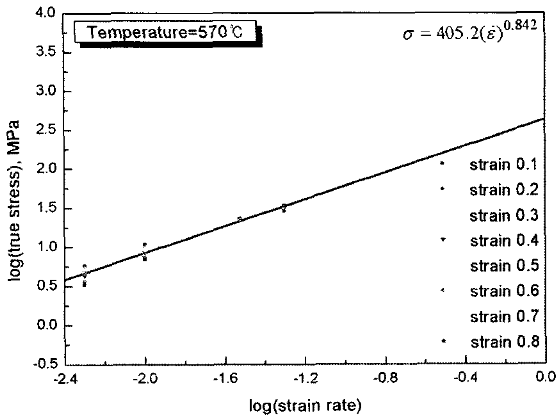
TABLE 2. Compression test conditions

(a) Experiment type I

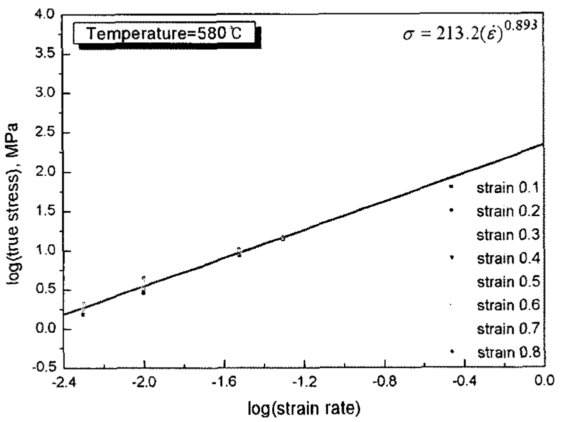
Temp. (℃)	$\dot{\varepsilon}$ (1/sec)			
570	0.005	0.01	0.03	0.05
580	0.005	0.01	0.03	0.05
590	0.005	0.01	0.03	0.05

(b) Experiment type II

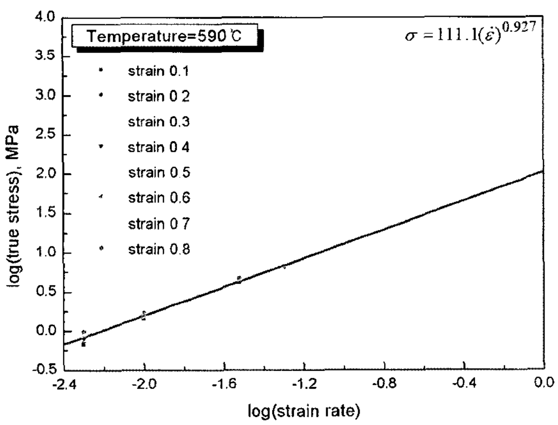
Temp. (℃)	$\dot{\varepsilon}$ (1/sec)			
570	0.01	0.03	0.05	0.1
580	0.01	0.03	0.05	0.1
590	0.01	0.03	0.05	0.1



(a) Flow stress function : 570℃



(b) Flow stress function : 580℃



(c) Flow stress function : 590℃

FIG. 6. Compression test results for experiment type I.

$$\sigma = k(\dot{\varepsilon})^m \tag{1}$$

where σ is the flow stress, k is the strength coefficient, $\dot{\varepsilon}$ is the strain rate and m is the strain rate sensitivity [3, 4]. From experiment type I, flow stress functions of glass lens material could be obtained at 570, 580, 590℃ and can be expressed as Equation (2), (3), (4).

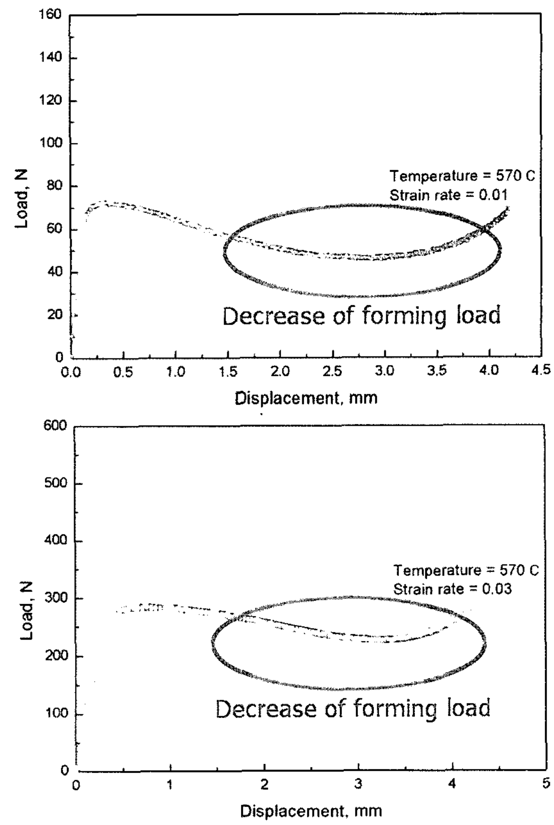


FIG. 7. Compression test results for experiment type II.

$$\sigma = 405.2(\dot{\varepsilon})^{0.842} \text{ at } 570℃ \tag{2}$$

$$\sigma = 213.2(\dot{\varepsilon})^{0.893} \text{ at } 580℃ \tag{3}$$

$$\sigma = 111.1(\dot{\varepsilon})^{0.927} \text{ at } 590℃ \tag{4}$$

From experiment type I, we could know that the strain rate sensitivity is proportional to temperature while the strength coefficient is in inverse proportion to temperature.

Figure 7 shows the results of experiment type II when test temperature is 570℃ and strain rate is 0.01 and 0.03. From the load-displacement curve, it was found out the decreasing zone of forming load after sharply load increasing. It seems that the decreasing zone was caused by the deformation energy of a specimen and the high temperature of a test jig. So, it could be expected that this forming load decreasing zone would be appeared in the forming stage of a progressive GMP process from the results of experiment type II.

III. COMPRESSION TEST SIMULATION

Figure 8 shows the simulation model for a compression test simulation. To take into account the fact that the simulation model is axisymmetric, a 2D half model was used in a compression test simulation. The major purpose of a compression test simulation is to obtain the friction coefficient between glass gob and mold. The simulation was completed when the displacement of a simulation model is 4.2 mm and simulation conditions are shown in Table 3. According to the results of experiment type I, location variation of upper jig was adopted such as Figure 9 and flow stress functions that were obtained from experiment type I were used for mechanical properties of a simulation model. MSC marc software was used in a simulation.

Forming load and radius of deformed model is shown in Table 4 and barreling shapes of various friction conditions are shown in Figure 10. According as friction coefficient is increased, barreling shape became clear. In the case that the friction coefficient is 0.6, the radius of the simulation model was the same as that of the

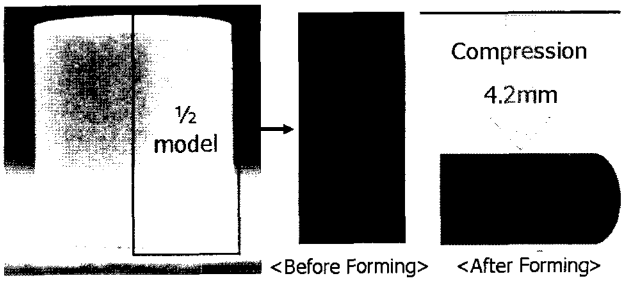


FIG. 8. Compression test simulation model.

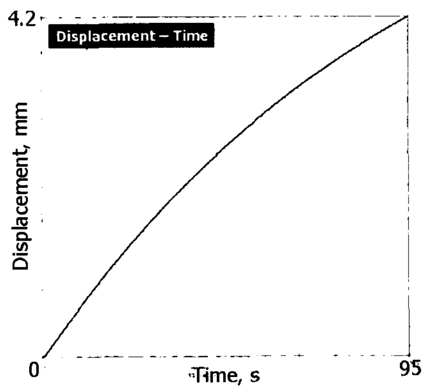


FIG. 9. Displacement of upper jig in compression test simulation.

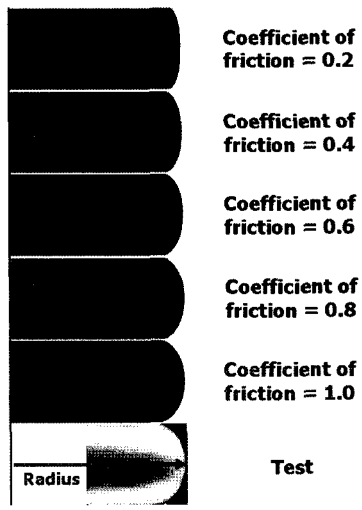


FIG. 10. Compression test simulation results (Barreling shape).

TABLE 3. Compression test simulation condition

Temperature / Strain rate	k	m	Friction coefficient
570℃ / 0.01 (1/s)	405.2	0.842	0.1~1.0

TABLE 4. Comparison compression test results and compression test simulation results

	Friction coefficient	Load (N)	Radius (mm)
Compression test simulation	0.1	908	5.66
	0.2	920	5.69
	0.3	975	5.71
	0.4	1,019	5.73
	0.5	1,060	5.74
	0.6	1,131	5.75
	0.7	1,162	5.76
	0.8	1,243	5.77
	0.9	1,329	5.78
	1.0	**1,542**	**5.79**
Compression tests	-	**1,596**	**5.75**

experiment (5.75 mm), but there was not a vast difference in aspect of deformed shape between 0.6 and 1.0. In the case that the friction coefficient is 1.0, the forming load (1542 N) of compression test simulation is similar to that (1596 N) of the experiment. Results of experiment and simulation are shown in Figure 11. Finally, to consider that simulation results, forming load and stress distribution of an aspheric glass lens mold, coefficient of friction (1.0) that shows a similarity in the side of forming load was applied to an aspheric glass lens forming simulation.

Figure 12 shows the lens forming simulation model for isothermal condition. To take into account the fact that the shape of simulation model and upper/lower core is axisymmetric, 2D half model was used in a lens forming simulation. An axisymmetric quadrilateral and adaptable element was used and MSC marc software was used in a simulation. Also, to consider that forming temperature and time of actual forming process for an aspheric glass lens are about 570℃ and 30 sec respectively, simulation conditions were determined as Table 5. Friction coefficient used in a lens forming simulation was 1.0.

Figure 13 shows variation of forming load that was obtained through a forming simulation. When the displacement of a lens forming simulation model is to be 1.53 mm, maximum forming load that is obtained from simulation was 1519 N. Distribution maps of stress, strain and contact are shown in Figure 14. After a lens forming simulation, because a barreling shape appeared, we knew that additional processing would be needed such as grinding and polishing. Contact normal force between a core and an aspheric glass lens was 147.6 N and maximum stress of an aspheric glass lens was 40.1 MPa.

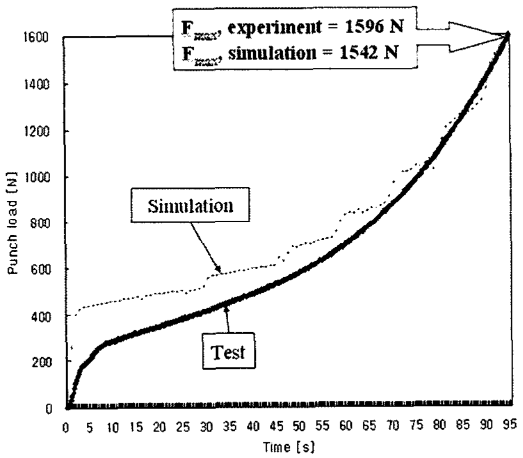


FIG. 11. Comparison simulation and experiment.

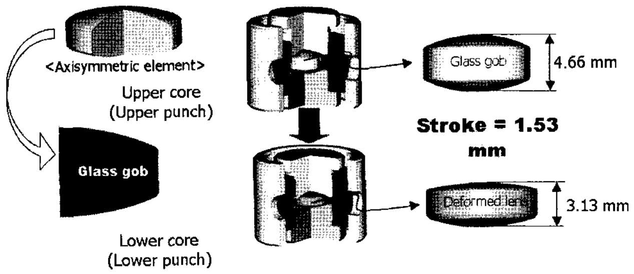


FIG. 12. Lens forming simulation model and forming rate for isothermal condition.

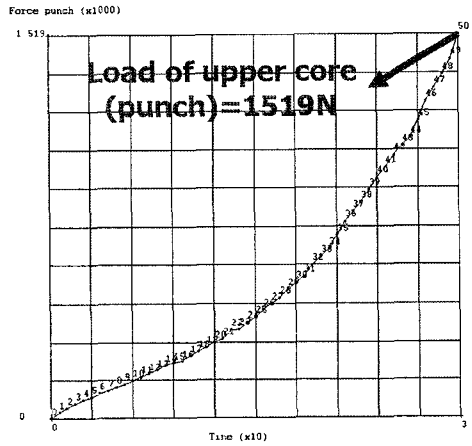


FIG. 13. Variation of forming load for upper core.

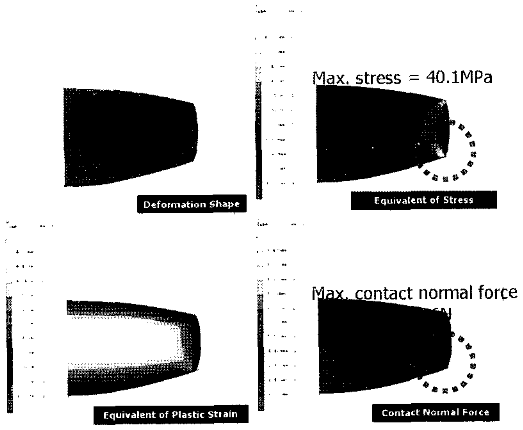


FIG. 14. Distribution maps of lens forming simulation for isothermal condition.

TABLE 5. Lens forming simulation condition for isothermal condition

Temperature (℃)	Forming time (s)	Velocity of upper core (mm/s)	*k*	*m*	Friction coefficient
570	30	0.051	405.2	0.842	1.0

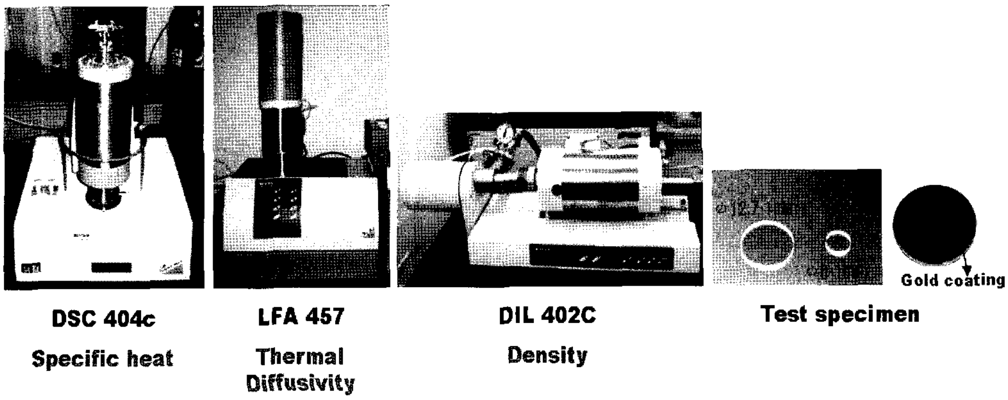


FIG. 15. Test equipment and test specimen for thermal property tests.

TABLE 6. Test temperature for thermal property tests

Test temperature(℃)										
470	480	490	501	520	530	549	560	570	580	590

TABLE 7. Simulation conditions

Type	Forming time	Temperature of mold / glass gob	Friction coefficient
I	25	570 / 565	1.0
II	30		
III	35		

IV. THERMAL CONDUCTIVITY TEST

Thermal conductivity test was conducted using the LFA (Laser Flash Analysis) method. Because LFA has the merits that measurement is simple and easy and the test result is more accurate than other test method, LFA has been widely used to obtain thermal properties. Figure 15 shows the test equipment and the test specimen. In LFA, thermal conductivity is calculated by the measured thermal diffusivity, specific heat and density using each equipment, and thermal conductivity is expressed as

$$\lambda = \alpha \cdot C_p \cdot \rho \quad (5)$$

where λ is the thermal conductivity, α is the thermal diffusivity, C_p is the specific heat, and ρ is the density. Test conditions are shown in Table 6. In case of density, to consider that there is no variation in density of glass material by temperature, density measurement was only carried out at a room temperature.

Figure 16 shows test results. Density was 2.382 g/cm^3 at a room temperature. Specific heat and thermal conductivity were increased rapidly after T_g point (501℃) and decreased after 530℃. But diffusivity was uniform nearly to 549℃ and decreased rapidly after the yielding point (A_t: 549℃). Obtained thermal properties were used in a lens forming simulation considering temperature variation.

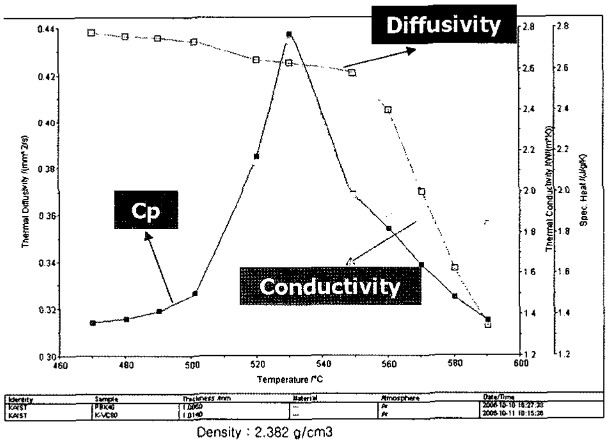


FIG. 16. Thermal property tests results.

V. LENS FORMING SIMULATION CONSIDERING THE VARIATION OF TEMPERATURE

Simulation model is the same as Figure 12. Table 7 shows simulation conditions. Mechanical and thermal properties that were obtained from compression tests

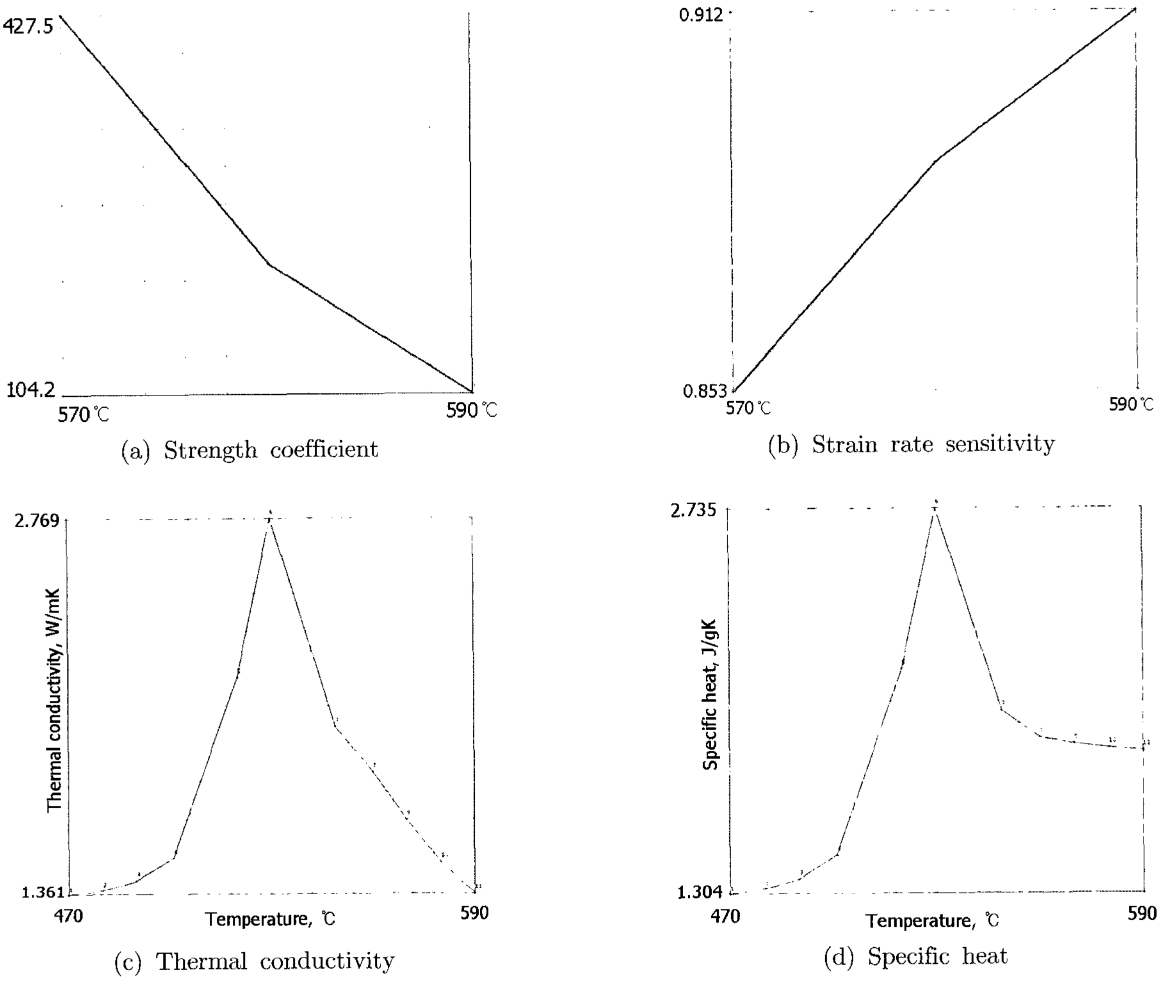


FIG. 17. Mechanical and thermal properties for lens forming simulation.

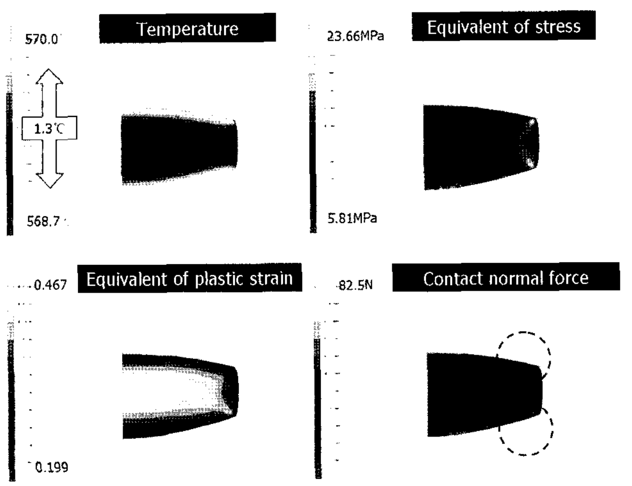
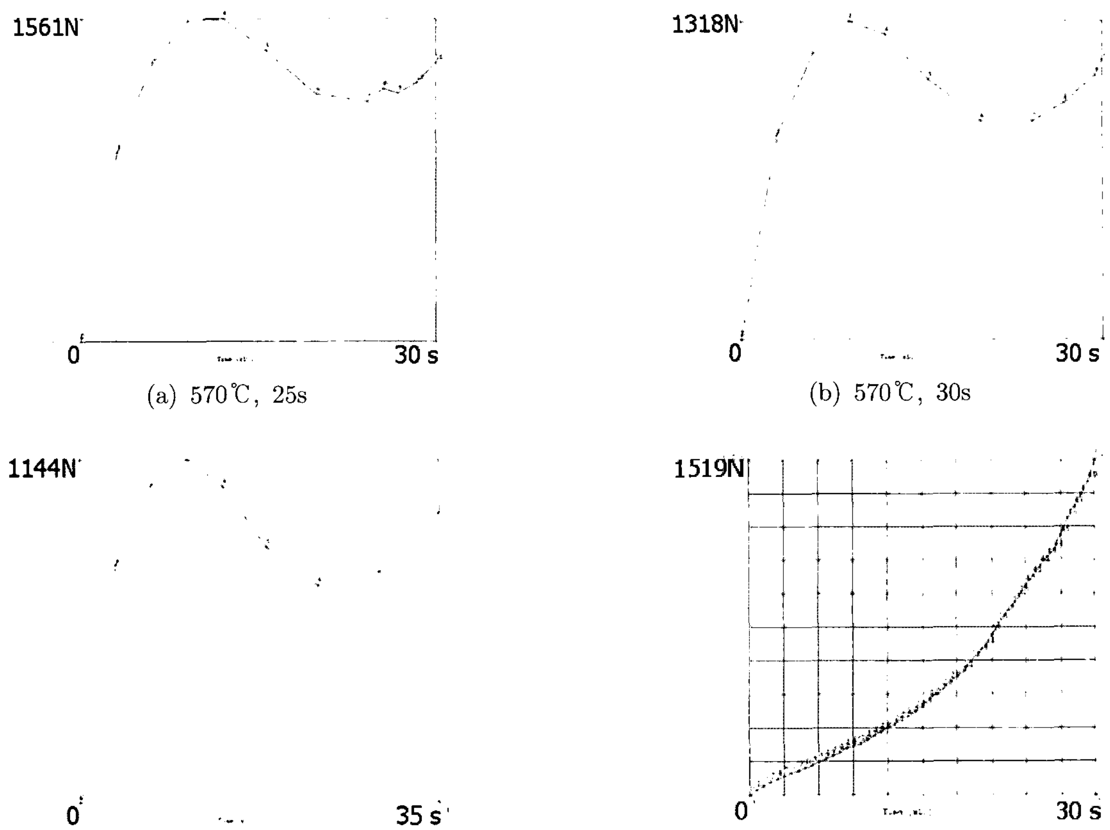


FIG. 18. Distribution maps for lens forming simulations (570℃, 30s).

and thermal property tests and friction coefficient that was obtained from compression test simulation were used in lens forming simulation. Mechanical and thermal properties are shown in Figure 17.

Figure 18 shows distribution maps for type I (570℃, 30s). Maximum stress was 22.66 MPa and contact normal force was 82.5 N in case of type I (570℃, 30s) at forming stage. From these results, we could predict that a fair amount of this stress was remained as a residual stress in a glass lens after cooling and coating surface would be damaged by contact normal force and forming load. In the end, the quality of glass lens will be deteriorated by these causes. Load - forming time curves are shown in Figure 19. In the case of isothermal condition, there was no section where the forming load is decreased. But, for a variation of temperature, the section where the forming load is decreased appeared, such as in experiment type II (plate heating type) and the difference in the value of the forming load was 201 N in the same condition (507℃, 30s). Though these results, for more reliable copy of a progressive GMP process, we could know that consideration for temperature variations of the inner parts of a glass gob is necessary.



(a) 570℃, 25s (b) 570℃, 30s (c) 570℃, 35s (d) 570℃, 30s for isothermal condition

FIG. 19. Load-forming time curve.

VI. CONCLUSIONS

In this study, the lens forming simulations for the forming stage were carried out and we obtained conclusions such as those below:

(1) From compression tests (experiment type I), flow stress functions were obtained at 570, 580, 590℃

(2) From the plate heating type compression tests (experiment type II), decrease of forming load was predicted in the forming stage of progressive GMP process.

(3) From the compression test simulation, friction coefficient (1.0) was determined for the lens forming simulations.

(4) From the lens forming simulation considering heat transfer, forming load, stress, strain and contact normal force could be predicted and predicted maximum load and load curve was good agreement with that of experimental results.

(5) For more reliable copy of a progressive GMP process, we could know that consideration for a variation of temperature within a glass gob is necessary.

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*Corresponding author: shchang@kitech.re.kr

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