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Optimization of Polishing Conditions for Anodized Inner Surfaces in Large Hydraulic Devices

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아노다이징 처리된 대형 유압장치의 내면에 대한 연마 조건의 최적화

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ABSTRACT

Large-diameter hydraulic devices such as the hydraulic reservoir in aircraft that serves to balance the hydraulic pressure in the various hydraulic devices in the cabin and to store hydraulic oil are operated by the internal piston systems. However, since this operates in an environment with high temperature and humidity, it may cause the inner surface to flake during its operation. Therefore, an anodizing surface treatment is applied to improve the corrosion resistance, abrasion resistance, and smooth operation. However, anodizing increases the surface roughness. Accordingly, the polishing process that improves the surface roughness after anodizing is important. However, the existing polishing process is performed manually, which results in an inefficient process. Therefore, in this study, we selected the optimum polishing conditions for effective polishing using the experimental design to improve the polishing process for the Al_2O_3 film that forms after anodization. Through experiments, we confirmed that the surface uniformity after polishing was superior as the feed rate was slower when the same polishing time had been applied.

Key words : Anodizing Surface Treatment(아노다이징 표면 처리), Superfinishing(슈퍼피니싱), Polishing Film (연마필름), Surface Roughness(표면거칠기), Design of Experiment(실험계획법)

1. Introduction

Large-diameter hydraulic devices in transport systems, such as those in the case of aircraft equipment, replenish fluid to various hydraulic components and circuit to maintain the balance of pressure between the high-pressure and low-pressure lines and to store hydraulic oil. With the development of the aerospace industry, such devices have been associated with wide-scale production. In principal, these hydraulic reservoirs operate through the motion of an internal piston within an ambient temperature of -40℃ to 135℃. Nonetheless, as surface particles may

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peel off with the piston motion, the inner surface of the material should possess the resistance to abrasion and corrosion a long with an additional requirement for a uniform surface Ra of 0.2 ㎛ or less to entail a smooth operation[1-3]. Typically, such requirements are effectively corresponded by a well scheduled polishing process. Fig. 1 depicts the manufacturing process of a hydraulic reservoir, which undergoes an anodizing surface treatment of Al7075, for improved abrasion and corrosion resistance.

Because the surface roughness of the reservoir after the treatment increased, it would be difficult for the 0.2 ㎛ Ra of surface roughness to be satisfied to ascertain its smooth operation. On this aspect, a two-step polishing process, which aims to improve the surface roughness of the reservoir before and after the anodizing surface treatment, should be necessary. Nonetheless, the conventional process employs sand paper manually for the primary and secondary polishing stages for several times depending on the skill of the operator, which result in uneven surfaces and increased working time and affect the productivity and the working environment. Such disadvantages call for the automation of the process and optimization of the essential parameters.

A certain research initiated an attempt to investigate the improvement of the primary polishing process[4] for the purpose of enhancing the surface roughness of Al7075 prior to the anodizing surface treatment. Some advanced studies asserted the efficiency of a micro turning process for an aluminum alloy[5-8] by integrating the primary polishing stage with the finishing process based on the study results to achieve the fine surface roughness of approximately 0.2 ㎛, even at the extent where the feed rate of the tool was varied in the turning experiment using R bite. Consequently, these studies indicated the enhancement of the polishing process with its integration with the final process by simultaneously achieving the purpose of the primary polishing process when the finishing process was conducted using R bite.

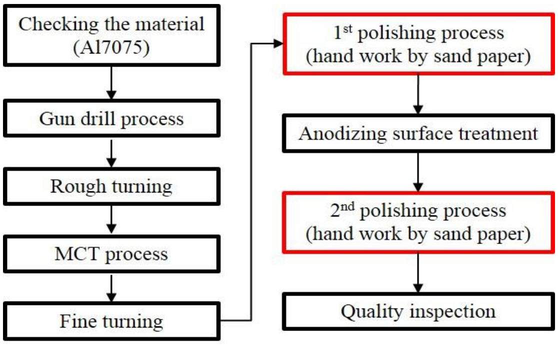

Fig. 1 Manufacturing process of hydraulic reservoir

Therefore, this study highlights the objective to improve the secondary polishing stage, which concerns the improvement of the surface roughness that has increased following the anodizing surface treatment. As such, the optimum condition for efficient polishing is selected and verified through the design of experiment approach with a developed superfinishing machine[9]. Furthermore, the polishing conditions are selected to ensure the uniformity of the inner surface of the hydraulic reservoir.

2. Experimental apparatus and method

The superfinishing machine is an apparatus that uses an abrasive film with the advantage of the new abrasive grains being continuously supplied by the transfer of the abrasive during the polishing process. Fig. 2 displays the developed device, mounted and operated on a lathe, and Table 1 shows its specifications. The KOSAKA SE-3500K model was used for performing the surface roughness measurement, and the average value was obtained from measurements in the circumferential direction four points within intervals of 90˚.

Fig. 3 illustrates the experimental setup. Cylindrical specimens of 300 mm outer diameter and 250 mm inner diameter were subjected under a polishing film of 50 mm width, at an interval of 20 s until Ra of 0.2 ㎛ or less was achieved.

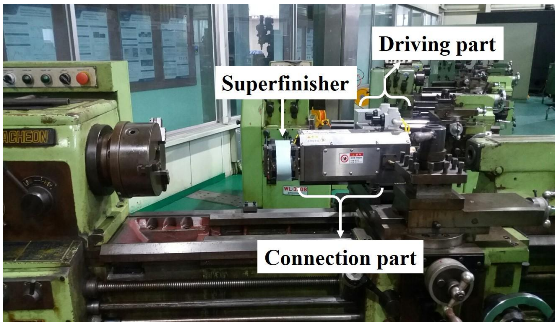

Fig. 2 Manufactured inner surface superfinishing equipment using turning machine

Table 1 Specification of the developed superfinishing machine

Items	Unit	Target value
Polishing film feed rate	mm/rev	Max 100
Oscillation amplitude	mm	4
Oscillation speed	rpm	Max 1800
Air pressure	bar	Max 10
Contact roller hardness	Hs	30, 50, 70, 90

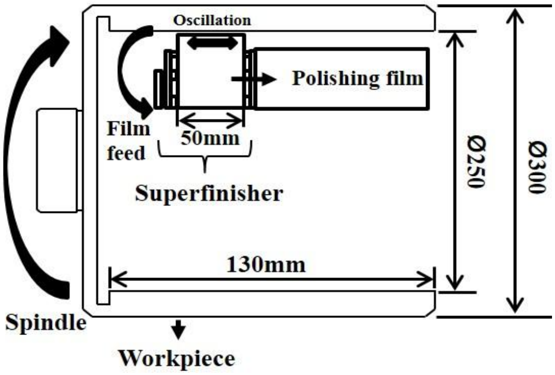

Fig. 3 Schematics of inner surface superfinishing equipment using in this experiment

3. Determination of optimum polishing time

Fig. 4 shows the behavior of the surface roughness (Ra) of the polished surface according to the polishing time for Al_2O_3 under these conditions : V_s = 112 rpm, f_f = 300 mm/min, V_o = 500 rpm, H_r = 30 Hs, P_c = 5 bar, G_r = 9 ㎛, Diamond MF film. The surface roughness was measured after polishing for 20 s.

The surface roughness was drastically improved, whereas the initial polishing process for removal of irregularities on the polishing surface proceeded. Apparently, the stable value of Ra at 0.1 ㎛ was maintained after approximately 60 s of elapsed time.

Of the results, the polishing time needed to reach the Ra value of 0.2 ㎛ required for the inner surface of the hydraulic reservoir was defined as the optimum polishing time (T_0). For instance, a small T_0 value indicates that the target surface roughness can be reached in a short time, and that the polishing condition minimizing T_0 is an efficient polishing condition.

A series of corrections was employed to give confidence in comparing the trends of the T_0 values under various polishing conditions. The curve fitting in Fig. 4 was the graphical representation from the output of a quadratic function using the least squares method. Here, the values on the horizontal axis were obtained by defining the T_0 value on the vertical axis at 0.2. The other values of T_0 were determined using same initial surface roughness, number of data, and experimental time.

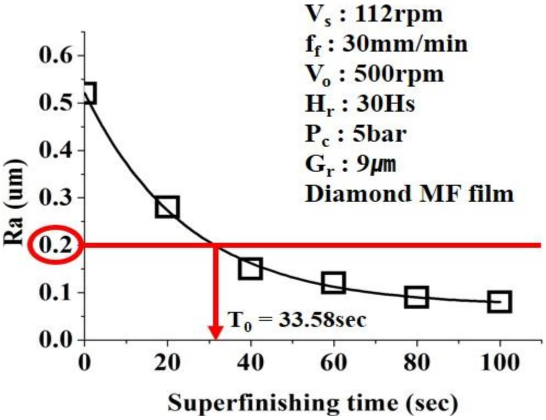

Fig. 4 Variation of roughness with superfinishing time and value of the proper polishing time (T_0)

4. Determination of optimum polishing conditions by Taguchi method

The polishing experiment employed the Taguchi method for selecting the optimum polishing conditions under the given conditions with the minimum experiment.

Experimental factors were selected in reference to previous studies[9-10], from a range of several factors that are presumed to have an impact on the results, such as the spindle speed of the specimen, the polishing film feed rate, the oscillation speed of the superfinisher, contact roller hardness, contact pressure between the specimen and the polishing film, and polishing film grain size. Additionally, the levels for each factor were selected based on flexibility, in reference to a previous research, as well as the experience of the experimenter within the range of safe operation of equipment. Consequently, the experimental conditions were set as indicated in Table 2.

Table 3 provides the experimental results, based on the table of orthogonal arrays of L8. Such results were considered for the signal-to-noise (SN) ratio and ANOVA analyses with such selection of the significant factors and optimal conditions. One essential factor for the SN ratio analysis is the different analytical characteristics to be applied depending on the results. In this study, an efficient process is indicated by achieving as small value of T_0 as possible to yield a short polishing time feasible for reaching the target surface roughness. This principle was the basis for the performed analyses.

Fig. 5 and Table 4 show the results of the SN ratio and ANOVA analyses, respectively. Here, spindle speed and oscillation speed were the significant factors for selection. Accordingly, the selected optimum conditions are shown in Table 5[9-10].

Table 2 Selection of factors and levels

Control factor	Symbol	Level 1	Level 2
Spindle speed (rpm)	V_s	32	112
Film feed rate (mm/min)	f_f	30	90
Oscillation speed (rpm)	V_o	100	500
Contact roller hardness (Hs)	H_r	30	90
Contact pressure (bar)	P_c	3	5
Polishing film grain size (㎛)	G_r	9	20

Table 3 Results of Taguchi method using orthogonal array $L_8(2^7)$

	V_s	f_f	V_o	H_r	P_c	G_r	T_0	SN ratio
1	32	30	100	30	3	9	186.43	-45.41
2	32	30	100	90	5	20	100	-40
3	32	90	500	30	3	20	112.62	-41.03
4	32	90	500	90	5	9	85.63	-38.65
5	112	30	500	30	5	9	33.58	-30.52
6	112	30	500	90	3	20	50.62	-34.09
7	112	90	100	30	5	20	88.37	-38.93
8	112	90	100	90	3	9	69.99	-36.90

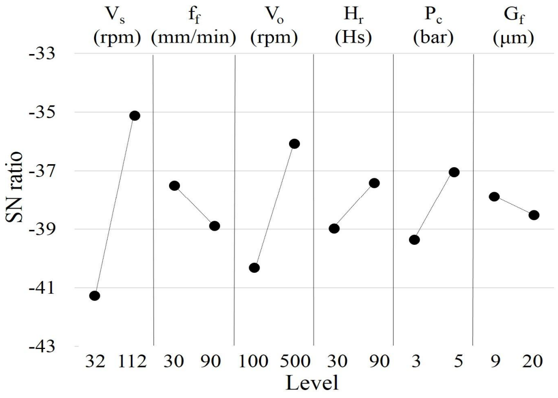

Fig. 5 Results of the SN-ratio analysis

Table 4 Results of the ANOVA analysis

P-Value Factor	Initial value	1st Pooling	2nd Pooling
V_s	0.238	0.070	0.024
f_f	0.907	-	-
V_o	0.337	0.13	0.065
H_r	0.440	0.233	0.138
P_c	0.447	0.240	0.144
G_r	0.842	0.757	-

Table 5 Selected optimum superfinishing conditions

	V_s	f_f	V_o	H_r	P_c	G_r	T_0	SN ratio
Op.	32	30	500	90	5	9	31.5	-29.97

5. Determination of optimum polishing conditions by Box-Behnken method

The Taguchi method only considered the selection of the optimum condition within the level set by the experimenter, and other conditions were not accounted for. Thus, after the reaction surface was created from the analysis of the influence between the set conditions, or rather, when the curvature effect on the response surface of the factor was judged, the optimum conditions were then selected using the response surface, for selecting the same conditions at the level between the set levels, and whose results were subsequently compared with those of the Taguchi method.

For the ANOVA analysis performed to the results of the Taguchi method, the experimental parameters and the level were selected by setting three factors : V_s, V_o, and P_c, in order of significance, as depicted in Table 6. Accordingly, the Box-Behnken method was applied to the experimental design, for a total of 15 experimental conditions, as in Table 7.

Table 8 shows the results of the ANOVA analysis for the creation of response surface based on the experimental results. Considering the result (P-Value) of the lack of fit term and pooling the non-significant term twice yielded a second-order term of the oscillation speed, an identified linear term as a significant factor, and the derivation of a response surface creation equality (Eq. (1)).

$$T_0 = 87.52 - 29.09V_s - 12.67V_o + 6.27P_c + 36.90V_o^2 \tag{1}$$

Table 6 Experimental factors and levels

Control factor	Symbol	-1	0	1
Spindle speed (rpm)	V_s	32	82	112
Oscillation speed (rpm)	V_o	100	300	500
Contact pressure (bar)	P_c	3	4	5

Table 7 Experiment design using Box-Behnken method

Standard order	V_s	V_o	P_c	T_0 (s)
1	-1	-1	0	180.26738
2	1	-1	0	94.96236
3	-1	1	0	160.3936
4	1	1	0	70.31251
5	-1	0	-1	103.1521
6	1	0	-1	68.25612
7	-1	0	1	103.43343
8	1	0	1	80.95688
9	0	-1	-1	129.1437
10	0	1	-1	96.9867
11	0	-1	1	143.9708
12	0	1	1	119.31427
13	0	0	0	70.01002
14	0	0	0	88.79781
15	0	0	0	92.02425

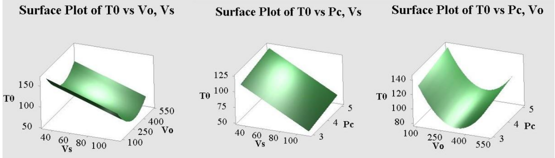

Fig. 6 Created response surface

Fig. 6 shows the response surface created using the derived equation. Here, the optimum conditions were spindle speed = 112 rpm, oscillation speed = 334 rpm, and contact pressure = 3 bar[11-14].

Moreover, the optimum superfinishing conditions were selected based on the results of both Taguchi and Box-Behnken methods, which yielded an oscillation speed and contact pressure different from those shown in Table 9. Such difference in optimum conditions was verified through experiments, which revealed the polishing time difference of approximately 2 s between the contact pressures of 3

Table 8 Result of ANOVA analysis (Box-Behnken method)

	1st		2nd		3th	
Source	F-Value	P-Value	F-Value	P-Value	F-Value	P-Value
Model	3.81	0.077	8.85	0.004	16.11	0.000
Linear	7.06	0.03	10.97	0.003	13.36	0.001
V_s	17.13	0.009	26.63	0.001	32.44	0.000
V_o	3.25	0.131	5.05	0.055	6.15	0.033
P_c	0.79	0.413	1.24	0.299	1.5	0.248
Square	4.33	0.074	6.73	0.014	24.35	0.001
$V_s \times V_s$	0.13	0.733	0.2	0.665	-	-
$V_o \times V_o$	12.88	0.016	20.02	0.002	24.35	0.001
$P_c \times P_c$	0.00	0.971	0.00	0.963	-	-
2-way Interaction	0.05	0.984	-	-	-	-
$V_s \times V_o$	0.01	0.909	-	-	-	-
$V_s \times P_c$	0.1	0.767	-	-	-	-
$V_o \times P_c$	0.04	0.858	-	-	-	-
Lack-of-Fit	8.52	0.107	4.39	0.197	3.39	0.248

Table 9 Comparison of optimum superfinishing conditions between Taguchi and Box-Behnken methods

	V_s	f_f	V_o	H_r	P_c	G_r	T_0
B-B	112	30	334	90	3	9	39.1694
Change P_c	112	30	334	90	5	9	37.3208
Taguchi	112	30	500	90	5	9	52.5769

Table 10 Selected optimum superfinishing conditions

Factor	Level
Spindle speed (rpm)	112
Film feed rate (mm/min)	30
Oscillation speed (rpm)	334
Contact roller hardness (Hs)	90
Contact pressure (bar)	5
Polishing film grain size (㎛)	9

and 5 bar. When the oscillation speed was changed, the polishing time difference elevated to 13 s, for an optimum value of 334 rpm. Table 10 shows the defined optimum superfinishing conditions.

6. Uniformity of polishing surface

Depending on the application of an aircraft, its typical reservoir manufacturing length is 270 mm. In this study, the width of the abrasive film was 50 mm, which made the transfer of the superfinishing machine for polishing of the whole area of the material. With this objective, static polishing was the initial process employed for polishing as much of the abrasive film width, to effect a uniform polish for the entire specimen. This was succeeded by transfer polishing. On an advantageous note, applying such method creates the advantage for polishing uniformity of the surface. Nevertheless, an excessive, slow-feeding speed may lead to an inefficient polishing process due to the increase in time. Thus, the appropriate polishing time should be set.

Furthermore, experimental conditions selected from the optimum conditions by the Taguchi method were accompanied by selection of feed rate of the super finishing machine and polishing time, as the parameters with great impact on the uniformity of the surface roughness, after the polishing process (Table 11).

For surface roughness measurements, 8 points were considered within 1 cm intervals to the polishing section, whereas 6 points were in the circumference direction, for a total of 48 point measurements, which were exploited comparison of the resulting uniformity (Fig. 7).

For this experiment, the polishing time of 48 and 69 s were not effective in satisfying the required surface roughness. That is, in those polishing times, the

Table 11 Experimental conditions

Superfinishing feed rate (mm/rev)	f_S	0.558	0.385	0.279
Polishing speed (mm/s)	V_p	1.041	0.719	0.521
Polishing time (sec)	T_p	48.003	69.57	96
Number of experiment	No.	3	2	1
Final polishing time (sec)	T_p	144	139.14	96

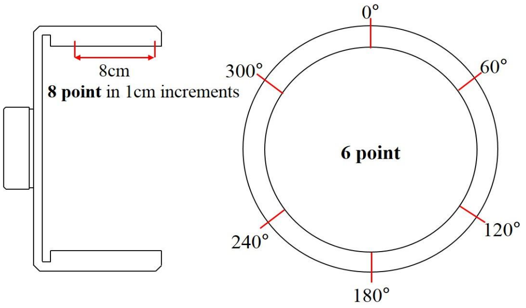

Fig. 7 Measurement points for validation of surface roughness

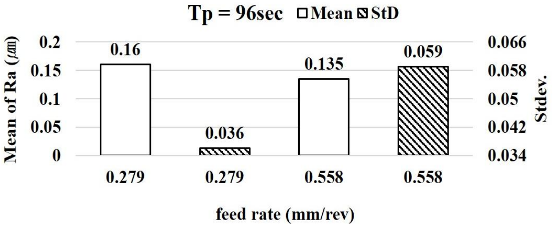

Fig. 8 Experimental result (T_p = 96 s)

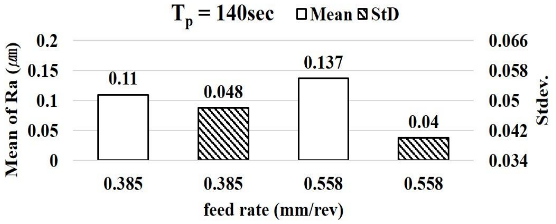

Fig. 9 Experimental result (T_p = 140 s)

uniformity was not that good; therefore, those were not the proper transfer polishing time. Interestingly, increasing the time to 96 s yielded excellent surface roughness, as depicted in Fig. 8, with an apparent standard deviation of 0.03 ㎛, at the feed rate of 0.279 mm/rev.

Additionally, increasing the polishing time to an excessive 140 s (Fig. 9) gave a 0.007 ㎛ difference in the standard deviation. Such value was insignificant, which indicates that no further surface roughness improvement could result from excessive polishing.

7. Conclusion

The secondary polishing stage during the manufacture of a hydraulic reservoir was improved through the conducted experiments, which employed the design of experiment approach, for optimum conditions determination. The generalizations for deriving the conditions yielding a uniform surface after polishing could be stated as follows:

1. After the optimum superfinishing conditions were defined for the Al_2O_3 materials through the Taguchi and Box-Behnken methods, the results of the verification experiment showed a significant difference in the oscillation speed and contact pressure. The optimum conditions include: spindle speed = 112 rpm, polishing film feed rate = 30 mm/rev, oscillation speed = 334 rpm, contact roller hardness = 90 Hs, contact pressure = 5 bar, polishing film grain size = 9 ㎛.
2. The polishing time of 96 s at a feed rate of 0.279 mm/rev ascertained excellent surface roughness uniformity. Likewise, the uniform surface could be obtained with slower transfer speed, but not higher.

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