Paper

Optimization of Bonding and Sizing Process for Automotive Wet Clutch Discs applying “Robust Design”

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Abstract: Many parts for transmitting power are incorporated in an automatic transmission of an automobile. The technical problems of the wet clutch disc (DISC) having important functions related to gear shifting are to improve the automatic gear shifting performance and to ensure the stability of the power transmission torque in the contact action between the DISCs. DISC is manufactured by adhesive bonding of friction material (Fa) and iron core plate (C/P). In particular, the stabilization of the DISC adhesive strength and thickness accuracy suppresses fluctuations in the surface friction coefficient and is effective in reducing the shock phenomenon during shifting. In this study, the robustness of the DISC bonding sizing method by applying robust design was aimed at stabilizing the bonding strength and thickness accuracy, and the optimum processing conditions were extracted to optimize the mass production method.

Keywords: Wet clutch disc, Transmission performance, Robust design, Functionality evaluation, Energetic S/N ratio,

1. Introduction

As shown in Fig. 1, many parts for transmitting power are incorporated in the automatic transmission of automobiles. The technical problem of the wet clutch disk (DISC), which has important functions related to gear shifting, is to improve the automatic gear shifting performance and to make the power transmission torque robust in the contact action between the DISCs [1]~[4]. DISC is manufactured by adhesive bonding of a friction material (Fa) impregnated with a synthetic resin in special raw paper and a core plate (C/P) that is an iron material. In the field of tribology technology, stabilizing the adhesive strength and thickness accuracy of DISC is extremely effective in reducing the rate of change of the dynamic friction coefficient (μ) on the surface and increasing the robustness of the power transmission torque [5]~[7]. In particular, stabilization of the DISC plate thickness accuracy after bonding has been reported to be effective in reducing fluctuations in the surface friction coefficient and reducing shock phenomena during shifting [8] [9].

In this study, we examined the mechanism of adhesive penetration during bonding and approached the optimization of the bonding sizing (plate thickness uniformity) method by verifying the correlation between the bonding strength and the plate thickness accuracy using a robust design.

Figure 1: Components in clutch pack.

2. Outline of bonding sizing method

In the DISC production process, in the pre-bonding process, Fa and C/P are temporarily attached by applying an adhesive, followed by a drying process for the purpose of volatilization of the solvent and water classification contained in the adhesive. As shown in Fig. 2, a hydraulic hot plate press type adhesive sizing method is adopted to ensure both DISC adhesive strength and plate thickness uniformity. The DISC after provisional application placed in the pressurization/heating station is lowered and pressurized (press load: 400kN) by the cylinder thrust by hydraulic control. At the same time, heating with a hot plate heater for a certain time (mold surface temperature; 250°C. $\pm$ 10). The temperature of the hot plate heater is controlled by PID control

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Figure 2: Bonding and Sizing process.

Figure 3: Adhesion failure phenomenon due to Fa peeling.

using an embedded heater and a thermocouple. Moreover, the side surface of the hot plate mold has a heat insulating structure for the purpose of increasing thermal efficiency.

3. Quality problem and inference of factors

3.1 Extract quality problem As shown in Fig. 3, Fa peeling occurs in part after bonding sizing, and there is a quality problem of defective bonding. Fa peeling significantly deteriorates the automatic transmission performance which is an important function of the clutch disk [10]. Moreover, it will lead to the occurrence of a serious failure related to the safe driving of the automobile.

3.2 Inference of factors Figure 4 is a photograph showing the Fa peeling phenomenon in detail. In Fig. 4(a), the Fa peeled part occurred in one direction (facing direction) of the DISC, and the expansion displacement of the DISC due to pressure and heating during bonding was observed. In Fig. 4(b), almost no adhesive remained in the peeled portion on the C/P side, and it was observed that the adhesive penetrated into the peeled Fa.

As shown in Fig. 5, in the drying process after the adhesive application and tacking process, the solvent and moisture contained in the adhesive remain due to insufficient drying, and they penetrate into Fa. The non-uniformity in the amount of adhesive applied is presumed to be a Fa peel-

(a) Fa peeling location

(b) Application state of adhesive

Figure 4: Verification/estimation of adhesion failure mode.

Figure 5: Adhesive unevenness mechanism.

ing factor.

4. Application of “Robust design”

In the previous chapter, we extracted the quality problems of DISC adhesion failure due to Fa peeling and made inferences about the factor system. In this chapter, we approached the stabilization of DISC adhesive strength and plate thickness accuracy of the adhesive sizing method by applying the functional evaluation method of parameter design, which is the central method of “Robust design”.

4.1 Overview of Robust design Figure 6 shows the concept of robust design in quality engineering. The concept of improving technology to bring it closer to what it should be is called robust design. Robust means stability in quality engineering. Parameter design is one of the central methods of robust design, and is a method for evaluating functionality and determining system parameter values. Parameters are design constants and components of the sys-

tem and are selected as control factors in parameter design experiments. In the combination of system parameters, robustness is improved by deliberately generating variations by noise factors and optimizing the level of strong control factors that can counter the variations [11]~[13].

In parameter design, it is important to understand the target function of the system. The objective function refers to the role that the system should play, and the quality characteristics are divided into the following four types. By taking up the objective function, the design information can be utilized in other similar systems, and the versatility of the technology is expanded [14] [15].

- (a) Preferably small characteristics (nonnegative and smaller the better)
- (b) Preferably large characteristics (nonnegative and larger the better)
- (c) Preferably target characteristics (with target value)
- (d) **Dynamic characteristics (I/O correlation, output stability)**

In this study, stabilization of DISC adhesive strength and plate thickness accuracy in the adhesive sizing method is the objective function, and the optimum parameter level condition for obtaining it is extracted by dynamic characteristic evaluation.

The evaluation procedure for robust design is shown in Fig. 7. In robust design, start by clarifying the functions of the system. We define it as an ideal function of the input (signal factor) and output (characteristic value) of the system. In order to realize the ideal function, the experiment is performed efficiently using the orthogonal table, and the effect of each control factor is grasped by the SN ratio, sensitivity, and slope β . After that, the optimum conditions and comparison conditions are determined from the factor-effect diagram, and the average of each process is obtained to estimate the magnitude of improvement. Finally, a confirmation experiment is performed to verify the reproducibility of the optimum condition gain.

4.2 Definition of ideal function The ideal function of many system technologies is that the output varies linearly with respect to the input. The total output characteristic value of the system (total work) must be proportional to energy or work. Especially in the bonding sizing process of DISC, there are input energy (bonding time, etc.) necessary to obtain bonding strength and energy (C/P surface temperature, etc.) that affects bonding time. In robust

Figure 6: Robust design.

design, a “Functional evaluation method” that defines functionality based on energy conversion and quickly evaluates its stability is important [16].

In this study, we focused on the fact that the ideal function representing the relationship between input and output becomes linear with energy conversion, and defined an ideal functional state as shown in Fig. 8. The main purpose of the “Functional evaluation method” is to efficiently extract parameters that reduce variations and fluctuations by bringing the stable function of adhesive strength and plate thickness accuracy closer to the ideal state. The difference from the ideal state can be considered as some energy loss.

4.3 Energetic S/N ratio The conventional SN ratio (Signal-to-Noise ratio) used in parameter design, which represents a measure of variation, may change depending on the size (range) of the input signal and the number of data. There is a problem that engineers must acquire and analyze data while keeping this in mind. The idea of the SN ratio is to evaluate the dispersion and non-linearity from the ideal function state ($y = \beta M$) by considering the functional stability to be poor. The “Energetic S/N ratio” adopted in this study is a new SN ratio that was researched by a research member of the Kansai Quality Engineering Society, and was announced in June 2008 [17].

Figure 7: Robust design procedure.

Figure 8: Definition of ideal function .

Table 1: Correspondence table for SN ratio calculation.

		Input signal M				
		M_1	M_2	M_3	$\cdots$	M_k
Noise factor N	N_1	y_{11}	y_{12}	y_{13}	$\cdots$	y_{1k}
	N_2	y_{21}	y_{22}	y_{23}	$\cdots$	y_{2k}
	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
	N_n	y_{n1}	y_{n2}	y_{n3}	$\cdots$	y_{nk}

Since all technologies involve energy conversion and transmission, an energy perspective is important in technology development and level evaluation. The energetic S/N ratio is a technical quality evaluation scale based on how various types of energy are used. The technical quality here means whether more energy input to the system can be stably used for the purpose (output) indefinitely.

In the energetic S/N ratio, the energy is decomposed into an active component (S_β) and a harmful component (S_N), and is calculated from these ratios. When using SN ratio in parameter design, it is expressed in decibel values [db] as 10 times the common logarithm. The following is the basic formula for energetic S/N ratio (η_E).

As shown in Table 1, noise factor n level, signal factor k level, noise factor level i ($i = 1, 2, \dots, n$), signal factor level j ($j = 1, 2, \dots, k$), suppose that the output y_{ij} is obtained.

- Total variation component S_T

This is the sum of the squares of nk pieces of data y_{ij} and shows the variation from $y = 0$.

$$S_T = \sum_{i=1}^n \sum_{j=1}^k y_{ij}^2 \quad (1)$$

- Average slope size β_{N0}

For some dynamic characteristics of the input signal, the slope of the noise factor N_i level β_{Ni} is obtained by considering the effective component as the average slope.

$$\beta_{Ni} = \frac{\sum_{j=1}^k M_j y_{ij}}{\sum_{j=1}^k M_j^2} = \frac{L_{Ni}}{r} \quad (2)$$

Here,

r : Effective divisor, L_{Ni} : Linear format

$$r \equiv \sum_{j=1}^k M_j^2 \quad (3)$$

$$L_{Ni} \equiv \sum_{j=1}^k M_j y_{ij} \quad (4)$$

$$\therefore \beta_{N0} = \frac{\sum_{i=1}^n \beta_{Ni}}{n} \quad (5)$$

- Average slope fluctuation (active ingredient) S_β

The variation of the average slope is expressed as the sum of squares of the size $y = \beta_{N0} M$.

$$\begin{aligned} \therefore S_\beta &= n \sum_{j=1}^k (\beta_{N0} M_j)^2 = n \beta_{N0}^2 \sum_{j=1}^k (M_j)^2 \\ &= nr \beta_{N0}^2 \end{aligned} \quad (6)$$

- Harmful component S_N

The harmful component represents the variation of the difference between each data and the proportional equation of the average slope, and is obtained by subtracting the effective component from the total variation component.

$$\therefore S_N = \sum_{i=1}^n \sum_{j=1}^k (y_{ij} - \beta_{N0} M_j)^2 = S_T - S_\beta \quad (7)$$

- SN ratio η_E

$$\eta_E = 10 \log \left(\frac{S_\beta}{S_T - S_\beta} \right) = 10 \log \left(\frac{S_\beta}{S_N} \right) (db) \quad (8)$$

4.4 Analysis by “Dynamic characteristic” It was verified by “Dynamic characteristic evaluation (energetic S/N ratio)” with the objective function of stabilizing the DISC adhesive strength and plate thickness accuracy in the adhesive sizing method.

Dynamic characteristic is a characteristic that examines the output by changing the input. It is a method to evaluate the condition that minimizes the two-dimensional variation of input and output among various combinations of factors. Even under various usage conditions and environments, it is desirable that the input and output signals are in a proportional relationship, and a more robust improvement effect can be obtained in terms of reproducibility, precedence, and versatility.

4.5 Determination of level tables and factors Table 2 shows the control factor level table in this experiment. As control factors, seven parameters were extracted: [Drying method], [Press load], [Heater capacity], [Adhesive coating thickness], [DISC transport speed], [Drying temperature], and [Dry hot air pressure]. Table 3 shows the level table

Table 2: Control factors.

Symbol	Parameter	Unit	Level		
			1	2	3
A	Drying method	[Pass]	2	1	-
B	Press load	[$\times 10^2$ kN]	2.2	3.2	4.2
C	Heater capacity	[kw]	6.5	7.5	8.5
D	Coating thickness	[μ m]	7	9	11
E	Transport speed	[m/min]	8	10	12
F	Drying temperature	[°C]	100	120	140
G	Hot air pressure	[kgf/cm ²]	1.5	2.5	3.5
H	Virtual factor	[—]	e1	e2	e3

Figure 9: Adhesive energy characteristics for each experiment.

Table 3: Noise factors.

	Unit	Noise factors	
C/P surface temperature	[°C]	N1	N2
		23±3	0±3

with the C/P surface temperature (N1; 23 ± 3 °C, N2; 0 ± 3 °C) before tacking as noise factor.

Table 4 shows the L18 orthogonal data table of this experiment, and the adhesion time (M1; 4.0 [second], M2; 5.0 [second], M3; 6.0 [second]) was set as the input signal factor. The measurement data, which is the output characteristic value, is a plate thickness stability factor [dimensionless unit] obtained by calculating the reciprocal of the plate thickness difference average value at 6 locations per DISC. The purpose of setting the output characteristic value

is to evaluate the stability of the adhesive strength and the plate thickness accuracy as the plate thickness difference is smaller and the plate thickness stability rate is increased.

4.6 Consideration of adhesive energy characteristics

Figure 9 shows the results of the discussion on the relative relationship between Fa peeling and adhesion energy characteristics from L18 orthogonal table experimental results. The horizontal axis of the graph is the experiment number, and the vertical axis represents the characteristic value based on the load energy related to adhesion. From the graph, it can be considered that the expansion of C/P and the penetration of the adhesive into Fa are promoted and Fa peeling occurs under the condition that the pressure and heating energy related to adhesion is large and the drying energy is insufficient.

Figure 10 shows the input/output relationship between

Table 4: L18 orthogonal table/experimental data.

EXP. NO.	Control factors									M1		M2		M3		Fa peeling
	A	B	C	D	E	F	G	H		N1	N2	N1	N2	N1	N2	
1	2	2.2	6.5	7	8	100	1.5	e1		20.00	20.83	16.95	14.71	13.70	14.93	
2	2	2.2	7.5	9	10	120	2.5	e2		8.20	9.43	6.80	8.00	10.99	10.53	
3	2	2.2	8.5	11	12	140	3.5	e3		5.03	5.49	5.13	5.29	5.52	4.93	
4	2	3.2	6.5	7	10	120	3.5	e3		18.18	20.00	16.67	15.38	14.08	14.71	
5	2	3.2	7.5	9	12	140	1.5	e1		13.70	14.71	13.33	12.20	11.63	12.50	
6	2	3.2	8.5	11	8	100	2.5	e2		4.00	3.65	3.30	4.20	3.52	3.77	~
7	2	4.2	6.5	9	8	140	2.5	e3		17.86	19.61	16.67	14.93	13.89	14.49	
8	2	4.2	7.5	11	10	100	3.5	e1		5.41	5.21	4.78	4.83	3.34	3.68	
9	2	4.2	8.5	7	12	120	1.5	e2		3.82	3.69	3.14	4.18	3.50	3.62	~
10	1	2.2	6.5	11	12	120	2.5	e1		5.85	5.65	4.78	5.41	3.82	4.22	
11	1	2.2	7.5	7	8	140	3.5	e2		12.35	11.63	14.08	12.66	9.90	11.24	
12	1	2.2	8.5	9	10	100	1.5	e3		6.67	5.88	6.21	7.52	5.15	5.56	
13	1	3.2	6.5	9	12	100	3.5	e2		6.85	6.45	6.71	7.14	6.13	5.62	
14	1	3.2	7.5	11	8	120	1.5	e3		6.45	6.85	6.25	6.49	7.52	6.06	
15	1	3.2	8.5	7	10	140	2.5	e1		4.24	3.91	4.48	3.86	4.03	3.41	~
16	1	4.2	6.5	11	10	140	1.5	e2		7.30	6.85	7.09	6.62	6.41	5.65	
17	1	4.2	7.5	7	12	100	2.5	e3		8.20	8.70	6.99	8.33	11.24	8.77	
18	1	4.2	8.5	9	8	120	3.5	e1		2.90	2.34	3.10	2.23	3.56	2.94

Figure 10: Relationship between bonding time and thickness stability factor.

the adhesion time (horizontal axis), which is the input for each L18 orthogonal table experiment No., and the plate thickness stability factor (vertical axis), which is the output. The graph shows that the relationship between input and output is a characteristic element that evaluates the presence or absence of linearity related to the stability of adhesive strength and plate thickness accuracy.

4.7 Calculation of SN ratio and slope β The characteristic evaluation of the functionality evaluation method uses the SN ratio of dynamic characteristics, and it is ideal that a stable output can be obtained even if there are various noise that affect the functional characteristics. To evaluate the functionality, change the input signal and examine the linearity of the output. This is the SN ratio of the dynamic characteristics.

Table 5: SN ratio and slope β .

EXP. NO.	A	B	C	Parameter D E F G H					SN ratio (db)	Slope β (-)
1	2	2.2	6.5	7	8	100	1.5	e1	9.75	3.20
2	2	2.2	7.5	9	10	120	2.5	e2	16.14	1.78
3	2	2.2	8.5	11	12	140	3.5	e3	15.31	1.02
4	2	3.2	6.5	7	10	120	3.5	e3	10.79	3.15
5	2	3.2	7.5	9	12	140	1.5	e1	12.51	2.51
6	2	3.2	8.5	11	8	100	2.5	e2	14.00	0.73
7	2	4.2	6.5	9	8	140	2.5	e3	10.83	3.11
8	2	4.2	7.5	11	10	100	3.5	e1	9.43	0.86
9	2	4.2	8.5	7	12	120	1.5	e2	13.80	0.71
10	1	2.2	6.5	11	12	120	2.5	e1	9.97	0.94
11	1	2.2	7.5	7	8	140	3.5	e2	12.58	2.32
12	1	2.2	8.5	9	10	100	1.5	e3	11.95	1.19
13	1	3.2	6.5	9	12	100	3.5	e2	13.06	1.25
14	1	3.2	7.5	11	8	120	1.5	e3	15.36	1.29
15	1	3.2	8.5	7	10	140	2.5	e1	13.36	0.77
16	1	4.2	6.5	11	10	140	1.5	e2	12.57	1.28
17	1	4.2	7.5	7	12	100	2.5	e3	16.17	1.72
18	1	4.2	8.5	9	8	120	3.5	e1	16.56	0.56
MAX									16.56	
MIN									9.43	

Table 6: Factor effect table.

Factors	SN ratio Total average 13.008				Slope β Total average 1.577			
	Dispersion	Level 1	Level 2	Level 3	Dispersion	Level 1	Level 2	Level 3
A	4.512	2.0	1.0	–	1.832	2.0	1.0	–
		-0.501	0.501	–		0.319	-0.319	–
B	0.693	2.2	3.2	4.2	0.21	2.2	3.2	4.2
		-0.392	0.173	0.219		0.164	0.04	-0.204
C	15.627	6.5	7.5	8.5	2.767	6.5	7.5	8.5
		-1.844	0.689	1.155		0.58	0.167	-0.747
D	1.130	7.0	9.0	11.0	1.487	7.0	9.0	11.0
		-0.268	0.501	-0.233		0.402	0.155	-0.557
E	1.944	8.0	10.0	12.0	0.411	8.0	10.0	12.0
		0.172	-0.636	0.463		0.290	-0.071	-0.219
F	2.941	100.0	120.0	140.0	0.307	100.0	120.0	140.0
		-0.615	0.762	-0.147		-0.085	-0.171	0.256
G	0.856	1.5	2.5	3.5	0.065	1.5	2.5	3.5
		-0.349	0.401	-0.053		0.12	-0.07	-0.05
H	5.359	e1	e2	e3	0.531	e1	e2	e3
		-1.078	0.684	0.394		-0.102	-0.233	0.335

In this experiment, “Energetic S/N ratio based on zero-point proportionality” is adopted, and Table 5 shows the SN ratio and slope β value from the output data. Here, the slope β is an index of the degree of variation with respect to the magnitude of the average output slope, and is expressed as a true number.

4.8 Factor effect analysis Figure 11 shows the SN ratio and slope β for each control factor in a factorial effect diagram. The factor effect table (Table 6) shows the influence of a factor or combination of factors on characteristic values, and the diagram showing it is a factor effect diagram. The meaning of this diagram extracts factors that have a large effect on the SN ratio and do not affect the output slope β . It can be judged that the level is highly significant in sta-

bilizing the DISC adhesive strength and thickness accuracy in the adhesive sizing method. In Fig. 11, the optimum levels are the factors [A1: 2.0], [B3: 4.2], [C3: 8.5], [D2: 9.0], [E3: 12.0], [F2: 120.0], [G2: 2.5], and [H2: e2]. The characteristic values obtained vary with respect to the average value for each level. This variability scale was evaluated in the analysis of variance table (Table 7).

From this table, [A; drying method], [C; heater capacity] and [D; adhesive coating thickness], which are factors with a large dispersion ratio, affect the stability of DISC adhesive strength and plate thickness accuracy. It can be estimated that the factor is high. Table 8 shows the optimal combination of control factor levels to obtain stable DISC adhesive strength and thickness accuracy in the adhesive sizing

Figure 11: Factor effect diagram.

Table 7: Variance table.

SN ratio Factors	Sum square	Freedom	Dispersion	Contribution
A	4.512	1	4.512	0
B	1.386	2	0.693	0
C	31.254	2	15.627	4.416
D	2.26	2	1.13	0
E	3.888	2	1.944	0
F	5.881	2	2.941	0
G	1.712	2	0.856	0
H	10.718	2	5.359	0
Total	88.94	17	5.232	

Slope β Factors	Sum square	Freedom	Dispersion	Contribution
A	1.832	1	1.832	12.05
B	0.421	2	0.21	0.5
C	5.534	2	2.767	37.716
D	2.973	2	1.487	19.077
E	0.822	2	0.411	3.419
F	0.614	2	0.307	1.907
G	0.131	2	0.065	0
H	1.061	2	0.531	5.159
Total	13.74	17	0.808	

Table 8: Optimization results.

Condition	A	B	C	D	E	F	G	H	Estimated		Gain	
									SN ratio	Slope β	SN ratio	Slope β
Optimal	1	4.2	8.5	9	12	120	2.5	e2	17.694	-0.231	9.559	-3.495
BM	2	2	6.5	7	8	100	1.5	e1	8.135	3.264		

method.

4.9 Reliability evaluation of L18 orthogonal table experiment

As shown in Table 8, the L18 orthogonal table test results were checked for reliability (additivity) based on the result that the estimated value of the optimum condition was higher than the benchmark condition (BM) and the gain was secured. First, the maximum value and the minimum value of the SN ratio obtained in the L18 orthogonal table experiment are obtained. The judgment method can be judged to be reliable if the difference from the SN ratio of the BM condition estimated from the value of 10% of the difference is within 10% from the statistical rule of thumb [18].

Table 9 shows the reliability evaluation results. Evaluate the dispersion of the proportional relationship between the DISC bonding time and plate thickness stability rate, and it is a desirable condition for stabilizing the DISC bond strength and plate thickness accuracy in the bonding sizing method, it is judged that the L18 orthogonal table experiment is reliable.

Table 9: Reliability of L18 orthogonal experiment.

L18 orthogonal exp.		By inverse estimation	
SN ratio		Reliability check	
Maximum	16.56	Obtained from exp.	9.75
Minimum	9.43	SN ratio of BM.	8.14
Difference	7.13		-
10% of diff.	0.71	$\geq$	-1.61
Judgment		Reliable	

4.10 Evaluation of reproducibility by confirmation experiment

The purpose of the confirmation experiment is to confirm whether the output is stable even when the time, place, and environment change compared to the orthogonal table experiment. Table 10 shows the evaluation results of the confirmation experiment data. In the confirmation experiment, the SN ratio of the selected optimum condition and BM condition is obtained, and the same two types as in the orthogonal table experiment are performed again to obtain the SN ratio. By comparing the difference

Table 10: Reliability of L18 orthogonal experiment.

Signal factor	M1; 4.0(s)		M2; 5.0(s)		M3; 6.0(s)		Slope β	SN ratio
Noise factor	N1	N2	N1	N2	N1	N2	β	η
BM	8.2	4.5	17.1	5.6	11.2	8.8	1.85	7.68
Optimal	18.2	13.7	19.1	14.1	18.0	19.3	3.37	16.31

Figure 12: Input/output linearity verification results.

Table 11: Reproducibility of confirmation experiment.

	SN ratio [db]		
	Estimated	Confirmed	Reproducibility
BM	8.14	7.68	94%
Optimal	17.69	16.31	92%
Gain	9.55	8.63	90%
Repro.	70% ≤	90%	≤ 130%
Gain diffe.	0.92	≤ ±3dB	
Judgment	Reproducible		
Thickness stability	39%		

between the estimated values of the two and the difference (gain) in the confirmation experiment, the reproducibility of the experiment is examined [18].

Table 11 shows the reproducibility evaluation results in the confirmation experiment. In parameter design, if the reproducibility of gain (%) is within the range of 70% to 130%, or the gain difference (db) is within ± 3 db, it can be judged that there is reproducibility. In this experimental result, the reproducibility of the gain was 90% and the gain difference was 0.92 (db). It was judged that there was reproducibility. Furthermore, the plate thickness stability with respect to the BM condition was improved by about 40%, and it was shown that the optimum condition extracted was appropriately selected and approached the defined ideal function state.

Figure 12 is a graph comparing the input and output variations and the linear relationship between the optimum and BM condition in the verification experiment. It shows the change of output (plate thickness stability factor) with respect to input (adhesion time), and it can be seen that the optimal condition is a stable linear proportional relationship with less variation than the BM condition.

4.11 Process capability evaluation by confirmation experiment

Table 12 shows the evaluation results of process capability under BM conditions and optimum conditions for the DISC thickness standard (2.50 ± 0.03 mm) after adhesion sizing by a confirmation experiment. The measurement data represents the average value of the plate thickness at 6 locations per DISC, and the number of samples is $n = 20$ (DISC).

“Process capability” is the probability capability that falls within the product specifications for quality. The “Process Capability Index (C_p)” is used as a measure that shows the degree of variation in quality characteristics due to process variations and the stability with respect to the standard width. $C_p \geq 1.00$ is necessary, and if $C_p \geq 1.33$, it can be determined that the process capability is sufficient. From the results of Table 12, the process capability is insufficient at $C_p = 0.75 < 1.33$ under the BM condition, but the process capability is sufficient at $C_p = 1.53 \geq 1.33$ under the optimum condition.

C_p is calculated by the following formula.

$$C_p = \frac{USL - LSL}{6\sigma} \quad (9)$$

USL : upper limit specification value

LSL : lower limit specification value

σ : Standard deviation

$$\sigma = \sqrt{\frac{1}{n} \sum_{i=1}^n (x_i - \bar{x})^2} \quad (10)$$

n : Total number of data

x_i : Individual data

$\bar{x}$: Average value

Table 12: Process capability index.

BM condition		Optimal condition	
Sample	Data	Sample	Data
1	2.540	1	2.500
2	2.540	2	2.510
3	2.520	3	2.510
4	2.530	4	2.500
5	2.520	5	2.495
6	2.540	6	2.510
7	2.505	7	2.510
8	2.510	8	2.500
9	2.520	9	2.520
10	2.510	10	2.510
11	2.535	11	2.500
12	2.520	12	2.505
13	2.510	13	2.500
14	2.530	14	2.500
15	2.495	15	2.495
16	2.520	16	2.500
17	2.540	17	2.510
18	2.535	18	2.500
19	2.535	19	2.500
20	2.530	20	2.510
Average	2.524	Average	2.504
σ	0.013	σ	0.007
C_p	0.75	C_p	1.53
STW.	0.060	STW.	0.060
USL.	2.530	USL.	2.530
LSL.	2.470	LSL.	2.470

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5. Conclusion

In this study, we dealt with the quality issues of adhesion failure and uneven thickness in DISC adhesion sizing process. In particular, we approached the problem of gear shifting performance and power transmission torque deterioration, which are important functions of DISC, due to Fa peeling and uneven thickness. Focusing on the correlation between DISC adhesive strength and plate thickness accuracy, we verified the optimization of the processing conditions of the adhesive sizing method using the robust design functionality evaluation method.

As a result of research, we considered the cause system of Fa peeling phenomenon, which is poor adhesion, and applied functional evaluation method. The optimum processing conditions contributing to the stabilization of DISC adhesive strength and plate thickness accuracy could be clarified. In addition, the reproducibility of the optimum conditions obtained was evaluated, and it was confirmed that the plate thickness stability was improved by about 40% compared to the BM conditions and the process capability was improved by about 50% ($C_p = 0.75 \rightarrow 1.53$).

Improving automatic transmission performance of automobile automatic transmission is an ongoing technical proposition. In future research, we plan to tackle issues related to the relative thickness accuracy of DISCs installed in multiple transmissions and their effects on gear shifting performance.

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