Optimization of Coil Baking Parameters Using Design of Experiments

Phantasak Punnarungsri, Wimalin Laosiritaworn

***Abstract*—Hard disk drives are a crucial component for data storage computers. One of the important tools in a hard disk drive is the hard disk actuator which influenced the drive quality. The hard disk actuator main component was a coil attached to an actuator arm. The coil quality has direct effect on the hard disk drive's performance. At present, the study found that the companies that manufactured hard disk drive actuator faced problems in coil production. One of the problems occurred during the coil baking procedure because there was no proper parameters set for the oven. Therefore, the coil transformed or swelled and led to wrong sizes. The purposes of this research were to seek for the best coil baking parameters and analyze other factors affecting coil baking. The research applied experimental design methodology to find the most optimal parameters. The research utilized three-level factorial design considering 4 factors with 3 levels of factors. The experiment then measured the difference of coil thickness before and after the baking. The control factors were baking durations, baking temperatures, coil positions in the oven, and the pressure levels of the oven air duct. The research found that all factors affected the coil baking. The optimal parameters were at baking duration of 6 hours, oven temperature at 175 ^{o}C, middle level in the oven and low level air duct pressure.**

***Index Terms*—Experimental design, factorial design experiment, three-level factorial design experiment, coil baking**

I. Introduction

Electronic industry is essential to Thailand's economic expansion. The number one export electronic products are computers along with their appliances and components. The hard disk drives are included and have been the main export product of Thailand. The hard disk drive industry is one of the greatly expanding industries nowadays due to the exceedingly high demand. Moreover, hard disk drives tend to be widely used as a component in other electronic products. Therefore, the result of the hard disk drive industry expansion leads to development and growth in other involving industries. It is obvious that the hard disk drive industry is very important to industrial and economic development in Thailand.

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The actuator as shown in figure 1 is regarded as an essential component to the quality of the hard disk drive. The main components of an actuator are a coil, an actuator arm, and a head which function in reading and deleting data on the hard disk drive. The electric current that runs through the coil allows the operation; the electric current flows to the coil causing voice coil motor assembly to operate and move the actuator. Vibration and actuator movement control make the data readable and deletable.

Fig 1: Components of Actuator

Coil then is the important part of hard disk drive that has direct effect on the operating efficiency of the drive. The false operations causing from coil on the actuator arm may be resulted from conductivity, resistance, coil shape, etc. The properties differ depending on hard disk drive types.

The production process of coil is shown in figure 2.

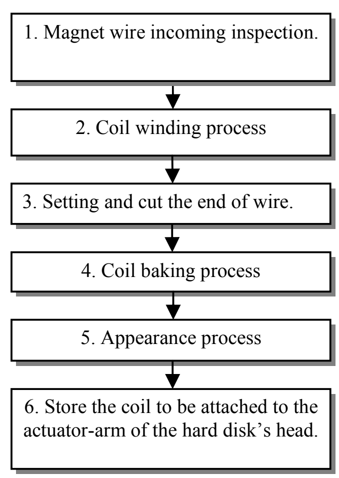

Fig 2: Process of Coil Production

Figure 2 shows important steps in hard disk drive actuator manufacturing procedure which need quality control for the coil to meet each product's need. The coil on the hard disk drive actuator arm is winded by the coil winding machine

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(step 2) which the winding parameters are determined by the types of the coil. Then it is the baking step (step 4) before attaching the coil with the actuator arm afterward.

In the baking step, the coil is put into the oven. The temperatures are set based on the types of the products. There are many factors that affect the coil quality in the baking procedure for instance, temperature, duration, position of coil in the oven. These factors depend on the coil material. Currently, most coils are copper but there is an increase in aluminium design.

The case studies from hard disk drive actuator manufacture companies showed that at present the companies faced problem in coil manufacture procedure. One of the serious problems occurred in the coil baking process. The coils after being baked got swollen, transformed, and they failed to meet the customers' thickness criteria. As a result became wasted. From the primary analysis, the waste problem after the coil baking process always occurred because there was no study on the causes and main factors that caused the waste. The case study companies mainly used the 'box oven type (figure 3) to bake their coil'.

Fig 3: The oven used for coil baking

From all causes mentioned above, the purposes of this research were to find the optimal parameters in coil baking procedure by implementing experimental design methodology. The experimental design methodology was a method used to find the most optimal coil baking parameters that also gave the relationship between factors that affect the coil baking. The experimental design methodology was used to test the relation of the involving factors or affecting the coil baking by collecting data from the experimental group to find the most optimal values from the experiments. In the experimental design, there were 4 factors; temperature, duration, position in the oven, and pressure level of the oven air duct. The experiment used 'box oven' to bake the coils and tested by measuring the differences of the coil thickness before and after the coil baking. The results revealed the factors that affected the baking which led to finding the most suitable parameters in coil baking and analyzing the relations of each factor to know the factors that affect the coil quality. The results from analyzed statistic data were used to improve the manufacture efficiency and the quality control in coil baking procedure was able to reduce the waste, which led to lowering the cost in the manufacture process.

II. Background

A. Experimental Design

An experimental design is a test (or a series of tests) that aims to change the input variables of a process and observe the changes in the output response. The uncontrollable factors are set as $z_1, z_2, \ldots z_p$, also known as noise factors. The purposes of the study involve

- to find out the most influential factor on effect y
- to find out how to set value x that influences effect y for the preferred y value
- to find out how to set value x that influences effect y for the minimum y value
- to find out how to set value x for uncontrollable factor with the minimum z value

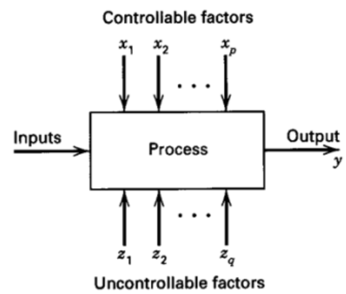

Fig 4: General Model of a process or system. (Source: Montgomery [1])

The experimental design is widely used in different sections of the hard disk manufacturing industry where high production quality control is required. For example, D. J. Lee *et al*. [2] used experimental design and response surface method to analyze and find the most optimal values to design linear actuator, and analyzed the data with the finite element method to get the highest impulse and smallest actuator size. As the primary design, the linear actuator is suitable for optical disk drives as for the miniature storage drives type.

D. J. Lee *et al*. [3] applied the experimental design to design the swing arm actuator for optical disk drives in thin type and small type. The experiment analyzed electromagnetic circuit variance and analyzed the results from experimental design. The study found that it was possible to integrate with mobile storage devices.

However, in the involving hard disk drive manufactures, the research seeking for the most optimum parameters in baking process has not yet been found.

Punnarungsri and Laosiritaworn [4] applied Taguchi methodology, L_4 (2^3) design arrays in coil baking process. The experiment measured differences in coil thickness before and after the baking. Three types of coils, including normal, coils with abnormal wire width, and coils with overlapped wire winding, were used in the experiment. The experimental results showed that every factor could affect coil baking. The appropriate baking conditions were six hours at 125˚C in the top of the oven and there were no significant difference in the mean thickness of the three types of coils.

B. Factorial Experiments Design (3^k)

The three-level factorial experimental design is a design that consists of *k* factors. There are 3 levels of factors in the three-level factorial experimental design; high (+1), medium (0), and low (-1).Therefore, 3x3x3…x3=3^k experiments are needed to perform.

C. Analysis Regression Equation

The variance analysis can be written as a regression equation to show the relation between factors. A variable (y) is equal to the mean value plus influence from factors and deviation (Montgomery [5]).

$$y_{ij} = \mu + \tau_i + \varepsilon_{ij} \quad (1)$$

μ = mean value

T = influence from factors

ε = deviation

III. METHODOLOGY

A. Factorial Experiments Design

From the study about experimental design theory including and the consideration of the problems in coil baking process, it was found that 4 factors had effects on coil baking; temperature, duration, position in the oven, and pressure level of oven air duct. This study would test all 4 factors (k = 4). There were 3 levels for each factor hence it was called 3^4 factorial design. The experiments were repeated twice (Rep = 2), so altogether there were 162 experiments.

B. Selection Output Response Variable

From the issues of the case study companies about waste from coil baking process due to the transformation of the coils, to select the output response variables the researcher considered the coil thickness before and after baking. If there was a major change to thickness, the coil quality would be affected. The thickness measure was made at the position as shown in figure 5 which was the actual point to be measured in the manufacture process to make it easy in data collecting and implementing in the manufacture process later on.

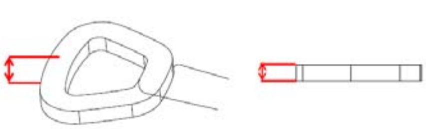

Fig 5: The thick side of the coil

C. Selection Level and Regional Factors

The factorial experimental design (3^k) is to find the optimal level factor in coil baking. According to the earlier study, there are 4 factors and 3 levels for each factor which can be determined as follows.

Determining the level of factor A: the duration of coil baking was set at the low level (-1) of 2.5 hours which was the minimal amount of time in coil baking that the glue could melt and attach; the medium level (0) of 4.5 hours which was the median value in baking duration; and the high level (+1) of 6 hours because it was the longest period the case study companies used. Longer than 6 hours wasted energy and might damage the coils.

Determining the level of factor B: the coil baking temperature was set at the low level (-1) of 125 °C which was the minimal temperature in coil baking that the bond coat melted and attached; the medium level (0) of 150 °C; and the high level (+1) of 175 °C because it was the highest temperature in coil baking and the oven did not have to overload.

Determining the level of factor C: the coil position in the oven due to the 3 grates in the box oven serving as the stand, the spaces between the grate and the fanjet differed which could affect the coil baking. The low level (-1) was the grate at the bottom of the oven, the medium level (0) was the middle one, and the high level (+1) was the top one.

Determining the level of factor D: the pressure level of oven air duct was set at the low level (-1) of low air volumes which allowed less air to be taken out, the medium level (0) of medium air volumes, and high level (+1) of high air volumes which allowed air to be taken out most.

All determinations of levels of factors can be shown in table 1.

TABLE I
FACTORS AND LEVELS FOR COIL BAKING.

Factors	Levels		
	1	2	3
A: Baking time	2.5 hr	4.5 hr	6 hr
B: Temperature	125˚C	150˚C	175˚C
C: Position in the Oven	Bottom	Middle	Top
D: Pressure of Air-Vent Pipe in the Oven	Low	Moderate	High
Y = Different Thickness of Coil before and after baking (10^{-4} Inch)			

IV. RESULT AND DISCUSSION

A. Analysis of Variance

After baking coil following the determined conditions of the 3^4 factorial designs, the variance can be analyzed as followed.

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Source	DF	Seq SS	Adj SS	Adj MS	F	P
A	2	23.7427	23.7427	11.8714	60.25	0.000
B	2	45.7905	45.7905	22.8952	116.20	0.000
C	2	1.1768	1.1768	0.5884	2.99	0.056
D	2	93.8579	93.8579	46.9290	238.17	0.000
A*B	4	1.8821	1.8821	0.4705	2.39	0.058
A*C	4	0.2136	0.2136	0.0534	0.27	0.896
A*D	4	12.8002	12.8002	3.2001	16.24	0.000
B*C	4	2.8802	2.8802	0.7201	3.65	0.009
B*D	4	41.0902	41.0902	10.2726	52.14	0.000
C*D	4	1.6062	1.6062	0.4015	2.04	0.097
A*B*C	8	4.5916	4.5916	0.5740	2.91	0.007
A*B*D	8	13.2705	13.2705	1.6588	8.42	0.000
A*C*D	8	0.8768	0.8768	0.1096	0.56	0.810
B*C*D	8	2.6123	2.6123	0.3265	1.66	0.122
A*B*C*D	16	5.3525	5.3525	0.3345	1.70	0.064
Error	81	15.9600	15.9600	0.1970		
Total	161	267.7042				

S = 0.443889   R-Sq = 94.04%   R-Sq(adj) = 88.15%

From ANOVA table, the factor A, B, D, AD, BC, BD, ABC, ABD have statistical significance of the 95% confidence interval when p-value less than $\alpha = 0.05$.

B. Normal Distribution

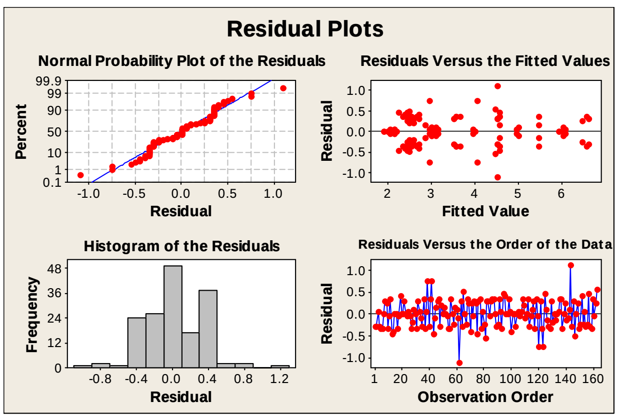

Fig 6: Mean Response Graphs

From Figure 6 the normal probability plot to judge the normal distribution, the residuals distribute normally along with the linear.

The variance graph (residuals versus the fitted values graph in figure 6) to judge the variance stability (σ^2), the residuals has varied values with no specific trend. In conclusion, the data have variance stability.

For the validation of independence using the scatter plot (residuals versus the order of the data graph in figure 6), the residuals distribute freely with no specific pattern and the specific pattern cannot be determined. Therefore the residuals are independent.

In conclusion, the data are suitable to be analyzed by using experimental design methodology.

C. Main Effects Analysis

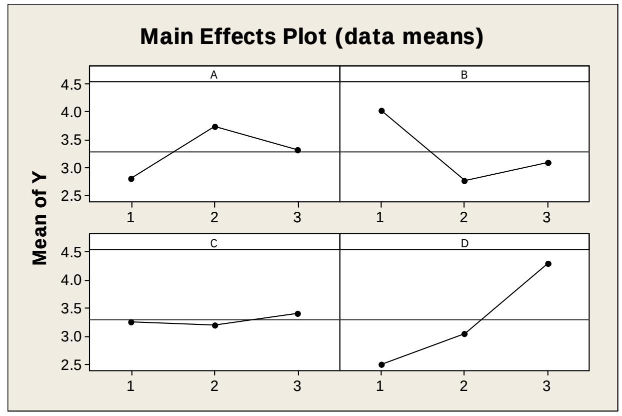

Fig 7: Main Effects Plot

From the main effects plot which is a graph of the mean values for each factor, the influence of the factors for each product baking process can be determined. Factor A, B, and D have significant effects on the coil baking where the slope is very steep. The factor C has no significant effect on the baking and the slope is not steep. The experiments require least changes of coil thickness before and after baking. Therefore the factors that significantly affect the coil are A, B, and D and the optimal factors are A_1, B_2, C_1, and D_1 observed from the lowest points of each factor.

D. Interaction Analysis

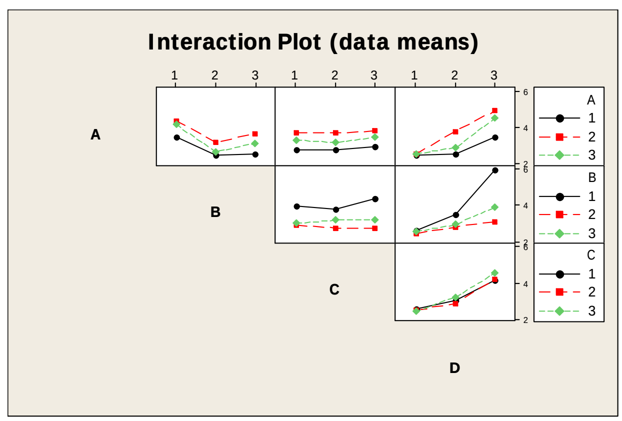

Fig 8: Interaction Plot

From the interaction graph, the factors that affect coil baking conform to the variance analysis. The interactions that affect the coil baking are AD and BD which can be observed from the high values from the highest points of the graph. The levels that affect the coil thickness for each interaction are as follow.

For the interaction AD, the level that affects the coil baking is A_2D_3. For the interaction BD, the level that most affects the coil baking is B_1D_3.

E. Analyzing Regression Equation

The results from the variance analysis can be written as a regression equation (1) to show the relation between factors that affects the coil baking with the minimal value of Y as

$$\text{Minimize } Y = 9.24 + 0.415A - 0.0433 B - 9.57D_1 - 9.24D_2 + 0.287AD_1 + 0.687AD_2 - 0.00094BC_1 + 0.00012BC_2 + 0.0617BD_1 + 0.0601BD_2 - 0.000106ABC_1 - 0.000394ABC_2 - 0.00436ABD_1 - 0.00630ABD_2 \quad (2)$$

Because the interactions of the factors have significant effects, the determinations of the factors require the levels of each variable that make variable Y in the regression equation minimal. From the analysis, the optimal parameters of the coil baking are A_1, B_3, C_3 and D_1 where the Y value is minimal. This conforms to the variance analysis result and the interaction analysis results earlier.

V.CONCLUSION

The experiment about the factors that affect coil baking and the most optimal parameters in coil baking found that the factors that affect the coil baking are factor A, B, and D which had significant effect while factor C had less effect and did not affect the interaction. The optimal parameters in coil baking, the optimal levels were factor A at 6 hours, factor B at 175 ^{o}C, factor C which was coil position in the oven at middle level, and factor D the oven air duct pressure level at low air volumes.

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REFERENCES

[1] *Montgomery, Douglas C. (2005). "Design and Analysis of Experiments".6th Edition. USA : John Wiley& Sons Inc.,*

[2] *Lee DJ, et al (2005) "Design and optimization of a linear actuator for subminiature optical storage devices."*

[3] *Lee DJ, et al (2007) "Design of swing arm actuator for small and slim optical disc drives"*

[4] *Punnarungsri and Laosiritaworn (2012) "Coil baking parameters Optimization Using Taguchi methodology"DST-CON 2011The 4th International Data Storage Technology Conference, Jan 2012.*

[5] *Montgomery, Douglas C. (2002). "Applied Statistics and Probability for Engineers"3rd Edition.USA : John Wiley& Sons Inc.,*