Research on the Optimal Degree of Fire Retardant Coating on Wood-Based Materials Using Taguchi Method

Abstract

Keywords: Taguchi method, thermal radiation, orthogonal array, ignitability.

The purpose of this research is to find out the optimal strategy for wood-based materials subjected to fire retardant treatment using Taguchi method when wood-based finishing and decoration materials are under the effects of different factors of ignitability experiment, such as material of the boards, thickness of boards, the degree of fire retardant treatment and the formulation of coating, etc, using the orthogonal array of $L9(3^4)$ as the experiment setup, and the thermal radiation and ignitability experiments are carried out based on the experiment specification of ASTM E1623. The result of the experiment shows that the factor affecting ignitability the most is the formulation of fire retardant coating, which contributes 4872% of effect, when wood-based materials are subjected to a thermal radiation of $25kW/m^2$. And more, according to the optimal factor level combination of the Taguchi experiment, further experiment and research are conducted and focused on the factor of the formulation of coating, and the optimal degree of coating for fire retardant treatment on wood-based materials is 391 g/m^2. The orthogonal array established in Taguchi method for discussion on the number of factors and levels simplifies the complicated experiments that consist of multiple variables, and the number of experiments is less than that of full factors experiment, and the reproducibility of experiments is higher, which contributes for the research and development of fire retardant treatment on wood-based materials.

1. Preface

At a fire scene, the transmission of heat comes in three ways: conductivity, convection and radiation. In Taiwan, research has been focused considerably on thermal conductivity and convection in spreading fires, but the effect of thermal radiation in a fire scene has been somehow neglected. Searching through the reference materials, it is found that when thermal radiation goes beyond $25kW/m^2$, the wooden structures will be ignited, and when thermal radiation reaches approximately 15 kW/m^2, wood pieces can catch fire even with fire retardant treatment [1][2]. Therefore, this research focuses on the ignitability of wood-based material when subjected to thermal radiation.

Currently in Taiwan, the specification of test for ignitability of finishing materials is based on CNS6532 "Method of test for incombustibility of interior finish material of buildings", which specifies that specimens sized in 22cm x 22cm are used to test the incombustibility level. The incombustibility levels are categorized in three levels, which are classified qualitatively. The standard of judgment on tests includes the temperature of exhaust, the enclosed area of temperature-time curve, smoke generating coefficient, cracking and lingering flames [3]. However, test specimens of larger sizes are widely used internationally in simulation and tests and it is believed that such tests generate better results in simulating real fires. Besides, Fire Risk Assessment Method of NFPRF (National Fire Protection Research Foundation) has classified the combustibility of materials into three categories, which are “extremely inflammable”, “inflammable” and “not inflammable,” as shown in Table1 [4]. In Reference [5], it is suggested that the ignition point of wood subjected to thermal radiation is 12kW/m, and the self ignition point is 28kW/m, which are qualitative classifications, as shown in Table 2. Therefore, this research follows the foot steps based on the test specification of ASTM E1623 to build a “radiation heater” of 70cm x 140cm to simulate the scheme of thermal radiation heating up a wood specimen of 60cm x 60cm in a real fire. The purpose is in search for the ignitability of wood-based material subjected to thermal radiation under various ignition factors.

The Taguchi method is extensively used for tests in recent years. The method conducts the test using experimental combinations of orthogonal array to find out what the experiment is looking for with the collection of test results, such as the contribution of each factor to the main effects and the optimal combination of factor levels. This can reduce the cost conducting experiments and increase the effectiveness. Therefore, this research adopts the Taguchi method to discover the ignitability of wood-based material subjected to thermal radiation under various ignition factors.

2. Theories and methods

（A）Taguchi method

This research conducts the 25kW/m^2 thermal radiation experiment to wood-based material specimen of 60cm x 60cm with orthogonal array based on the experiment specification of ASTM E1623 [6]. The experiment setup is as shown in Fig. 1. The center point of specimen aligns with that of radiation heater at the same horizontal axis to control the geometry of radiation heater and the specimen. According to Taguchi method, the optimal factor level combination of the ignitability of the wood-based material that is most affected by radiation and the levels of effects of thermal radiation to the ignitability of the wood-based material under each factor are analyzed. The levels of factors in the experiment are listed as shown in Table 3:

（1）The design flow of Taguchi method [7], as shown in Fig. 2:

1. Define the optimization. The research on the ignitability of wood-based material, as done in this research, is to find out the factors that have influence on the ignition caused by thermal radiation.
2. Define the goal of qualitative characteristics. The ignitability of wood-based material is Larger-the-Better.
3. Define the factors that affect the target values and the number of levels. For this research, the factors to be discussed are the type of wood-based material, the thickness of board and the degree of fire retardant coating.
4. Select the appropriate orthogonal array. There are 4 factors in this research and each factor consists of 3 levels. Therefore, the orthogonal array of $L9(3^4)$ is chosen for the setup of experiment.
5. Conduct the 9 experiment combinations that are set up in the orthogonal array. Each set of experiment is performed 3 times to make sure the accuracy. Hence, 9x3=27 experiments have been performed.
6. Proceed the calculation of S/N ratio of each factor level and the analysis of variance to further understand the optimized level of factors and the factor that contributes the most.

7. Run the confirmation with the optimal solution to verify the experiment to ensure the robustness of result.

(2) The relations among quality characteristics, quality loss functions and S/N ratio:

Before calculating the statistics and running the analysis of experiment result on the main effects of each factor, the quality characteristics must be studied, and these characteristics are in three categories and are listed as follows:

1. Qualitative characteristics: able to be measured in continuous scales, these characteristics are usually displayed in decimal points, such as abrasion, strength and dimension, and so on.

   There are three sub-categories for qualitative characteristics:

   1) Nominal-the-Optimal (NTB): there is a specific target value for this characteristic. Greater or less than that target value is not appropriate. The examples of this characteristic are dimensions, pressure and thickness, etc.

   2) Smaller-the-Better (STB): The extreme target value of this characteristic is 0. The examples of this characteristic are abrasion, degradation and defects, and so on.

   3) Larger-the-Better (LTB): The extreme target value of this characteristic is infinity. The examples of this characteristic are strength and illumination, etc.

2. Quantitative characteristics: unable to be measured in continuous scales, these characteristics can be categorized based on uncontinuous classification scales. For example, the finished products are categorized as good or defected, inferior, ordinary or superior, etc.

3. Dynamic characteristics: These are the quality characteristics of system functions, depending on the input of signal factors of system and their result. For example, the gear switches as the engine speed changes.

The quality characteristic for the goal of this research is LTB of the qualitative characteristics, of which the relation among the quality goal, quality loss function and S/N ratio is as follows:

1. LTB

   1) Quality loss function MSD

$$MSD = \frac{1}{n}\sum_{i=1}^{n}\frac{1}{Y_i^2} = \frac{1}{\overline{Y}_i}\left(1+\frac{3S^2}{\overline{Y}^2}\right) \text{………}(1)$$

   2) S/N ratio

$$S/N = -10\times\log\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{Y_i^2}\right) \text{………}(2)$$

（3）The use of orthogonal array

There are 4 factors dominating the ignitability in this research. The mutual interactions among the 3 levels of each factor are not taken into account. After calculating the degrees of freedom, the orthogonal array of $L9(3^4)$ is utilized for the setup of experiment, as shown in Table 4:

$L_a(b^c)$…………………………(3)

L: Latin squares, representing the orthogonal array.

a: the number of experiments, which is the number series.

b: the number of levels for the control factor.

c: the number of interactions between factors, which is the number of columns.

Table 1 Classification table for combustibility in Fire Risk Assessment Method of NFPRF [4]

Combustibility class	Thermal radiation range kW/m^2（surface measurement）
Extremely inflammable (thin drapes)	≦14.1（10）
Inflammable (decoration and furniture)	14.1-28.3（20）
Not inflammable (thick wood)	＞28.3（40）

Table 2 The draft of table for limitation values of material subjected to thermal radiation in BSI standard [5]

Material	Thermal radiation of ignition kW/m^2		The surface temperature at ignition ℃	
	Ignition point	Self ignition	Ignition point	Self ignition
Wood	12	28	350	600
Hard cardboards	18	—	—	—
Hard cellulous boards	27	—	—	—
PMMA (transparent acrylic)	21	—	270	—
Elastic PU	16	—	270	—
PVC	17	—	—	—
Polymethylene	12	—	—	—
PE	22	—	—	—

Table 3 The factor levels of experiment parameters

Number	Factor	Levels
A1	Type of board	plywood
A2		medium density fiberboards
A3		particleboards
B1	Thickness of board	9mm
B2		12mm
B3		18mm
C1	* The formulation of coating	carrier resin 10%
C2		carrier resin 20%
C3		carrier resin 30%
D1	The degree of coating	$400g/m^2$
D2		$500g/m^2$
D3		$600g/m^2$

※Note: The formulation of coating is to control the proportion of carbonizing agent, catalyze and foaming agent in a certain coating material and to manipulate the proportion of carrier resin.

(B) Single factor experiment

The purpose is to find the optimal and most accurate solution for the ignitability of wood-based material affected using Taguchi method on the factor to be studied with single factor experiment and regression.

Table 4 The setup of parameters in the orthogonal array of L9（3^4）

NO.	The setup of factor levels (orthogonal array of L9 (3^4))							
	A	B	C	D	Type of boards	Thickness of boards	Formulation of coating	Degree of coating
1	1	1	1	1	plywood	9mm	carrier resin 10%	400g/m^2
2	1	2	2	2	plywood	12mm	carrier resin 20%	500g/m^2
3	1	3	3	3	plywood	18mm	carrier resin 30%	600g/m^2
4	2	1	2	3	medium density fiberboards	9mm	carrier resin 20%	600g/m^2
5	2	2	3	1	medium density fiberboards	12mm	carrier resin 30%	400g/m^2
6	2	3	1	2	medium density fiberboards	18mm	carrier resin 10%	500g/m^2
7	3	1	3	2	particleboards	9mm	carrier resin 30%	500g/m^2
8	3	2	1	3	particleboards	12mm	carrier resin 10%	600g/m^2
9	3	3	2	1	particleboards	18mm	carrier resin 20%	400g/m^2

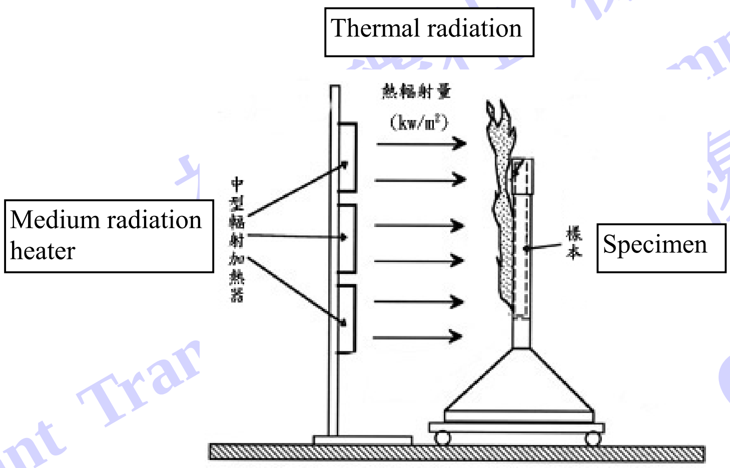

Fig. 1 The scheme of ignitability experiment

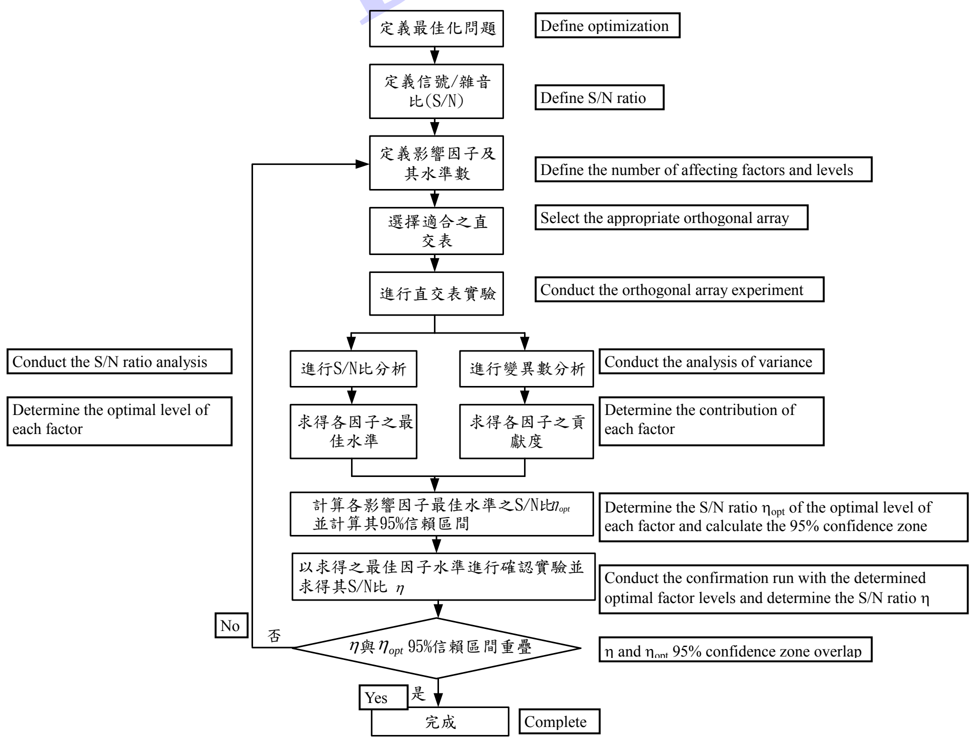

Fig. 2 Design flow of Taguchi method [7]

3. Research result and discussion

According to Taguchi method [8], the wood-based material is subjected to 25kW/m^2 of thermal radiation in the experiment. The result of experiment is summarized as follows:

(A) Taguchi theoretical analysis table

The thermal radiation ignitability experiment of ASTM E1623 was conducted based on the combinations of experiment parameters from the orthogonal array of L9(3^4). To maintain the reproducibility of the experiment result, each combination of experiment set has been conducted 3 times, therefore, 27 experiments conducted in total. The experiment result is shown in Table 5. In average, the quickest experiment combination to catch fire is set no. 2. The parameter combination is A1 (plywood), B2 (thickness 12mm), C2 (formulation 20% of resin) and D2 (degree of coating 500g/m^2), and the average igniting time is 9.85 minutes. The slowest experiment combination to catch fire is set no. 9. The parameter combination is A3 (particleboard), B3 (thickness 18mm), C2 (formulation 20% of resin) and D2 (degree of coating 400g/m^2), and the average igniting time is 47.62 minutes. Among all 9 sets of experiments in this research, the standard deviation of igniting time is 1.63.

For the process of wood-based material coated with expandable fire retardant coating ignited by 25kW/m^2 of thermal radiation, the research has found out through the experiments that the proportion of carrier resin in fire retardant coating affects the ability for the expanded carbonized layer formed after the fire retardant coating is heated to stay on the wood-based material, i.e. the expanded carbonized layer falls off the surface due to solidification or emulsification or the function of expanding itself to block the heat is compromised. Among all experiment sets, it is proved the optimal incombustibility that the formulation of coating is 10% of carrier resin.

Table 5 Analysis chart of Taguchi's theory

NO.	Factor level setup (L9(3^4) orthogonal array)									
	Boards	Thickness	Formulation	Degree of coating	TEST 1	TEST 2	TEST 3	Average (min.)	Standard deviation S	S/N ratio
1	1	1	1	1	32.42	35.82	35.31	34.52	1.83	30.74
2	1	2	2	2	7.50	10.60	11.45	9.85	2.08	19.42
3	1	3	3	3	17.83	14.05	17.63	16.50	2.13	24.19
4	2	1	2	3	20.75	21.33	24.65	22.24	2.10	26.87
5	2	2	3	1	21.08	17.08	19.45	19.20	2.01	25.57
6	2	3	1	2	41.27	41.68	40.02	40.99	0.86	32.25
7	3	1	3	2	13.67	13.60	14.53	13.93	0.52	22.87
8	3	2	1	3	37.20	39.18	39.35	38.58	1.20	31.72
9	3	3	2	1	49.28	48.07	45.52	47.62	1.92	33.54
							Average =	27.05	1.63	27.46

(B) Analysis of response table and response graphs

From the experiment result in Table 5, the average igniting time of each experiment set is transformed into S/N ratio for production of response graphs and response table. Since the quality characteristic that this research focuses on is LTB of the quantitative characteristics, therefore, the formula for transformation of average is shown as Eq. (2).

Examining the calculation result, the smallest S/N ratio appears in experiment set no. 2, which is 19.42; the largest S/N ratio locates in experiment set no. 9, which is 33.54. The average S/N ratio of all 9 sets is 27.46.

According to the average igniting time and S/N ratio of each experiment set, the main purpose of the quality characteristics of the production and the response table and graphs of factors is to understand the optimal experiment combination of each factor that has influence on the ignitability of wood-based material. The method of calculation is to add up all the average igniting time and S/N ratio of the factor level that is to be determined in Table 5 and find out the average of them. For example, the calculation of A1 is:

Quality characteristics of A1: (34.52+9.85+16.50)/3=20.29

S/N ratio of A1: (30.74+19.42+24.19)/3=24.78

We followed this approach to determine the quality characteristics of each factor level and the S/N ratio, and then to develop the response table and graphs of factors. The result is shown in Tables 6 and 7 and Fig. 3 and 4. After analysis, the optimal parameter combination for factor level and S/N ratio is A3, B3, C1 and D1. Therefore, it is evident that the optimal factor level combination for wood-based material subjected to 25kW/m^2 of thermal radiation in this research is A3, B3, C1 and D1, i.e. material is particleboards, thickness is 18mm, formulation of coating is 10% of resin, and degree of coating is 400g/m^2.

To determine the predicted value of S/N ratio $\eta_{opt} = 38.51(db)$ with the predicted optimal values of A3, B3, C1 and D1, the calculation is as follows:

$$\eta_{opt} = \bar{\eta} + \left(\eta_{A_3} - \bar{\eta}\right) + \left(\eta_{B_3} - \bar{\eta}\right) + \left(\eta_{C_1} - \bar{\eta}\right) + \left(\eta_{D_1} - \bar{\eta}\right)$$

=27.46+(29.38-27.46)+(29.99-27.46)+(31.57-27.46) +(29.95-27.46)

=38.51（db）…………………………(4)

η_{opt} : S/N ratio of the optimal theoretical value

$\bar{\eta}$: The average of S/N ratio

Table 6 Response table for quality characteristic factors

Factors		Level 1	Level 2	Level 3	Total	Best level
A	Material type	20.29	27.48	33.38	81.15	A3
B	Board thickness	23.56	22.54	35.04	81.15	B3
C	Coating formulation	38.03	26.57	16.55	81.15	C1
D	Degree of coating	33.78	21.59	25.77	81.15	D1

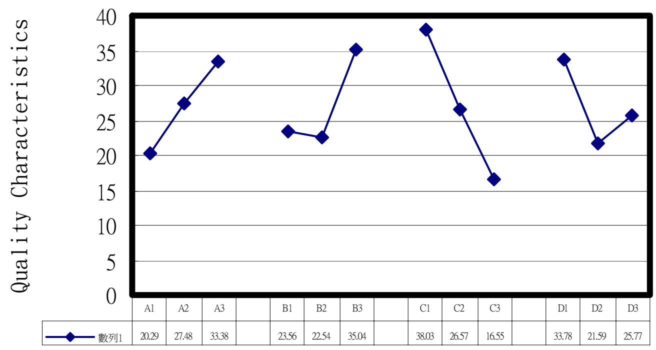

Fig. 3 Response graph of quality characteristic factors

Table 7 Response table for S/N ratio

Factors		Level 1	Level 2	Level 3	Total	Best level
A	Board types	24.78	28.23	29.38	82.39	A3
B	Board thickness	26.83	25.57	29.99	82.39	B3
C	Coating formulation	31.57	26.61	24.21	82.39	C1
D	Degree of coating	29.95	24.85	27.59	82.39	D1

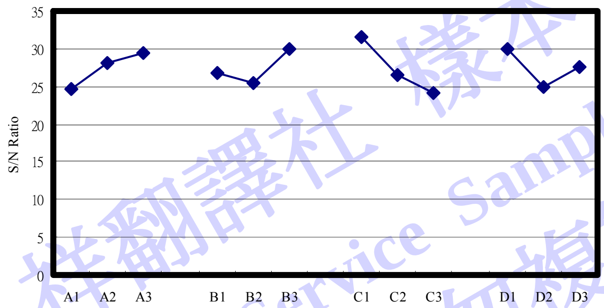

Fig. 4 Response graph of S/N ratio factor

(A) Analysis of variance and F examination

According to Table 5, analysis of variance and F examination have been conducted on the igniting time of each experiment set. The purpose of F examination is to understand that, at 95% of confidence, if the wood-based material is apparently affected by 25kW/m^2 of thermal radiation. If not, it is considered as error. The analysis of variance is to quantify the level of ignitability under the influence of each factor, which is to find out the contribution of each factor. The result is shown in Table 8:

(1) Analysis of variance: After analysis, the result shows that the formulation of coating has the most effect on the wood-based material when subjected to 25kW/m^2 of thermal radiation, and the contribution is 48.72%; the second in place is thickness of boards, which contributes 18.47%; the next is the material type of boards, which contributes 16.46%; and the last one is the degree of coating, which contributes 14.69%. And from the table of analysis of variance, the variance generated from errors is 2.98, indicating that there is small variance of experiment error created from the experiment conditions, i.e. the experiment is reproducible.

(2) F examination: After the F examination on each factor, the result indicates that every factor shows significant influence on the ignitability of wood-based material subjected to 25kW/m^2 of thermal radiation at 99% of confidence. Therefore, factors are not included in errors.

Table 8 Table of analysis of variance

Factors	SS	DOF	Var	F	Confidence	Significance *	ρ	Sequence
Material	773.56	2	386.78	129.84	100%	Yes	16.46%	3
Thickness	867.24	2	433.62	145.56	100%	Yes	18.47%	2
Formulation	2277.35	2	1138.68	382.25	100%	Yes	48.72%	1
Degree of coating	690.69	2	345.35	115.93	100%	Yes	14.69%	4
Error	53.62	18	2.98	S=1.73				
Total	4662.46	26	*Note:At least 99% Confidence					

(D) Confirmation run for Taguchi method

From the response table and graphs of quality characteristics and those of S/N ratio in this research, it is determined that the optimal combination of factor levels for the ignitability when wood-based material is subjected to thermal radiation is A3, B3, C1 and D1. After calculation, the predicted value of S/N ratio is $\eta_{opt} = 38.51(db)$. To confirm the credibility of the fact that the factor levels set up in the previous experiments match the factor levels affecting the ignitability of the wood-based material subjected to thermal radiation and the ignitability experiments, confirmation runs are required and S/N ratios of confirmation runs are acquired. If there is any overlap in the confirmation runs and the 95% confidence zone of S/N ratio of the predicted values of the optimal factor levels, it indicates that the result of experiments is credible. The result of calculation is shown in Table 9 and Fig. 5.

(1) The confidence zone CI when the predicted value of the optimal factor level at 95% confidence:

After analysis, the optimal combination of experiment parameters for both quality characteristics and S/N ratio is A3, B3, C1 and D1. Therefore, the optimal factor level combination for wood-based material subjected to $25kW/m^2$ of thermal radiation in this research is A3, B3, C1 and D1, and the predicted value of S/N ratio is $\eta_{opt} = 38.51(db)$. The confidence zone of the predicted value is shown as follows:

$$CI = \left| N_{\alpha/2} \times \frac{S}{m_e} \right| = \left| -1.96 \times \frac{1.73}{\sqrt{\frac{9}{8}}} \right| = 3.20 \quad \ldots\ldots\ldots(5)$$

S：Standard deviation of errors

$$m_e = \frac{\text{The total number of experiment statistics}}{\text{Total DOF in predicted value calculation}}$$

Hence, the confidence zone of the predicted value of the optimal factor level for S/N ratio falls between:

35.31 (db) < predicted value < 41.71 (db)

（2）The confidence zone CI of confirmation run at 95% confidence:

Three sets of confirmation runs are conducted based on the optimal experiment parameter combination A3, B3, C1 and D1. The result is shown in Table 9. The average igniting time of confirmation run is 55.19 minutes, the standard deviation is 2.75 and S/N ratio $\eta = 34.82(db)$. The confidence zone of confirmation run is shown in Fig. 5.

Table 9 Analysis table on result of confirmation run

Confirmation run	TEST1 (min.)	TEST2 (min.)	TEST3 (min.)	Average (min.)	Standard deviation	S/N ratio
NO.1	57.53	55.88	52.17	55.19	2.75	34.82

$$CI = \left| N_{\alpha/2} \times S \left[\sqrt{\frac{1}{m_e} + \frac{1}{r}} \right] \right| = \left| -1.96 \times 1.73 \left[\sqrt{\frac{1}{\frac{9}{8}} + \frac{1}{3}} \right] \right| = 3.83 \quad \ldots\ldots\ldots\ldots\ldots\ldots(6)$$

S: Standard deviation of errors

$$m_e = \frac{\text{總實驗數據個數}}{\text{計算預測值式中的總自由度}}$$

$$m_e = \frac{\text{The total number of experiment statistics}}{\text{Total DOF in predicted value calculation}}$$

r: Combination of orthogonal array, number of times per set of experiment.

Hence, the confidence zone of S/N ratio falls between:

30.99 (db) < confirmation run < 38.65 (db)

After comparison, the result shows that there is overlap between the predicted value of the optimal factor level combination and confirmation run. Therefore, it proves that the result of this ignitability experiment shows reproducibility and soundness.

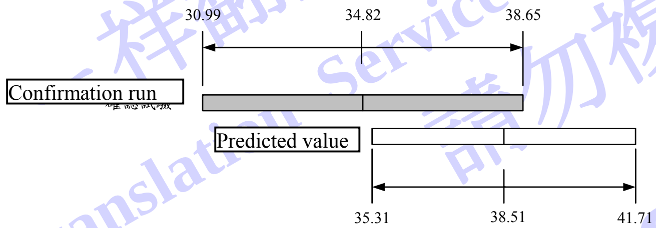

Fig. 5 The comparison of confidence zone for confirmation run

(E) Analysis on the result of the optimal degree of coating experiment

Based on the optimal factor level combination from the result of ignitability for thermal radiation using Taguchi method, experiments and research have been conducted on the factor of degree of fire retardant coating in order to discover the optimal degree of coating. Therefore, the configuration of experiment parameter is to use fixed the material and thickness of boards and the formulation of fire retardant coating and to control the degree of coating at $330g/m^2$, $365g/m^2$, $400g/m^2$, $435g/m^2$ and $470g/m^2$ as experiment variable in order to realize the ignitability when subjected to $25kW/m^2$ of thermal radiation. The result of experiment is shown in Table 10. The regression curve, shown in Fig. 6, is then created with the average igniting times and the degrees of coating.

$y=-0.0025x^2+1.9558x-333.45$ ……..………(7)

$R^2=0.9869$

x: The degree of fire retardant coating (g/m^2)

y: Igniting time (min.)

Differentiate the function and find out the inflection point to determine the optimal degree of fire retardant coating for ignitability, and the formula is shown as follows:

$$\frac{d}{dx}\left(-0.0025x^2 + 1.9558x - 333.45\right) = 0 \quad \text{……(8)}$$

x=391

Therefore, the optimal degree of fire retardant coating for wood-based material subjected to $25kW/m^2$ of thermal radiation in this research is $391g/m^2$.

Table 10 The experiment result of the optimal degree of fire retardant coating for ignitability

NO.	Specimen properties			Igniting time of each experiment set (min.)			Average (min.)
	Degree of coating (g/m^2)	Water content (%)	Density (g/cm^3)	TEST1	TEST2	TEST3	
1	330	8.21	0.692	47.28	44.34	42.10	44.57
2	365	10.37	0.687	52.68	54.63	49.70	52.34
3	400	9.58	0.702	57.53	55.88	52.17	55.19
4	435	8.46	0.711	51.67	54.04	53.63	53.11
5	470	10.54	0.691	43.78	41.50	41.51	42.26

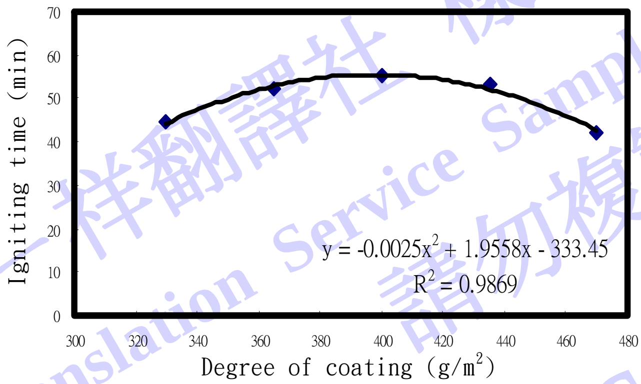

Fig. 6 The relation curve between the average igniting time and the degree of coating

4. Summary

The result of this research is summarized as follows:

1. After the analysis of variance, the result of ignitability experiment for thermal radiation indicates that the sequence of factors affecting ignitability is the formulation of fire retardant coating > thickness of boards > material type of wood-based material > degree of fire retardant coating, amongst which the formulation of coating has the most influence on the ignitability of wood-based material subjected to thermal radiation, contributing 48.72%.

2. After the analysis of response table and response graphs of factors, the ignitability experiment on wood-based finishing material subjected to $25kW/m^2$ of thermal radiation, the optimal combination of factor levels is particleboards, thickness 18mm, formulation of coating 10% of carrier resin, and $400g/m^2$ of the degree of coating. The incombustibility shows better performance at this combination of factor levels in the ignitability experiment on thermal radiation.

3. After analyzed the result of ignitability experiment for wood-based material subjected to $25kW/m^2$ of thermal radiation with F examination, the ignitability discussed in this research has significant influence on the ignitability of wood-based material subjected to thermal radiation.

4. After regression, the result of experiment on fire retardant coating indicates that, in this research, the optimal degree of fire retardant coating is $391g/m^2$ when wood-based material is subjected to $25kW/m^2$ of thermal radiation. Using Taguchi method and single factor experiment can easily obtain the optimal degree of coating and improve the quality of experiment.

5. The methods of experiment and analysis used in this research are Taguchi method in conjunction with single factor experiment. They simplify the complex multi-variable experiment procedures, and experiments show high reproducibility. Therefore, the experiment effects are improved, the R&D costs for products can be reduced and the efficiency of R&D is increased.

5. Reference

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