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Article

Analysis of Failing load and Optimization of Hot Air Welding Parameters on PVC-Acrylic Coated Polyester Fabric by Taguchi and ANOVA Technique

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Abstract. There are several factors affecting the strength of welding seam through hot air for PVC-acrylic coated polyester fabrics. To obtain the most durability of the welding seam for practical use, the experimental design of this study adopts Taguchi method for determining a number of experiments. Each input parameter has five different levels. The result shows that the input parameters providing maximum failing load for welding in warp and weft directions are the following: the distance between a head of blower and workpiece (Dis) of 10 mm, the temperature of hot air (Tem) of 160 ^{o}C, the torque (Tq) of 9,000 N.mm, and the speed of hot air (Sha) of 4,000 mm/s. The maximum failing loads are 95.38 kN/m and 86.17 kN/m for warp direction and weft direction, respectively. After filtering the input parameters at the significance level of 0.05, the input parameters which significantly affect the strength of welding seam are the distance between a head of blower and workpiece, and the temperature of hot air. Additionally, the relationship between the input parameters and the failing load seams can be establishad. The comparison between the actual experimental data and the predicted values of the failing load for both welding directions shows that the average percentage error is less than 0.1% so that the forecast equation is appropriate for the explanation of the variables for this study and provide statistical reliability.

Keywords: Optimization, fabric, strength, Taguchi, ANOVA.

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1. Introduction

Nowadays scientists have applied the knowledge of textile chemistry with the combination of material coating technology to create numerous brand new materials. One of notable innovation, for example, is utilization of a polyester fabric coated by PVC-acrylic for cloth weaving. The dominant features of this developed material are their strength, light weight, fire resistance, tolerance to tensile force, light and humidity, thermal insulation, durability, easy installation, desirability in various colours and shapes. These advantages lead many designers, engineers, and architects utilize the PVC-acrylic coated polyester fabric instead of traditional materials for numerous building construction and interior design [1] such as O_2 Arena in London, United Kingdom [2] , building for Hajj pilgrimage in Mecca, Saudi Arabia, aviation exhibition hall in Singapore, various airports, stadium and convention center [3].

A standard width of manufactured PVC-acrylic polyester fabrics is generally between 1.4 and 2.5 metres. However, the fabrics larger than the standard ones are widely used in practice and hence pieces of fabrics are fastened by sewing threads or by thermal conduction. Fastening by sewing threads is disfavoured according to requirement in skilled labour and considerable deterioration in strength. In case of fastening by thermal conduction, two pieces of fabrics are placed between two thermal conducting plates and then the plates are pressed for five seconds until they are firmly tight. Nevertheless, the disadvantages of this technique are that a machine is costly, massive, and space-required so it is a rather difficult situation to install this machine on-site. To solve this problem, the researcher proposes an alternative by using a hot-air blower which its advantages are inexpensive, easily transferable, quick installation on-site. The main consideration of using a workpiece is the strength around fastened seam. Its strength depends crucially on plastic type, thickness and welding technique [4-5]. For the friction stir welding, a tool rotational speed, tool traverse speed, penetration depth, tiltangle are main components for the strength determination [6-9]. For the Rotary Friction Welding, key factors for the strength are the higher burn-off length and the higher rotation speed [10]. For the laser welding, key factors for the strength determination are laser intensity and a scanning speed [11-13]. For the ultrasonic welding, key factors for the strength of the thermoplastic seam are a frequency and duration of frequency applying to welded material [14]. Nowadays all research is investigating rigorously in the welding technique applied on thick and durable materials. Meanwhile, neither research has been studying the welding technique in the polyester fabric that is thinner and more flexible. In this paper, the optimization of hot air welding parameters on PVC-acrylic coated polyester fabric are specified.

2. Experimental Setup

2.1. Material Selection

This material used in this experiment is the polyester fabric and usually have two families, named warp and weft shown in Fig. 1 [15]. The fabric is weaved in the direction of warp and weft before coating with PVC to make it waterproof. The next layer of the fabric is coated by acrylic for antifungal and humidity resistant properties. The outermost layer is coated by PVDF for enhancing UV resistance and sun protection with 5 – 10 % light transmission. The fabric is completely made from polymers and consequently becomes an electrical insulator. According to technical data specified by a manufacturer, the basic properties of the fabric are tabulated in Table 1 [16].

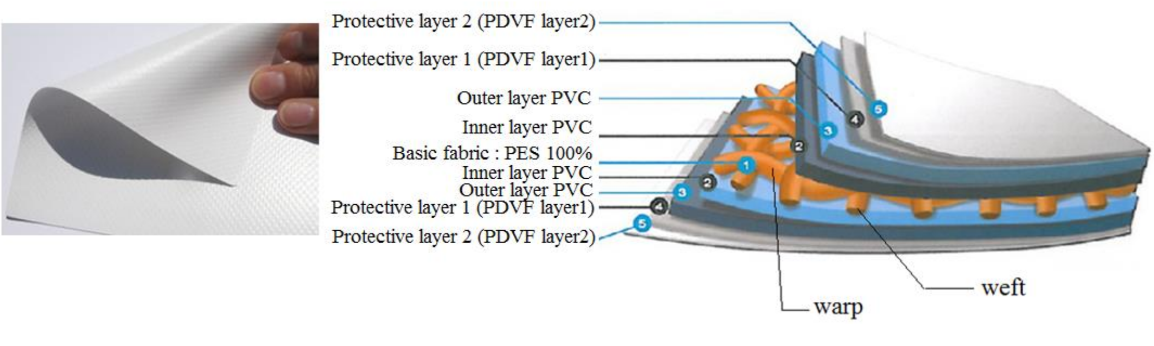


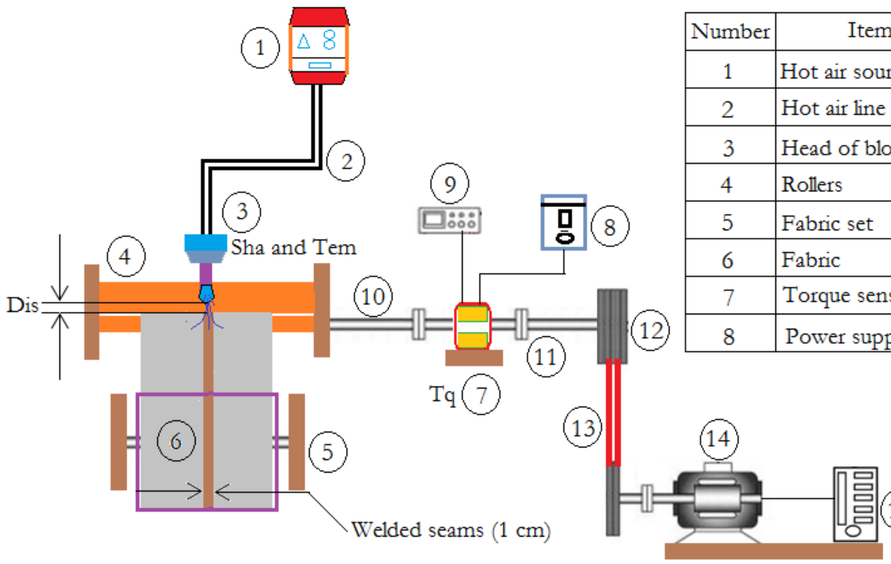
Fig. 1. PVC-coated polyester fabric.

Table 1. Physical and mechanical properties of PVC coated fabric.

Properties	Value
Weight	725 g/ m^2
Total thickness	0.78 mm
Breaking Strength	Warp 60 kN/m Weft 56 kN/m
Tear Strength	Warp 300N Weft 300N
Tensile strength	Warp 112.72 kN/m Weft 100.26 kN/m

2.2. Design of Workpiece and Hot-Air Welding Technique

The researcher constructed the hot-air welding machine, as shown in Fig. 2. to study factors which influence potentially on the strength along welded seam in warp and weft direction. In the experiment, two workpieces from fabric set are input to 0.5 horsepower motor - driving rollers. Compression force are measured by a torque sensor. A model of the torque sensor is Kistler Lorch GmbH series 4502A200RA. Temperature and speed adjustable hot air produced by a blower is fed to the workpieces at the entrance of the rollers. The width of the welded seam (lap joint) is controlled by the 1-cm head of the blower, as shown in Fig. 3. So the input parameters for this research are 1) distance between the head of blower and the workpieces (Dis) 2) temperature of the hot air (Tem) 3) torque (Tq) 4) speed of hot air (Sha). Each factor is divided into five different levels as shown in Table 2.



Number	Item	Number	Item
1	Hot air source	9	Voltmeter
2	Hot air line	10	Shaft
3	Head of blower	11	Coupling
4	Rollers	12	Pulley
5	Fabric set	13	Belt
6	Fabric	14	Motor
7	Torque sensor	15	Inverter
8	Power supply		

Fig. 2. Components of the hot air welding machine.

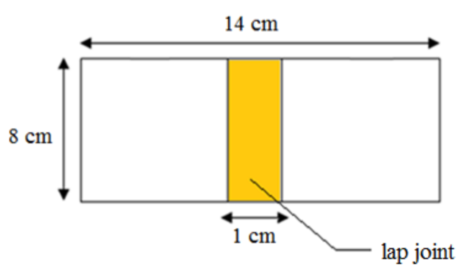


Fig. 3. Size of PVC coated fabric used in the experiment.

Table 2. Input parameters of the experiment.

Input parameters	Notation	Unit	Levels				
			1	2	3	4	5
Distance between a head of blower and workpieces	Dis	mm	2	4	6	8	10
Temperature of hot air	Tem	^{o}C	160	170	180	190	200
Torque	Tq	N.mm	5000	6000	7000	8000	9000
Speed of hot air	Sha	mm/s	1000	2000	3000	4000	5000

2.3. Tensile Testing

Hot-air welded workpiece is investigated the failing load at room temperature by using universal testing machine (UTM), as shown in Fig. 4(a). The tensile testing is conducted by using grips separation. The distance between grips is 200 millimetres long and the extensometer distance is 50 millimetres long. The workpiece is subjected to be measured the failing load in warp and weft direction, as describing in the PN-EN ISO 1421:2016, by drawing at a grip speed of 100 millimetres per minutes until the welded seam is torn off as shown in Fig. 4(b). 25 Sample of welding workpieces are magnified up to 10,000 times by the SEM, for studying physical properties of air cavity.

(a) (b)

Fig. 4. (a) A universal testing machine (UTM); (b) A tear around welded seam.

3. Optimization Technique for Parametric Determination

3.1. Taguchi Method

This research is utilized the experimental design by the qualitative engineering method proposed by Taguchi, which is effectively operational and systematic method for determining the optimum values of the process. To achieve the most effective engineering design, the researcher should design well-organized process with the least operational variation by applying experimental design principle and simplifying the analysis by introducing a ratio of output signal (S) to systemic noise (N), which is also called "S/N ratio", as an qualitative indicator. The analysis is classified in 3 cases as the following: [17-20]

1. Larger-is-Better case: This is expressed as

$$\frac{S}{N_L} = -10.log_{10}\left(\frac{1}{n}\right)\sum_{i=1}^{n}\frac{1}{y_i^2} \tag{1}$$

2. Small-is-Better case: This is expressed as

$$\frac{S}{N_S} = -10.log_{10}\left(\frac{1}{n}\right)\sum_{i}^{n} y_i^2 \tag{2}$$

3. Target-the-Best case: This is expressed as

$$\frac{S}{N_T} = -10.log_{10}\left(\frac{\bar{y}^2}{S^2}\right) \tag{3}$$

where n is the number of observations., y_i is experimental result, and the $\bar{y}$ and S are the average and deviation of all observations in each combination, respectively. The first case "Larger-is-Better", as shown in Eq. (1), is exploited in this research. The failing load, which is one of input parameters, is measured for calculating mean and ratio S/N and ultimately determining the optimum input parameters for welding process [21]. The mean and the ratio S/N are determined from the variable assessment for the hot-air welding process. The input parameters for the welding process of PVC-coated polyacrylic fabrics are classified into four factors. Each factor is divided into five different levels and hence L25 orthogonal arrays (OAs) is used in the design of experiments conducted by using the programme Minitab Release 18. A total number of 25 observations are experimented with the implemented input parameters and output parameters shown in Table 3.

Table 3. Experimental results of hot air welding process for PVC-coated fabrics by L25 Taguchi orthogonal arrays.

Number of observations	Input parameters				Output parameters	
	Dis (mm)	Temp (°C)	Tq (N.mm)	Sha (mm/s)	Failing load of Warp (Ten) (kN/m)	Failing load of weft (Ten) (kN/m)
1	2	160	5000	1000	70.34	61.34
2	2	170	6000	2000	64.62	55.74
3	2	180	7000	3000	58.63	51.06
4	2	190	8000	4000	50.54	41.54
5	2	200	9000	5000	45.42	37.11
6	4	160	6000	3000	80.25	70.89
7	4	170	7000	4000	74.96	66.12
8	4	180	8000	5000	63.22	54.67
9	4	190	9000	1000	56.74	48.53
10	4	200	5000	2000	49.76	41.25
11	6	160	7000	5000	83.15	73.86
12	6	170	8000	1000	72.91	62.93
13	6	180	9000	2000	67.78	56.99
14	6	190	5000	3000	60.92	51.24
15	6	200	6000	4000	55.73	47.16
16	8	160	8000	2000	90.43	81.77
17	8	170	9000	3000	81.26	71.64
18	8	180	5000	4000	74.14	65.14
19	8	190	6000	5000	67.23	58.57
20	8	200	7000	1000	63.22	53.53
21	10	160	9000	4000	95.38	86.17
22	10	170	5000	5000	89.59	79.88
23	10	180	6000	1000	81.82	72.45
24	10	190	7000	2000	75.44	65.6
25	10	200	8000	3000	68.59	59.61

3.2. Analysis of Variance

A statistical technique so-called analysis of variance (ANOVA) is used for determining the statistical significance of the input parameters. This technique identifies the correlation between independent variables and dependent variables. It is also used for the assessment of experimental errors at some extent of significance level. In this study the optimum strength of welded seam for the hot-air welding process will be evaluated from the mean of standard variance while the percentage of contribution for each variable will be calculated from the mean of variance [16].

4. Experimental Result and Discussion

4.1. Failing Load

This fabric welding used in this experiment follows the Taguchi experimental design by using L25 orthogonal arrays. Since there are four input parameters with five levels for each, the researcher repeated the trials five times for each pair. The output factors of the experiment are the failing load tabulated in Table 3. Maximum failing load in both directions occurs at the following input parameter: distance between the blower and the workpiece (Dis) = 10 mm, temperature of the hot air (Tem) = 160 ºC, torque (Tq) = 9,000 N.mm, and speed of hot air (Sha) = 4,000 mm/s. Examples of specimen after welded show in Fig. 5. The maximum failing load in warp direction and in weft direction are 95.38 kN/m and 86.17 kN/m, respectively. The larger the failing load obtains from the workpiece the longer time it is used for breaking down the bond joining between the two fabrics.

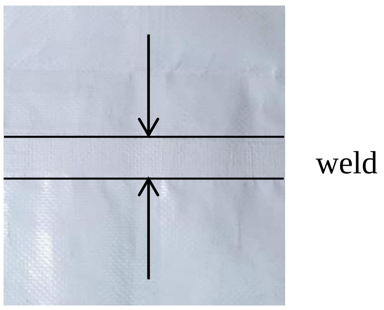


Fig. 5. Welded seams

4.2. Air Cavity Size

The 10000 magnification micrograph of the fabric taken from a scanning electron microscope (SEM) is illustrated in Fig. 6. Results of physical air cavity size is shown in Fig. 7. For the sample with maximum failing load in warp direction, the grain attaches uniformly with 1.127 μm size of air cavity, which is represented by white color in the micrograph. The air cavity in the sample with maximum failing load in weft direction also behave similarly but have a larger extent of grain distribution than in warp direction and the size of air cavity is approximately 2.357 μm. However, the grain distribution and the size of air cavity found in the sample with minimum failing load are relatively larger; the sizes of the air cavity in warp direction and weft direction are 4.828 μm and 11.293 μm, respectively.

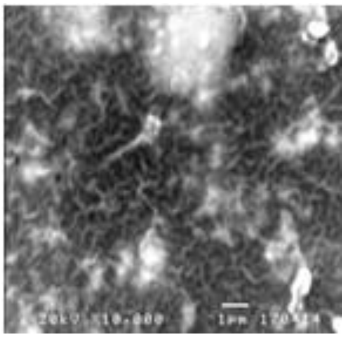
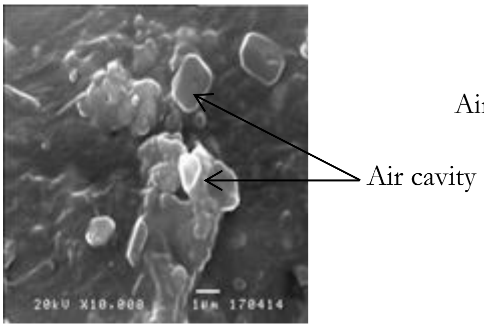
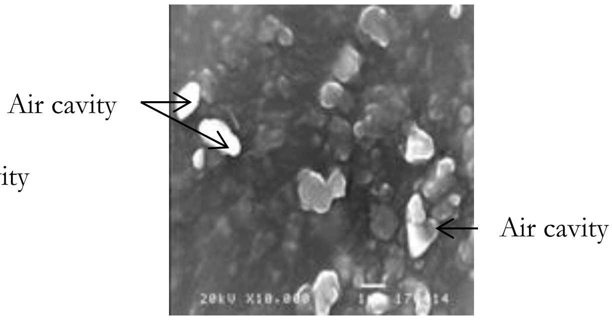


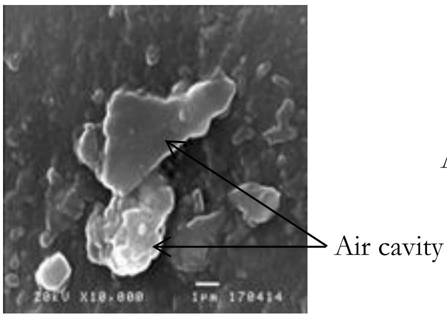
Fig. 6. A SEM micrograph of PVC coated fabric.



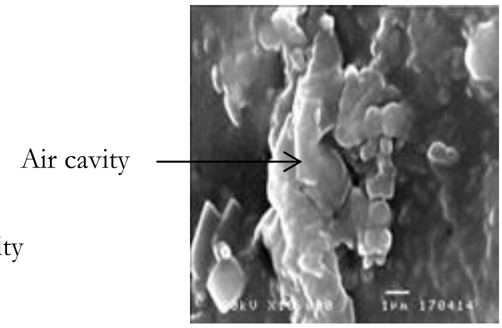
(A) Maximum failing load in warp direction is 95.38 kN/m



(B) Maximum failing load in weft direction is 86.17 kN/m



(C) Minimum failing load in warp direction is 45.42 kN/m



(D) Minimum failing load in weft direction is 37.11 kN/m

Fig. 7. Micrographs taken at weld seams of hot-air welded workpieces.

4.3. Residual Distribution

Residuals is used for investigating the distribution of data from considering a normal probability plot. Fig. 8. and Fig. 9. are used for the warp direction and the weft direction respectively. In both figures, Scatter plots (upper left) show the linearity and histograms (lower left) illustrate the concavity; this implies that the residual is normally distributed. The test for independence is considered based on the graph of Versus Order (lower right). It can be clearly seen that the residual distribution is random and not patterning; hence, the data represents the independence. The test for the variance stability is considered based on the graph of Versus Fits (upper right). It is found that the distribution of residual is balance about the zero value; hence, the data is uniformly distributed and the variance is constant.

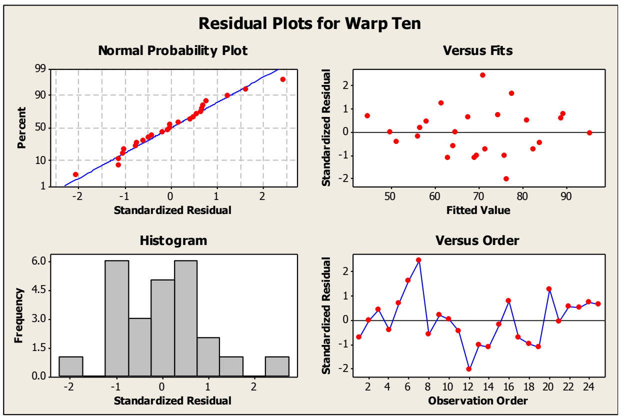


Fig.8. Plots for the residual distribution of failing load in warp direction.

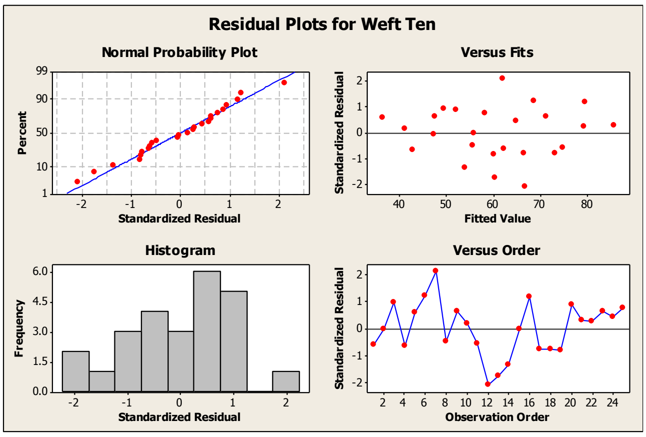


Fig.9. Plots for the residual distribution of failing load in weft direction.

4.4. Results of Signal-to-Noise Ratio

A result of failing load is used for determining the signal-to-noise (S/N) ratio in order to identify reliability and quality of welding seam in each workpiece with various the input parameters. The "larger-is-better" case expressed as in Eq. (1) is used in this study. Fig. 10. and Fig. 11. demonstrate the relationship of average responses at different levels of the 4 input parameters in warp and weft direction. The average S/N ratio in warp and weft direction are 36.71 dB and 35.45 dB, respectively. Responsiveness of the S/N ratio to the failing load in warp and weft direction are tabulated in Table 4 and Table 5. From the analysis, the input parameters in which influences the failing load ranked from the most to the least are the temperature of hot air, the distance between head of blower and workpieces, the torque, and the speed of hot air. When considering the S/N ratio by using a qualitative indicator "Larger-is-better", the optimal factors for welding the PVC-acrylic coated polyester fabrics in warp and weft direction are: Tem = 160 ^{o}C, Dis = 10 mm , Tq = 7,000 N.mm, and Sha = 3,000 mm/s

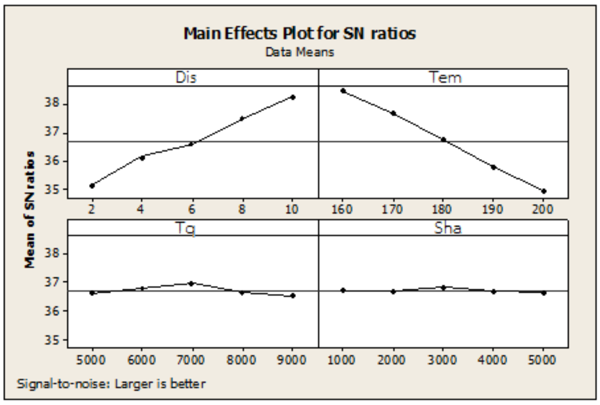


Fig. 10. Relationship between average responses of failing load in warp direction and the input parameters.

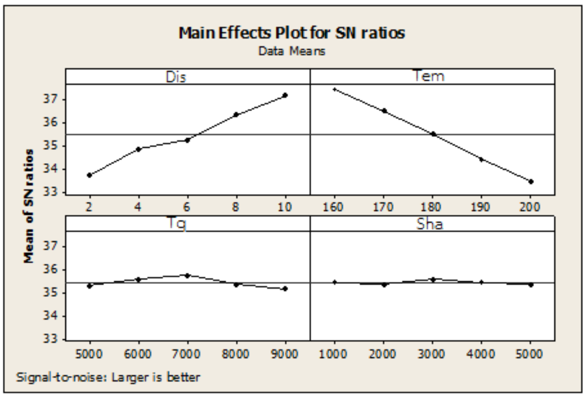


Fig. 11. Relationship between average responses of failing load in weft direction and the input parameters.

Table 4. Responses of S/N ratio "Larger-is-better" for the failing load in warp.

	Dis (mm)	Tem (°C)	Tq (N.mm)	Sha (mm/s)
1	35.15	38.43	36.60	36.71
2	36.12	37.64	36.81	36.69
3	36.58	36.73	36.97	36.81
4	37.46	35.79	36.64	36.70
5	38.23	34.95	36.53	36.63
Delta	3.09	3.48	0.44	0.18
Rank	2	1	3	4

Table 5. Responses of S/N ratio "Larger-is-better" for the failing load in weft.

	Dis (mm)	Tem (°C)	Tq (N.mm)	Sha (mm/s)
1	33.72	37.42	35.32	35.44
2	34.84	36.49	35.59	35.39
3	35.22	35.5	35.77	35.59
4	36.31	34.39	35.37	35.45
5	37.16	33.45	35.21	35.38
Delta	3.44	3.97	0.56	0.21
Rank	2	1	3	4

4.5. Results of ANOVA

The ANOVA is used for determining of a percentage of failing load distribution for hot-air welding PVC-acrylic coated polyester fabrics. The result of analysis shows that contribution of the input parameters at the significance level of 0.05 are: 41.80 % for Dis, 57.39% for Tem, 0.36% for Tq, and 0.09% for Sha for welding in warp direction (Table 6), and 40.76% for Dis, 58.23% for Tem, 0.41% for Tq, and 0.17% for Sha for welding in weft direction (Table 7). The temperature of the hot air (Tem) is the input parameter which affects the most on the failing load in both welding directions. Figures 12 and 13. express the relationships of the input parameters toward the output factors to which the result of ANOVA is conformed the result of the S/N ratio. Furtuthermore, these results comply with those of Mendes et al. [9] and Sorensen et al. [22], who welded polyprolylene and conclude that speed and torque do not influence the weld quality.

Table 6. The result of ANOVA for welding in warp direction.

Input parameter	DF	Adj.SS	Adj.MS	F	P	Percentage of contribution (%)
Dis	4	1750	438	3.59	0.023	41.80
Tem	4	2402	600	6.74	0.001	57.39
Tq	4	15	4	0.02	0.999	0.36
Shair	4	4	1	0.00	1.000	0.09
Error	20	4171	209	-	-	0.36
Total	24	4186	-	-	-	100

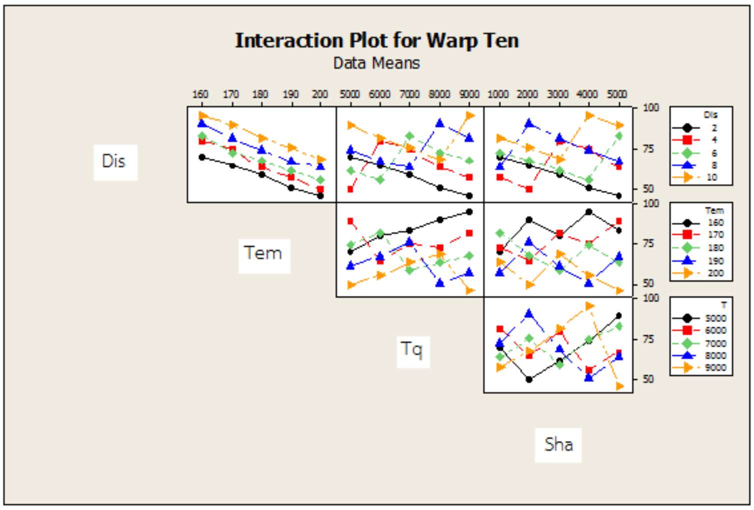


Fig.12. The relationship of the input parameters toward the output factors for welding in warp direction.

Table 7. The result of ANOVA for welding in weft direction.

Input parameter	DF	Adj.SS	Adj.MS	F	P	Percentage of contribution (%)
Dis	4	1643	411	3.44	0.027	40.76
Tem	4	2347	587	6.97	0.001	58.23
Tq	4	17	4	0.02	0.999	0.41
Shair	4	7	2	0.01	1.000	0.17
Error	20	4025	201	-	-	0.43
Total	24	4032	-	-	-	100

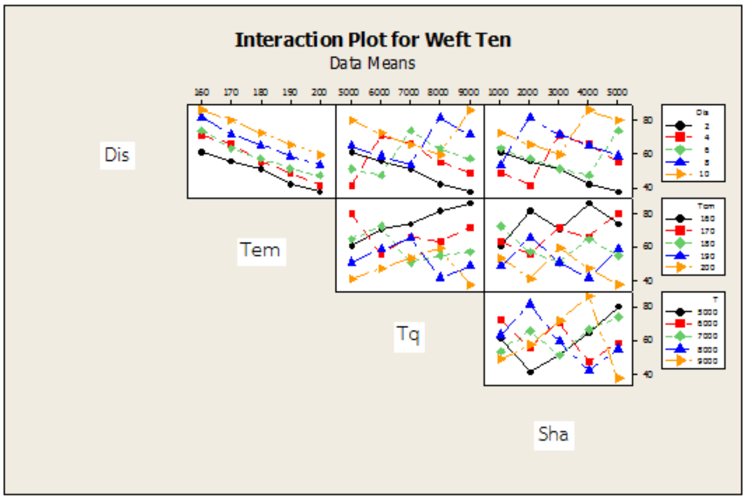


Fig.13. The relationship of the input parameters toward the output factors for welding in weft direction.

4.6. Results of Regression Analysis

A regression model with the highest statistical power can be determined from the result of residuals, as in section 4.6. The residuals is independent and identically distributed and the variance is constant. The level of significance is set at 5% or 0.05. The p-value are less than 0.05 for the input parameters of distance between the head of blower and the workpieces (Dis) and temperature of hot air (Tem). In contrast, the p-value for the input parameters of torque (Tq) and speed of hot air (Sha) are larger than 0.05 and the percentage of contributions of these two factors is lower than 1%, therefore the regression analysis is conducted only for the factors Dis and Tem. The results of the regression analysis are expressed by Eq. (4) and Eq. (5):

a regression equation for the failing load in warp direction,

$$\text{Failing load (warp)} = 176.65 + (2.94) \times \text{Dis} - (0.60) \times \text{Tem} \quad (4)$$

a regression equation for the failing load in weft direction.

$$\text{Failing load (weft)} = 166.56 + (2.83) \times \text{Dis} - (0.68) \times \text{Tem} \quad (5)$$

The input parameters Dis and Temp will be substituted in the above equations for determining the maximum failing load. Fig. 14. illustrates the comparison of the failing load in warp direction obtained from the experiments and the regression model. The forecasted maximum failing load is 95.33 kN/m at Dis = 10 mm and Tem = 265 ^{o}C. Fig. 15. the comparison of the failing load in weft direction where the maximum forecasted failing load is 86.06 kN/m at Dis = 10 mm and Tem = 160 ^{o}C. The forecasted values of the failing load in both directions conform to the experimental results. Table 8 tabulates empirical values, predicted values, and percentage error of the failing load in warp and weft direction. The mean percentage error and the mean absolute percentage error are 0.01% and 1.74% for welding in warp direction, and 0.01% and 2.42% for welding in weft direction. Therefore, the equations obtained from regression analysis can be used for the forecast of the failing load.

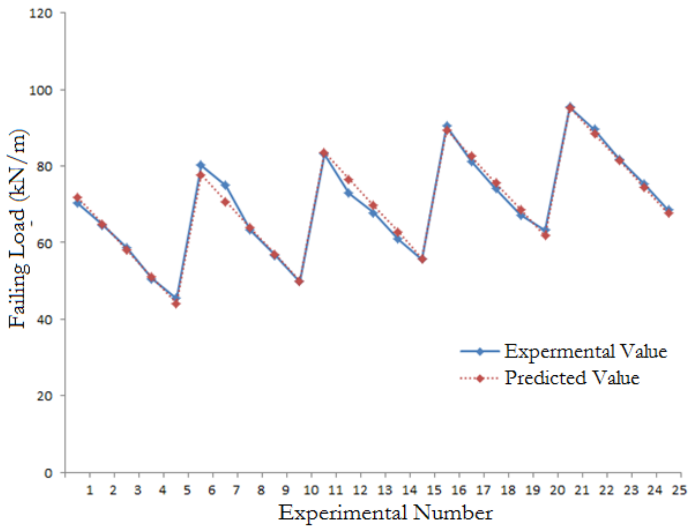


Fig.14. The comparison of the failing load in warp direction obtained from the experiments and the regression model.

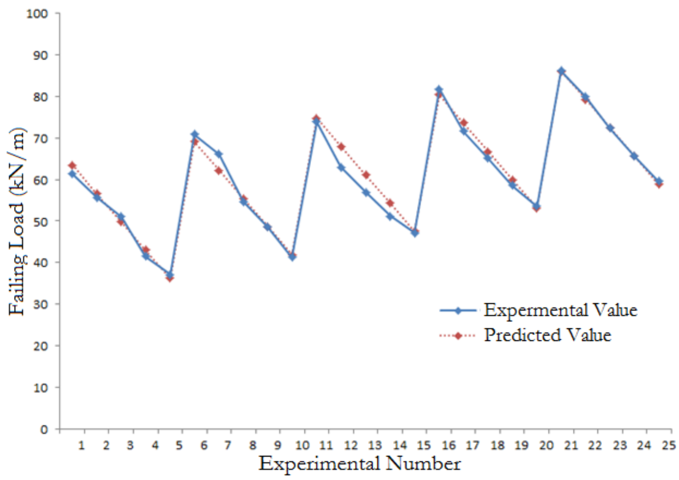


Fig.15. The comparison of the failing load in weft direction obtained from the experiments and the regression model.

5. Conclusions

The optimum input parameters for hot-air welding of PVC-acrylic coated polyester fabrics can be determined by using Taguchi technique. The maximum failing load in both directions is generated by the following input parameters: Dis = 10 mm, Tem = 160 ^{o}C, Tq = 9,000 N.mm, and Sha = 4,000 mm/s. The maximum failing loads are 95.38 kN/m and 86.17 kN/m for welding in warp and weft direction respectively. The grains of the welded fabrics attach uniformly at the maximum failing load, while they expand further at the minimum failing load. The responses of the signal-to-noise ratio indicate that the input parameters influenced the failing load, ranked in descending order, are Temp, Dis, Tq, and Sha. The optimum conditions of the input parameters for welding in both directions are: Dis = 10 mm, Temp = 160 ^{o}C, Tq = 7,000 N.mm, and Sha = 3,000 mm/s. The largest contributions of the input parameters for welding in warp and weft directions at the optimal conditions with the significance level of 0.05 are Dis, Temp, Tq and Sha, respectively. The mean percentage errors obtained from the regression analysis are less than 0.1% for welding in both directions which implies that the regression equations are reasonable for predicting the failing loads with conditions of the input parameters used in this work.

Table 8. Comparison between experimental and predicated value.

Number of observations	Failing load of warp (Ten) (N/mm) or (kN/m)			Failing load of weft (Ten) (N/mm) or (kN/m)		
	Experimental Value	Predicted Value	%error	Experimental Value	Predicted Value	%error
1	70.34	71.81	2.090	61.34	63.42	3.391
2	64.62	64.89	0.418	55.74	56.62	1.579
3	58.63	57.97	-1.126	51.06	49.82	-2.428
4	50.54	51.05	1.009	41.54	43.02	3.563
5	45.42	44.13	-2.840	37.11	36.22	-2.398
6	80.25	77.69	-3.190	70.89	69.08	-2.553
7	74.96	70.77	-5.590	66.12	62.28	-5.808
8	63.22	63.85	1.000	54.67	55.48	1.482
9	56.74	56.93	0.335	48.53	48.68	0.309
10	49.76	50.01	0.502	41.25	41.88	1.527
11	83.15	83.57	0.505	73.86	74.74	1.191
12	72.91	76.65	5.1296	62.93	67.94	7.961
13	67.78	69.73	2.877	56.99	61.14	7.282
14	60.92	62.81	3.102	51.24	54.34	6.050
15	55.73	55.89	0.287	47.16	47.54	0.806
16	90.43	89.45	-1.084	81.77	80.4	-1.675
17	81.26	82.53	1.563	71.64	73.6	2.736
18	74.14	75.61	1.983	65.14	66.8	2.548
19	67.23	68.69	2.172	58.57	60	2.441
20	63.22	61.77	-2.294	53.53	53.2	-0.616
21	95.38	95.33	-0.052	86.17	86.06	-0.128
22	89.59	88.41	-1.317	79.88	79.26	-0.776
23	81.82	81.49	-0.403	72.45	72.46	0.014
24	75.44	74.57	-1.153	65.6	65.66	0.091
25	68.59	67.65	-1.370	59.61	58.86	-1.258
		Average	0.10		Average	0.01
		Absolute	1.74		Absolute	2.42

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