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Optimization of High Frequency Welding Parameters of PVC Coating on Polyester Fabric

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Abstract

This study optimized welding parameters on polyester fabric coated with PVC by applying high frequency welding technique. Taguchi experimental design was adopted in this evaluation. Three levels of width of seam and time of high frequency welding were applied and analyzed with ANOVA statistical method with $\alpha = 0.05$. The optimized result shows that the input parameters providing maximum failing load for welding in warp and weft directions are the following: Width of seam (27 mm) and time of welding (12 s). The maximum failing load were 87.8 and 75.8 N/mm for warp direction and weft direction, respectively, In addition, the statistic analytical result indicated that the width of seam was the most significant factor and the predicted optimal value of failing load were 88.5 and 80.5 N/mm for warp direction and weft direction, respectively, shows that the average percentage error is less than 2 % so that the forecast equation is appropriate for the explanation of the variables for this study and provide statistical reliability. The result was verified through confirmation experiments, the high frequency welding was suitable for welding PVC Coating on Polyester Fabric.

Keywords: Polyester, Fabric, High frequency, Variances, Prediction

Introduction

Fabric preparation has long history with advancement of civilization, and coated fabrics and tents have been used for centuries. This fabric was heavily utilized in architecture and was continuously developed throughout the years. Improvement in physical, chemical and mechanical properties were in constant stage for tent fabrics to advance and exhibited better performance. Light weight, highly resistant to stretch and tear, anti-UV, heat resistant, non-fading color material, and longer product life spans become normal characteristic of this type of product [1]. Due to varieties of benefit and advantage of this product, it was heavily utilized in various places, O_2 Arena in Greenwich-south-east of London, England [2], Qingdao ETSONG Stadium, China [3] and many others such as airport, shopping mall and restaurants around the world [4]. In addition, it is used for decoration, and as fabrics in the air circulation system [5]. Architecture fabric was mainly fabricated from polymer especially polyester and coat with Polyvinyl chloride (PVC). One of the main drawbacks of this fabric is its limited size. When used in large space such as in the air circulation system, the widths of 1.5 - 3.5 m and length of 50 - 70 m are not sufficient. Employing specialist in sewing became the necessary. However, sewed fabric has lower mechanical performance thus limits the potential of coated fabric. To overcome this limitation, welding method was utilized. The welding method has higher mechanical performance when compared with sewed fabric, production of tailored product was much faster, and process was more efficient. The only disadvantage of this approach is that the machine used is heavy and cannot deploy onsite in case of adjustment. To compensate with mobility, hot air welding is often used. Production conditions, distance between the outlet diffuser and specimen, the temperature of hot air, the torque and the speed of hot air

[6], affect product characteristics, for example, faster production yields end- products with rough surface [7,8].

Welding method is selected mainly based on the type of materials. Electrical current is the key parameter in arc welding [9]. Friction stir welding has several parameters that influence the welding performance such as speed, welding time, and pressure applied during welding [10-14]. Rotary friction welding has welding speed and burn-off length to control the welding performance [15]. Laser welding is controlled by laser power and scanning speed [16]. To optimize production parameter, Taguchi and Fuzzy logic approach in combination with orthogonal array, signal-to-noise ratio, multi-response performance index, neural network experiment design and analysis of variance were normally applied in the optimization [17,18].

High frequency welding method is widely used because this method does not alter product dimension and has less damage on the product surface [19] in addition to faster production, it can be applied on varieties of plastics [20]. Parameters that control the welding and influence the product performances are frequency, welding time, releasing heat form the welding process, sample thickness and applied pressure during the production [21]. Expensive welding equipment can precisely control these parameters, especially welding width of seam and welding time. In this study, welding width of the seam and time were monitored and optimized to achieve productivity with highest performance by adopting Taguchi, ANOVA and regression analysis compared with the author's previous work, Khaothong (2019), in hot air welding [6].

Materials and methods

Polyester fabric coated with PVC, acrylic and polyvinylidene difluoride (PDVF) allowed resistant against water and moisture. **Figure 1** shows the schematic diagram of coating structure of fabric [22]. The lengthwise (longitudinal) or vertical set of yarns in the fabric are called warp and the horizontal or transverse set of yarns in the fabric is known as weft. **Table 1** shows the fabric properties.

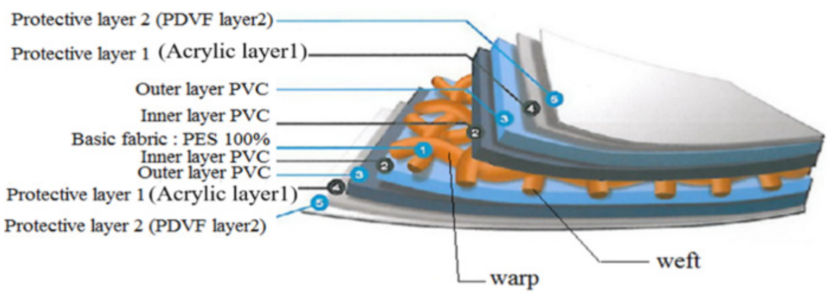


Figure 1 PVC-coated polyester fabric.

Table 1 Physical and mechanical properties of PVC coated fabric.

Properties	Directions	Value
Weight	Warp and Weft	725 g/ m^2
Total thickness	Warp and Weft	0.78 mm
Breaking strength	Warp	60 N/mm
	Weft	56 N/mm
Tear strength	Warp	300 N
	Weft	300 N
Thermal conductivity	Warp and Weft	0.0045W/m. K

Fabric measuring 35×80 mm^2, was dried at room temperature (25 °C) for 24 h. High frequency welding machine (VINITA) was used throughout the study, as shown in **Figure 2**. Due to fixed parameters from manufacture, such as frequency, heating rate and pressure could not be adjusted. Two fabrics were placed on the plates, where the machine generated heat through the plates by pressing at different times. Performance of product was monitored from failing load in association to welding width of seam and time, with 3 levels each as shown in **Table 2**. Universal testing machine (LLOYD, LR model) was used to determine mechanical properties of welded fabric at room temperature according to ISO 1421:2017 standard.

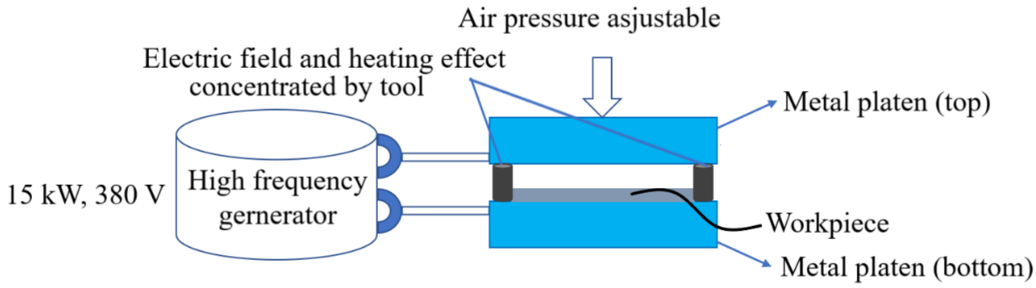
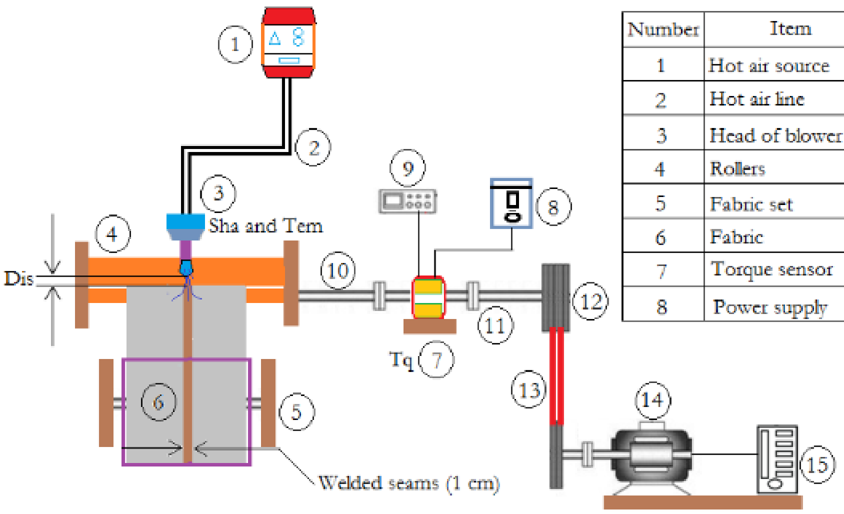


Figure 2 High frequency welding machine.

Table 2 Input parameters of the experiment.

Input parameters	Notation	Unit	Levels		
			1	2	3
Width of seam of seam	Width	mm	9	18	
Time of welding	Time	s	4	8	12

In the hot air welding experiment, Khaothong (2019) [6], 2 fabric set were input to motor - driving rollers. Compression force is measured by a torque sensor. 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 seam of the welded seam (lap joint) is controlled by the blower, as shown in **Figure 3**, 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.



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		

Figure 3 Hot air welding machine.

Investigation of welded seam on workpieces is magnified up to 10,000 times by the scanning electron microscope (SEM), for studying physical properties of air cavity size.

Results and discussion

Two factors and 3-level experimental design were used to identify the effect of high frequency welding performance by monitoring the failing load from different welding conditions. Taguchi experimental design and statistical analysis were used to quantify the effect. **Table 3** showed failing load of warp and weft of fabric from different welding condition. Minimum failing loads, of warp and weft, were observed at 62.2 and 54.1 N/mm, at the following input parameter: Welding width of seam of 27 mm and time of 12 s. The maximum failing load of warp was 87.8 N/mm, which is higher than maximum load of weft, 78.5 N/mm because of during weaving, warp is the yarns that are being stressed to maintain the tension, there will definitely have residual stress in the yarns that are in the warp direction. This eventually results in the reduction in the fabric strength. The observation number 1 - 6 showed complete peeling of seem, as shown in **Figure 4(a)**, while number 7 - 9 ruptured at the base material, as shown in **Figure 4(b)**. The number 7 - 9 had welding width of seam of 27 mm. However, the metal platens of high frequency welding machine can weld at maximum length of 18 mm. Therefore, welding of condition 7 - 9 were done twice, thus caused the differences in welding on the surface which affected bonding of fabric and eventually caused rupture on the base material. Similar results were reported by Kun *et al.* [23] who conducted welding on polyethylene fabric coated with PVC.

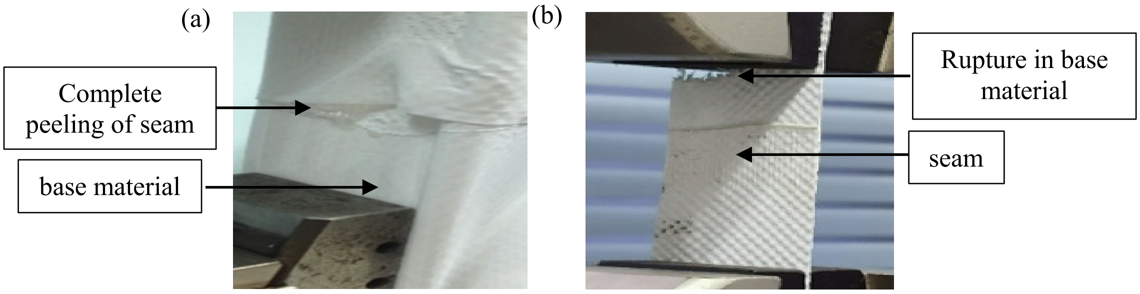


Figure 4 Example of rupture type. (a) Complete peeling of seam at number of observation 6. (b) Rupture in base material at number of observation 9.

Table 3 Experimental results of high frequency welding process for PVC-coated fabrics by L9 Taguchi orthogonal arrays.

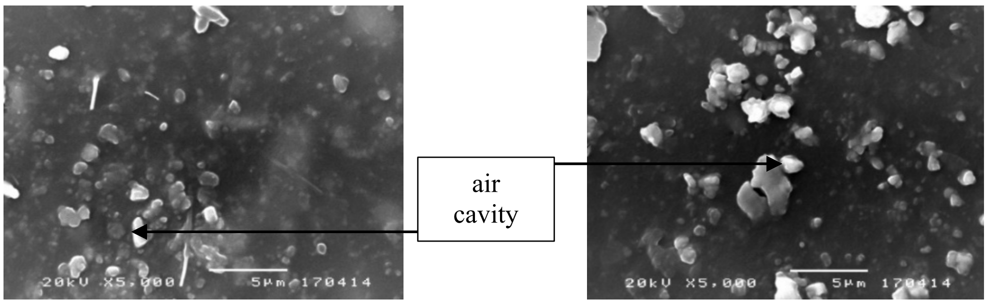
Number of observations	Input parameters		Output parameters		Rupture type
	Width (mm)	Time (s)	Failing load of warp (N/mm)	Failing load of weft (N/mm)	
1	9	4	62.2	54.1	Complete peeling of seam
2	9	8	68.9	60.7	Complete peeling of seam
3	9	12	74.3	65.4	Complete peeling of seam
4	18	4	69.2	61.0	Complete peeling of seam
5	18	8	76.7	69.1	Complete peeling of seam
6	18	12	83.1	76.4	Complete peeling of seam
7	27	4	78.4	69.3	Rupture in base material
8	27	8	82.7	73.1	Rupture in base material
9	27	12	87.8	78.5	Rupture in base material

Comparing the failing of fabric between high frequency welding and hot air welding, hot air welding yielded higher product performance, as shown in **Table 4**. This was due to the use of higher temperature and welding time during the process. Although the fact that the high frequency weld is more durable failing loads than the hot air welding, the hot air welding is applicable and economical operating in the manufacturing processes more than the high frequency welding.

Table 4 Comparation of failing load of high frequency welding and hot air welding.

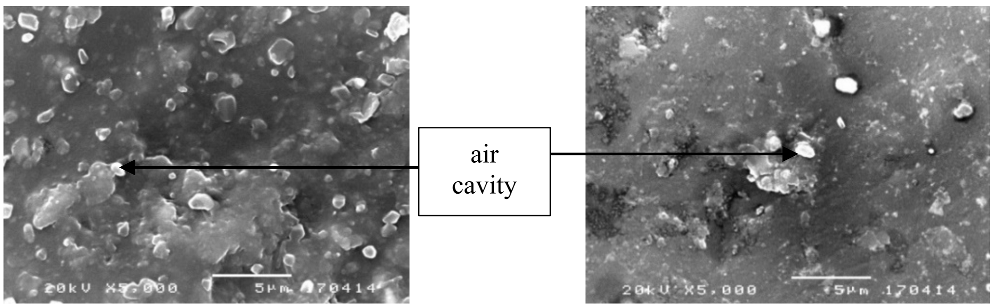
Process	warp (N/mm)	Weft (N/mm)
high frequency welding	87.8	78.5
hot air welding	95.4	86.2
% error	−7.9	−8.9

The effect of welding parameters and tool configuration on the surface appearance, mechanical and microstructural properties of similar and dissimilar. The scanning electron microscope (SEM) was used to analyze samples surface. Samples of different welding condition are shown in **Figures 5(a) - 5(d)**. At maximum failing load, grain sizes of weft were well dispersed with average air cavity size of 0.9 µm. At this loading, weft had more grain size distribution with average air cavity size of 2.2 µm. At the lowest failing loading from weld width of seam of 9 mm and time of 4 s, both weft and warp had average air cavity size of 2.9 and 6.2 µm, respectively. Although maximum failing load from high frequency welding method and hot air welding method were similar, average air cavity size of hot air welding were larger in all cases due to poor heat distribution during welding, as shown in **Table 5**.



(a) Maximum failing load in warp direction is 87.8 kN/m.

(b) Maximum failing load in weft direction is 78.5 kN/m.



(c) Minimum failing load in warp direction is 62.2 kN/m.

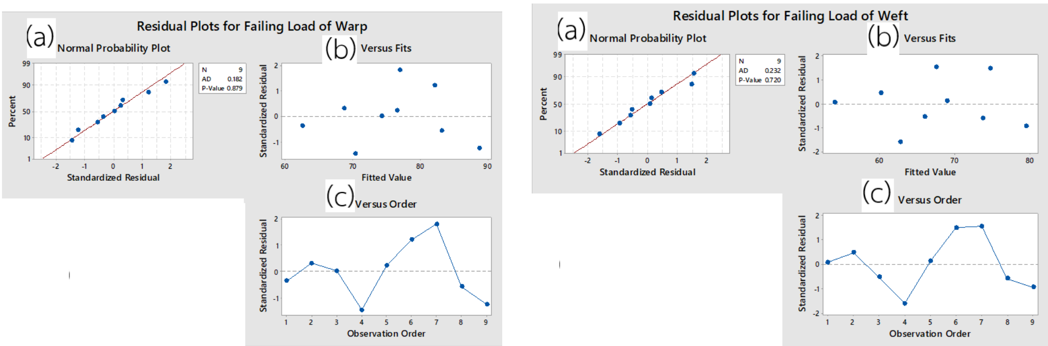
(d) Minimum failing load in weft direction is 54.1 kN/m.

Figure 5 Micrographs taken at weld seams of high frequency welded workpieces.

Table 5 Air cavity size from high frequency and hot-air welded workpieces.

process	warp (µm)		Weft (µm)	
	maximum failing load	minimum failing load	maximum failing load	minimum failing load
high frequency welding	0.9	2.9	2.2	6.2
hat air welding	1.1	4.8	2.3	11.3
% error	−18.2	−39.5	−4.3	−41.5

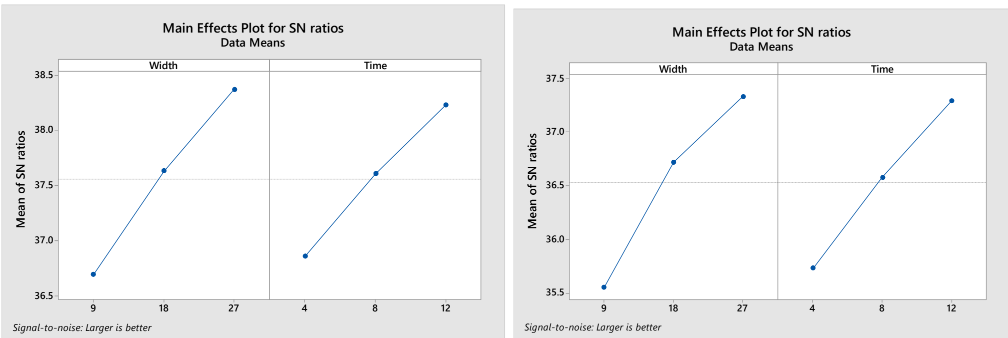
Residuals plot was used to identify distribution of sample values. Both warp and weft had balance area above and below linear line as shown in **Figure 6**. This implied low deviation and good distribution of sample values. However, when compare both warp and weft, the values were not random and correlated. Therefore, these values were independent from one another.



(A) warp direction (B) weft direction

Figure 6 Plots for the residual distribution of failing load.

As demonstrated in residual distribution analysis, both warp and weft were not related. An average signal to noise ratio between warp and weft were identified as shown in **Figure 7**. By this approach, the larger of S/N ratio, dB, as shown in **Tables 6** and **7**, implied that selected parameter has major effect on the welding process. It was found that welding width of seam exhibited greater effect on failing load than welding time. Based on this analysis, optimum welding conditions were welding width of seam of at 27 mm and welding time at 12 s. Result of ANOVA analysis confirmed that welding width of seam had more impact on failing load in both warp and weft thread direction than welding time as shown in **Tables 8** and **9**, and **Figure 8**.



(A) warp direction (B) weft direction

Figure 7 Relationship between average responses of failing load in weft direction and the input parameters.

Table 6 Responses of S/N ratio “larger-is-better” for the failing load in warp.

Level	Width of seam (mm)	Time (s)
1	36.69	36.85
2	37.63	37.60
3	38.37	38.23
Delta	1.68	1.37
Rank	1	2

Table 7 Responses of S/N ratio "larger-is-better" for the failing load in weft.

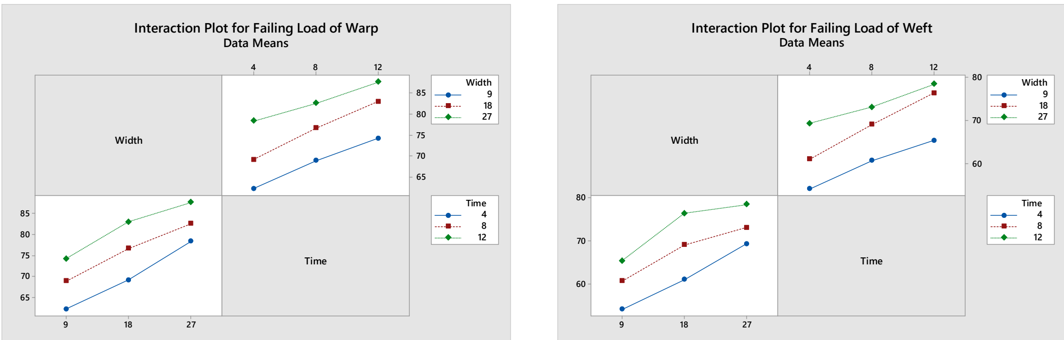
Level	Width of seam (mm)	Time (s)
1	35.55	35.73
2	36.72	36.58
3	37.33	37.29
Delta	1.78	1.56
Rank	1	2

Table 8 The result of ANOVA for welding in warp direction.

Source	DF	Seq ss	% contribution	Adj ss	Adj Ms	F-value	*p*-value
Width of seam	2	316.13	59.57 %	316.136	158.068	113.36	0.000
Time	2	209.00	39.38 %	209.002	104.501	74.94	0.001
Error	4	5.59	1.05 %	5.578	1.394		
Total	8	530.71	100.00 %				

Table 9 The result of ANOVA for welding in weft direction.

Source	DF	Seq ss	% contribution	Adj ss	Adj Ms	F-value	*p*-value
Width of seam	2	283.95	59.69 %	283.95	141.974	51057.36	0.001
Time	2	214.87	42.15 %	214.87	107.434	39.03	0.002
Error	4	11.01	2.16 %	11.01	2.753		
Total	8	509.83	100.00 %				



(A) warp direction (B) weft direction

Figure 8 The relationship of the input parameters toward the output factors for welding in weft direction.

The *p*-values in **Tables 10** and **11** represents the relation of welding width of seam and time to failing load. With $\alpha = 0.05$, those parameters affected failing load of warp and weft. Therefore, the equations obtained from regression analysis can be used for the forecast of the failing load are shown in Eqs. (1) - (2). Variance inflation factor (VIF) was used to monitor severity of error of warp and weft in this study. Results showed the value was less than 1.

Table 10 Coefficient of regression in warp direction.

Term	Coef	SE Coef	T-value	*p*-value	VIF
Constant	49.62	1.25	39.73	0.000	
Width	0.8056	0.0471	17.09	0.000	1.00
Time	1.475	0.106	13.91	0.000	1.00

Table 11 Coefficient of regression in weft direction.

Term	Coef	SE Coef	T-value	*p*-value	VIF
Constant	41.98	2.14	19.66	0.000	
Width	0.754	0.080	9.35	0.000	1.00
Time	1.496	0.181	8.25	0.000	1.00

Failing load of warp = 49.62 + 0.81 Width of seam + 1.42 Time (R-sq = 98.78 %) (1)

Failing load of weft = 41.98 + 0.76 Width of seam +1.49 Time (R-sq = 96.78 %) (2)

Table 12 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 0.4 and 1.0 % for welding in warp direction, and −0.2 and 1.8 % for welding in weft direction. Therefore, the equations obtained from regression analysis can be used for the forecast of the failing load.

Table 12 Comparison between experimental and predicted value.

Number of observations	Failing load of warp (N/mm)		%error	Failing load weft (N/mm)		%error
	Experimental value	Predicted value		Experimental value	Predicted value	
1	62.2	62.6	−0.6	54.1	54.8	1.3
2	68.9	68.3	0.9	60.7	60.8	−0.2
3	74.3	74.0	0.5	65.4	66.8	−2.2
4	69.2	69.9	−1.0	61.0	61.6	−1.1
5	76.7	75.6	1.5	69.1	67.6	2.1
6	83.1	81.2	2.2	76.4	73.6	3.6
7	78.4	77.2	1.6	69.3	68.5	1.2
8	82.7	82.8	−0.1	73.1	74.5	−1.9
9	87.8	88.5	−0.8	78.5	80.5	−2.5
		Average	0.4		Average	−0.2
		Absolute	1.0		Absolute	1.8

Conclusions

In this research, the experiments have been planned and conducted in order to investigate the effects of welding in the high frequency welding process. Optimized process conditions have been obtained for 2 responses- width and time using Taguchi and ANOVA optimization techniques. Following conclusions could be drawn from this investigation:

1) All the factors investigated in the study have been found to be highly significant for their effect on failing loads.

2) The percent contribution of the width of seam in the warp and weft directions are the following: 59.57 and 59.56 %, respectively.

3) The percent contribution of time in warp and weft directions are the following: 39.38 and 42.15 %, respectively.

4) Hot air welding was better than high frequency welding due to less failure and also affected failing load, when compared to the hot air method with 7.9 % for warp and 8.9 % for weft.

5) Microstructure analysis showed high frequency welding had less air cavities in fabric and also affected failing load, when compared to the hot air method with 18.2 % for warp and 4.3 % for weft.

6) The high frequency welding and hot air welding are suitable for welding PVC Coating on Polyester Fabric in construction and excellent mechanical properties.

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