Optimization of High-Pressure Laminate Manufacturing Process by Taguchi Method

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Abstract: The manufacturing process of High-Pressure Laminates was investigated using a strong optimization tool, the Taguchi method. High pressure laminates consist of various types. Each type has specific manufacturing process and uses. One of the utmost and crucial types of High-Pressure Laminate is Electrical Bakelite Sheet or industrial grade sheet. Electrical Bakelite Sheet is mainly used in Transformer as an insulated material. The Taguchi method was used to enhance the quality of the product and optimized the manufacturing process of Electrical Bakelite Sheet. Baking Time, Temperature, Resin Content, Pressure and Volatile Content are factors of industrial grade sheet manufacturing process and responses of these factors are electrical Insulation and thickness. Optimal value of these factors for the process are obtained through Taguchi method and found experimentally. As a result, the Taguchi technique is used to explore the effects of various electrical Bakelite Sheet parameters on responses such as electrical insulation and thickness. Pressure, Temperature, Volatile Content, Resin Content, and Baking Time are the factors which should be considered for the experiment. The Taguchi L27 orthogonal array is used for testing. The significant factors for responses of the electrical Bakelite Sheet are identified using analysis of variance (ANOVA). Determination of the significant factors value resulted in best achieving yield of the product.

Keywords*:* Optimization, Electrical Bakelite Sheet, ANOVA, Design of experiment, Taguchi method.

I. INTRODUCTION

The synthetic plastic was discovered accidentally by professor named “LEO HENDRIK BAKELAND”. The commercial age of the plastic “Phenolic Resin” started from the era of 1907. Formaldehyde and Phenol was cured at high temperature and pressure and novel product formed called Bakelite link with the name of the Leo Hendrik Bakeland. At that time there was no good insulation material and by the discovering of the Phenolic Resin change the world of electrical appliance [1]. In local industry, Electrical Bakelite Sheet is produced in Flat Sheet form. The product consists of different layers. The impregnated papers are compressed between the two metal plates under high pressure and temperature as per required thickness of the product. Decor paper impregnated with Melamine Formaldehyde resin is used for the top and bottom layers, while Kraft paper impregnated with Phenolic Formaldehyde resin is used for the core layer. The core layer is sandwiched between the above and bottom layer of décor paper and the product is named Electrical

Bakelite Sheet or industrial Grade Sheet. Temperature, Pressure, Resin Content, Volatile Content, Viscosity of the Phenolic and Melamine Formaldehyde effect the output variable [2].

Formica, Laminated Hard Board (LHB), Laminated Chipboard (LCB), High Density Fibre (HDF), Laminated Medium Density Fibre (LMDF), Bakelite, and Electrical Bakelite Sheet are laminates produced by the industry. The products booking is based on the "just in time" philosophy. Electrical Bakelite Sheet product produced in a wide range of colour, thicknesses, sizes, and surface finishes. This work involves the following objectives.

1. The study's findings include a reduction in the rate of defects, waste minimization, yield optimization, and thickness variation reduction of the Electrical Insulation Sheet process using the Taguchi method.
2. Improving process performance, quality of the product, and customer satisfaction by Taguchi method.
3. Optimizing parameters of Electrical Bakelite Sheet manufacturing process through Taguchi method.
4. Enhancing insulation properties of Electrical Bakelite Sheet through Taguchi method.
5. Obtained optimized results will be suggested for its implementation in the industry and observed its effectiveness.

The study is restricted to industrial grade sheet industry and transformer industry data is not taken into consideration.

II. LITERATURE REVIEW

Manufacturing process optimization can be accomplished in a variety of ways. At a certain investment cost, the system's yield is enhanced by selecting poor-performing manufacturing stages and raising their likelihood of successfully processing time [3]. Optimal experimental design is a way of saving time and money by reducing the amount of work you have to do. Dynamic input is determined and meaningful results are obtained in optimal experimental design analysis [4]. DOE is discussed in the disciplines of process control, biological systems, pharmacodynamics, and chemical kinetics, among others. DOE aids in the extraction of high-quality data in a short amount of time with little resource use [5]. The Taguchi Orthogonal Array technique, DOE, and boosting the quenching process are used to reduce the mean variance in the yield strength of Thermo Mechanically

Treated (RMT) steel Bar [6]. The DOE determined key input elements in sustainable building design in the UK, such as carbon emissions, operating costs, and overheating concerns [7]. The milling process' cutting parameters are optimised, and trade-offs between production rate, cutting quality, and durability are assessed [8]. For small data hybrid fuzzy regression-design of experimental model for consumption of energy estimation is developed, and the model is verified using data from Pakistan, Singapore, the United States, Canada, and Iran from 1995 to 2005 [9]. The Taguchi technique, a great tool for optimization of quality, is used to find the ideal cutting parameters for turning operations. An orthogonal array, (S/N) ratio, and ANOVA are used to evaluate the S45C cutting properties of steel bars utilising tungsten carbide cutting tools. [10]. The Taguchi technique is used for parametric optimization of Electric Discharge Machining on machining properties of die steel, including removal rate of material, Kerf width, and roughness of surface. [11]. Experimental design, Taguchi's L18 array is used for Machining process of Wire Electrical Discharge for optimization of the eight factor and their responses [12]. The optimization model was created to optimise, predicts and find the impacts of production factors on brake materials [13].The resistivity of Bakelite in Resistive Plate Chamber (RPC) has been investigated by Systematic approach which resulted that the resistivity of Bakelite is domain of humidity ranging between 35-65% and temperature ranging 20-30C^o [14].

One of the main factors of RPC electrode is when used with Melamine or Phenolic Bakelite showed electrode resistivity. In a control apparatus circumstances the different procedures were adopted to investigate and study the quantity measure of Bakelite resistivity with different humidity and temperature by different kinds of laminates [15]. On the aging of oil impregnated paper, experiments are conducted which effects the aging of cellulose in transformer having major factors of temperature, moister and oxygen [16]. The insulation performance of the equipment was disturbed containing aqueous oil impregnated Kraft Paper [17]**.** In a power transmission cable with an electric stress of 500 KV, the electrical insulation capabilities of oil impregnated polypropylene paper were investigated to see if it might replace insulating Kraft paper in cable transmission [18].The moister diffusion coefficient of impregnated Kraft paper insulation is computed using a novel method, and equation is obtained and experimentally validated [19]. In a power transformer, the thermal degradation of Kraft paper insulated with natural ester was investigated [20]. Epoxy-paper insulation approach is a novel insulation technology that is now being utilised to made brushings for high voltage for transformers with voltage ratings ranging from 15 to 69 kV**.** Other insulation material that is electrical porcelain oilpaper, phenolic paper, and mineral filled epoxy, are compared to the epoxy paper insulation system. The resin of Epoxy is fully utilized to permeate an electrical grade of Kraft in this innovative insulation system, resulting in a new product with new remarkable characteristics**.** It can withstand high voltages and has a high dielectric strength. Impregnated paper with Epoxy provides a strong system of insulation with excellent stability of thermal. Epoxy insulation based on resin-rich, with around 70 percentage of the material contributing to solid insulation systems suitable for high voltage systems [21].

III. SCOPE AND SIGNIFICANCE OF THE RESEARCH

In the open market, the product was sold 3 dollar per kg in Pakistan. The reduction of waste will enhance the industry's production line. Electrical Bakelite Sheet is mostly used in transformers and other electrical equipment. Resistance to high voltage is utmost essential qualities of Electrical Bakelite Sheet, which also serves as an insulation material [22]. Improving the insulation qualities of Electrical insulation Sheet will result in a significant change in the transformer industry and will save the transformer industry a significant amount of money.

IV. PROBLEM STATEMENT

Because the industry has difficulty on quality control, a substantial number of defective Electrical Bakelite Sheets are manufactured. The principal flaws include variations in thickness, less Resistance to Electrical Voltage, and unbaked product. Electrical Bakelite Sheet (EBS) production process is influenced by Pressure (P), Temperature (T), Baking Time (BT), plate type, Resin Content (RC), Volatile Content (VC), phenol formaldehyde, and melamine formaldehyde concentration.

To optimize the manufacturing process of electrical Bakelite sheet, it was important to identify the main factors and optimums level that affect the yield process.

V. INDUSTRIES PROCESS DETAILED

Kraft paper rolls of various grammages, Melamine paper, Phenol chemicals in aqueous forms, Formaldehyde, Urea, and Melamine Bags in Power form comes as raw materials to the industry. A quality expert supervisor inspects the raw material's quality. Raw materials that meet industry standards are accepted, while those that do not are returned to the provider. Melamine Formaldehyde resin is now made in a Melamine tank, also known as a Melamine kettle. In a phenol tank, also known as a phenol kettle, the phenol formaldehyde resin is manufactured. In a urea tank, formaldehyde resin is made. After preparation, the resin is held in an isolated tank and used as needed by impregnation machine. For the impregnation of Melamine paper or decor paper, both Melamine Formaldehyde and Urea Formaldehyde resins are employed in a plant known as a Melamine Impregnation Unit or a Programme Logic Control (PLC) Unit. The quality of the impregnated papers is examined after the decor and Melamine papers were impregnated. Standard grade impregnated paper is stored in a paper hall and used in a hot printing press as needed, while rejected impregnated paper is transported to a scrap store. The impregnation Kraft Unit uses phenol formaldehyde resin to impregnate Kraft paper rolls. The quality of impregnated Kraft paper is verified, and excellent impregnated grade paper is dispatching for storing and utilized in press for production as required, while scrap material is store in scraped yard.

Impregnated kraft and decor paper are dispatch in press for production of EBS product. The papers are heated at a high temperature and pressure for a specific time. The end-product is a sheet called Electrical Bakelite Sheet that comes out of the press. In the cutting stage, the excess Kraft paper from the Bakelite Sheet is removed with a saw cutter. Finally, the stacks of Bakelite Sheet are taken to the quality control division to be inspected for Electrical Bakelite Sheet quality. Digital Vernacular Caliper is used to verify thickness, and a High Voltage Device is used to check insulation. Electrical Bakelite Sheets are stored or supplied to customers after being inspected for quality, and those that are rejected are shipped to a scrap yard. The Design Specification of the EBS product is tabulated in Table 1.

Table 1 represent the design specifications for an electrical Bakelite sheet with a 6mm thickness.

Name of Response	**Unit**	**Lower Specification Limit (LSL)**	**Upper Specification Limit (USL)**
Electrical Insulation Resistance	Kilovolt Resistance (KVR)	36.00	---
Thickness	Millimetre (mm)	5.75	6.25

VI. METHODOLOGY

Taguchi's approach is a valuable instrument for creating high-quality production systems. The Taguchi technique is a simple method for improving the performance, quality, and cost of a manufacturing process. It has recently gained popularity in the field of design for the optimization of manufacturing processes in industries that play a crucial role in the process [10].The Taguchi model is first discussed in the next section. The next section describes the experimental specifics of employing the Taguchi parameters. The best parameter of the electrical Bakelite sheet production process is assessed in terms of performance indicators like electrical insulation and thickness.

The Taguchi practice was created by Taguchi. He proposed that product or process, engineering optimization should be done in three steps: design for factor, system and tolerance. The technical expertise creates a prototype. The product design stage includes the selection of materials, components, and estimated product factors values. The process design step includes the analysis of the processing sequence, the selection of equipment for production, and the estimation of process factor values. Because designing of the system is a first functional design. Factor design is the next stage after system design. The purpose of factor design is to discover product parameter values that are unaffected by changes in ambient conditions and other noise elements, as well as to optimize the settings of process factor values in order to improve quality attributes. Tolerance design calculates tolerance of the factor design. If less variation attained by factor design do not satisfy tolerance design and performance is necessary, which entails tightening tolerance on product factor or process factor, variation has a significant adverse impact on requisite product performance. Tightening tolerance usually entails spending more money on higher-quality materials, components, or machines. However, as discussed above, parameter design is an important stage in the Taguchi technique for achieving high quality without raising costs [10].

Fisher [23] was the one who created experimental design [24] methodologies in the first place. Traditional experimental design methods, on the other hand, are overly complicated and difficult to utilize. Furthermore, when the number of process parameters grows, a huge number of experiments must be conducted. To solve this difficulty, orthogonal arrays were used to examine the whole parameter space with only a few experiments

Data was collected from various departments engaged in the production of 6mm Electrical Bakelite Sheet. The resin content and volatile content of impregnated Kraft paper are noticed, and data is recorded throughout the impregnation process in Phenol Formaldehyde unit and a portion of the data are represented in table 2 and table 3.

Table 2 display resin content percentage and grammage mass of the kraft paper

Before impregnation, the Kraft paper's mass (grammage)	Kraft Paper mass after passed with Phenol Formaldehyde resin impregnation (grammage)	RESIN CONTENT %
148	207	23
148	207	29
148	207	36

Table 3 displaying a portion data of the impregnated Kraft paper volatile content

Before impregnation, Kraft paper's mass (grammage)	mass of Kraft paper after Phenol Formaldehyde resin impregnation (grammage)	Final mass of impregnated Kraft paper after 5 minutes in the oven (grammage)	Volatile content (%)
148	207	195	4
148	207	217	5
148	207	238	6

Pressure, Temperature, and Baking Time are also monitored and recorded for each press up-to the last stage of product manufactured in the press. Data is collected at random, and sample and population size are the same for every press. The volatile content, resin content, pressure, temperature, and baking time for each press with sample size 13 are observed and data is documented. The information was gathered for 27 presses.

The insulation and thickness of the Bakelite Sheet manufacturing process are modelled, optimised, and analysed using the ANOVA and Taguchi method. The results of 27 experiments, based on 05 factors and 03 levels model was gathered and thoroughly examined. Table 4 shows 05 factors and 03 levels of the Electrical insulation Sheet manufacturing process.

Experiment is conducted with 05 factors and 03 levels. A Taguchi method for the Electrical Bakelite Sheet process with three levels: 1,0,1 is made in MINITAB software, comprising 27 runs. The Taguchi approach is shown in Table 5 for a 05 factor with 03 levels.

Table-4 indicate 05 factors with 03 level of 6mm EBS

Factor	low level (-1)	median level (0)	high level (1)
Pressure	250	255	260
Temperature	145	150	155
Volatile content of Impregnated Kraft Paper	4	5	6
Resin content of Impregnated Kraft Paper	23	29	36
Baking time	55	60	65

Table 5 displays Taguchi Design arrangement for 27 experiments with 05 factors and 03 level of electrical insulation sheet manufacturing process

Sr.No	P(Bar)	T(C^0)	VC (%)	RC (%)	(BT)(Minutes)
1	-1	-1	-1	-1	-1
2	-1	-1	-1	-1	0
3	-1	-1	-1	-1	1
4	-1	0	0	0	-1
5	-1	0	0	0	0
6	-1	0	0	0	1
7	-1	1	1	1	-1
8	-1	1	1	1	0
9	-1	1	1	1	1
10	0	-1	0	1	-1
11	0	-1	0	1	0
12	0	-1	0	1	1
13	0	0	1	-1	-1
14	0	0	1	-1	0
15	0	0	1	-1	1
16	0	1	-1	0	-1
17	0	1	-1	0	0
18	0	1	-1	0	1
19	1	-1	1	0	-1
20	1	-1	1	0	0
21	1	-1	1	0	1
22	1	0	-1	1	-1
23	1	0	-1	1	0
24	1	0	-1	1	1
25	1	1	0	-1	-1
26	1	1	0	-1	0
27	1	1	0	-1	1

After designing the Taguchi model, the low, median and high value of five factor are equated in table 5 and responses means obtained in data collection were putted which is reproduced in table-6. The Taguchi model for the process was constructed using the table-6 and in-depth study, and the model's appropriateness was evaluated with electrical insulation and thickness analysis.

Table 6 showing arrangement of Taguchi method for 06mm electrical Bakelite sheet manufacturing process with 05 factors and three 03 for 27 experiments along-with means responses

E.No.	P(Bar)	T(C^0)	VC(%)	RC(%)	Baking time(B)	Thickness (mm) (Mean)	Electrical Insulation (KVR) (Mean)
1	250	145	4	23	55	6.25	37.02
2	250	145	4	23	60	6.23	37.14
3	250	145	4	23	65	5.75	36.05
4	250	150	5	29	55	6.07	39.02
5	250	150	5	29	60	6.21	37.30
6	250	150	5	29	65	6.19	37.42
7	250	155	6	36	55	5.77	36.09
8	250	155	6	36	60	6.17	37.55
9	250	155	6	36	65	5.95	39.64
10	255	145	5	36	55	6.15	37.67
11	255	145	5	36	60	5.80	36.25
12	255	145	5	36	65	6.13	37.79
13	255	150	6	23	55	5.77	36.07
14	255	150	6	23	60	6.11	37.87
15	255	150	6	23	65	5.86	41.94
16	255	155	4	29	55	6.10	37.93
17	255	155	4	29	60	5.88	40.90
18	255	155	4	29	65	5.97	40.59
19	260	145	6	29	55	5.85	41.00
20	260	145	6	29	60	5.83	36.49
21	260	145	6	29	65	6.00	43.36
22	260	150	4	36	55	6.04	42.23
23	260	150	4	36	60	5.79	36.20
24	260	150	4	36	65	5.90	42.84
25	260	155	5	23	55	6.99	42.43
26	260	155	5	23	60	6.09	42.00
27	260	155	5	23	65	5.82	36.38

VII. RESULTS AND DISCUSSION

Using analysis of variance with a 95 percent confidence interval, the result of input factors volatility content, pressure, baking time, temperature, resin content, and on the responses of EBS, i.e. electrical insulation and thickness is investigated.

Analysis of variance of Electrical insulation is carried out at 0.05 alpha values. Table 7 displays the findings of the analysis of variance, which reveal that pressure is the most important factor among the other factors that affect the electrical insulation of the Bakelite Sheet.

Table 7 displaying Analysis of Variance for 06mm electrical insulation

Source	DF	Adj SS	Adj MS	F-Value	P-Value
P	2	37.39	18.70	3.10	0.033
T	2	6.96	3.48	0.58	0.573
VC	2	1.34	0.67	0.11	0.895
RC	2	4.11	2.05	0.34	0.717
BT	2	11.40	5.70	0.95	0.409
Residual Error	16	96.50	6.03		
Total	26	157.7	6.01		

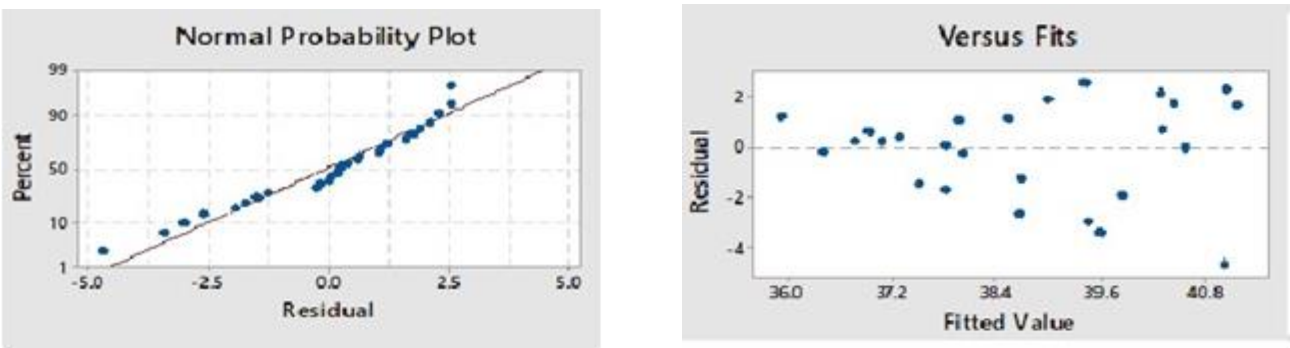
Table 8 Analysis of Variance for electrical insulation for regression

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	3	52.12	17.37	3.78	0.024
P	1	36.69	36.69	7.99	0.10
T	1	6.408	6.40	1.40	0.250
BT	1	9.020	9.02	1.96	0.174
Error	23	105.6	4.59		
Lack-of-Fit	14	55.51	3.96	0.71	0.72
Pure Error	9	50.09	5.56		
Total	26	157.7			

$$\text{Electrical Insulation (KVR)} = -38+0.286P+0.119T-0.245BT \quad (1)$$

R-square (Predicted), R-square (Adjusted), R-square, and residual plots are used to assess the model's suitability for electrical insulation. For electrical insulation, R-square (Predicted), R-square (Adjusted), R-square, values of 70 percent, 76 percent, and 84 percent were found. The difference between R-square (Predicted) and R-square and is less than 20%, no risk of over-fitting is involved in the derived electrical insulation model.

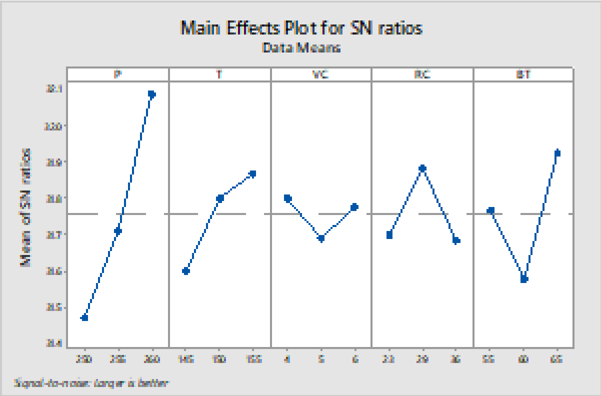
Residual plots representing in figure-1 to set the quality of the ANOVA results of Table-8 as well as the regression models established in equation (1). Figure 1(a) illustrates a normal probability plot for electrical insulation residuals. It shows that most data points are close to the fitted line, indicating that the data is normally distributed. Figure 1(b) shows a residuals VS fit plot for electrical insulation. The residuals have constant variance because the data points are randomly distributed above and below the fitted line. Based on the aforesaid research, it is considered that the electrical insulation model generated is suitable, and the data can be utilized for optimization.

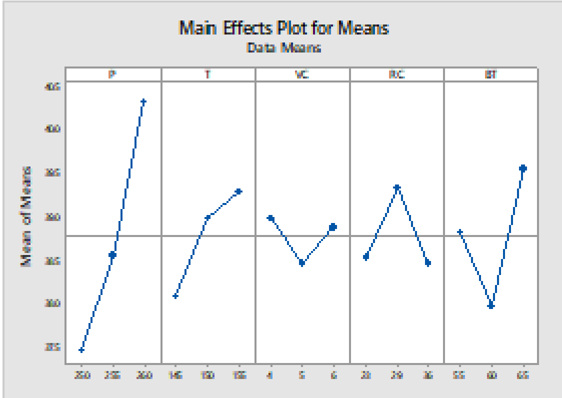


(a) (b)

Fig 1 (a) Residual plots Normality plot (b) Versus fit plot of Electrical insulation

The main effects plots for mean and SN ratio are plotted from table-6 for electrical insulation and are shown in Fig-2(a) and Fig-2(b). It shows that electrical insulation increases when the Pressure is increased from 250 bar to 255 bar and electrical insulation further increase when the Pressure increase above 150 bar and insulation is maximum at 260 bar. As the temperature increases from 145 C^{o} towards 150 C^{o} the electrical insulation increases and maximum at 150C^{o} and then start decrease above 150C^{o}. The electrical insulation is decreasing when the volatile content is increased from 4% to 5% and with the further increasing of Volatile Content the electrical insulation increases and maximum at 6%. The electrical insulation increased as the resin content increased from 23% to 29% and maximum at 29%. Above 29% the electrical insulation become decreasing with increasing of resin content. The electrical insulation decreased as the Baking time increase and it is minimum at 60 minutes and above 60 minutes when the Baking time increases the electrical insulation increase and maximum at 65 Minutes.





(a) (b)

Fig 2 (a) Main effect plots for means (b) Main effect plots S/N ratio of electrical insulation

The thickness analysis of variance is taken with 0.05 alpha values. Table 10 displays the findings of the analysis of variance, which reveal that Temperature is the most important element among the others that affect the thickness of the electrical Bakelite Sheet. The regression equation of thickness is obtained from table 10 and is given by equation (2).

Thickness (mm) = 5.07+0.0083T-0.00990RC (2)

Table 10 showing Analysis of Variance for thickness of 06mm electrical insulation sheet

Source	*DF*	*Adj SS*	*Adj MS*	*F-Value*	*P-Value*
Regression	2	0.10	0.052	0.82	0.02
T	1	0.013	0.312	0.49	0.492
RC	1	0.074	0.074	1.16	0.292
Error	24	1.54	0.064		
Lack-of-Fit	15	0.67	0.045	0.47	
Pure Error	9	0.86	0.096		0.907
Total	26	1.64			

Similar for thickness the main effects plot for means are plotted from table 6 of Taguchi arrangement and is shown in figure 3. It shows that the thickness decreases as the pressure increase from 250 bar to 255 bar and minimum at 250 bar. Further when the Pressure increases from 255 bar the thickness of electrical Bakelite Sheet increase and maximum at 260 bar. As the temperature increase from 145 C^o towards 150 C^o the thickness increases and when the temperature is further increased from 150 C^o to 155 C^o the thickness further increases and become maximum at 155 C^o. The thickness is increase when the volatile content is increased from 4% to 5% and then decreased when the Volatile Content is increased from above 5 to 6% and maximum at 6%. The thickness decreases as the resin content increase from 23% to 29% and maximum at 23%. Above 23% the thickness starts decreasing with increasing the resin content. The thickness decreasing as the Baking time increase from 55 to 60 minute.

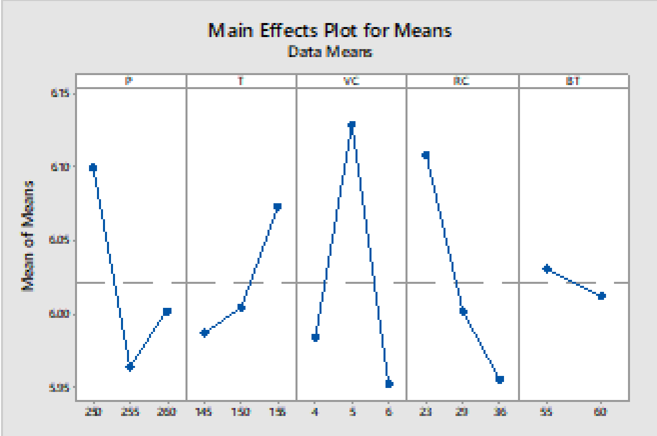


Fig 3: Main effect plots for means of thickness

VIII. CONCLUSION

Taguchi technique methodology successfully optimises the manufacturing process of 6mm Electrical Bakelite Sheet. Resin Content, Pressure, Volatile Content, Temperature, and Baking Time are the input factors of the EBS. Electrical Insulation and Thickness are vital quality criteria of the product. With the design of an experiment, a detailed analysis was carried out. The factorial design was used in experiment design. The Taguchi approach investigated the design tool and analysed. Resin content 29%, Pressure 260 Bar, Volatile content 6% Temperature 155 C^o, and baking time 65 minutes are the optimised parameters of electrical insulation response of the EBS manufacturing process, while %, Resin content 23%, Pressure 250 Bar, Volatile content 5%, Temperature 155 C^o and Baking time 60 minutes are optimised parameters of thickness response of the electrical Bakelite Sheet manufacturing process results. The process was optimised using these parameters, and the capability performance was increased.

Conflict of interest: The authors declare that they have no conflict of interest.

Ethical statement: The authors declare that they have followed ethical responsibilities.

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