# CHAPTER 6

# RESULTS AND DISCUSSION

Experimental results of in-process measurements and post-process measurement and testing for all sets of experiments have been discussed in this section. The effect of input parameters, on output parameters has also been discussed.

## 6.1 INVESTIGATIONS ON NUMBER OF LAYERS, POSITION OF RESIN SUPPLY AND LOCATION OF VACUUM SUPPLY FOR VARTM PROCESS

Investigation was carried out on the number of layers, position of resin supply and location of vacuum supply. The response parameters were 1) tensile strength 2) flow velocity 3) weight fraction and 4) thickness variation of cured laminate. Jute fabric and polyester resin were used to perform the experiments. Table 6.1 displays details of experiments, designed on Taguchi $L_9$ orthogonal array, parameters, their levels, tensile strength and flow velocity details.

**Table 6.1** Effect of number of layers, position of resin supply and location of vacuum supply on tensile strength and flow velocity

| Laminate Identification | Number of Layers | Position of Resin Supply | Location of Vacuum Supply | Tensile Strength MPa | Flow Velocity mm/s |
|---|---|---|---|---|---|
| 4TEC | 4 | Top (T) | Edge Centre (EC) | 53.12 | 6.25 |
| 4BCE | 4 | Bottom (B) | Centre Edge (CE) | 48.63 | 5.55 |
| 4MLR | 4 | Middle (M) | Left – Right(LR) | 47.61 | 8.33 |
| 5TCE | 5 | Top (T) | Centre Edge(CE) | 52.56 | 4.32 |
| 5BLR | 5 | Bottom (B) | Left – Right(LR) | 59.23 | 7.16 |
| 5MEC | 5 | Middle (M) | Edge Centre (EC) | 63.41 | 3.33 |
| 6TLR | 6 | Top (T) | Left – Right (LR) | 29.53 | 8.13 |
| 6BEC | 6 | Bottom (B) | Edge Centre (EC) | 50.04 | 6.16 |
| 6MCE | 6 | Middle (M) | Centre Edge (CE) | 54.20 | 5.83 |

Minitab 17 software was used to perform calculation based on design of experiments with Taguchi $L_9$ approach

The main effect plots for tensile strength and flow velocity are shown in Figures 6.1 and Figure 6.2 respectively. Effect of thickness variation is shown by bar graph in Figure 6.3.

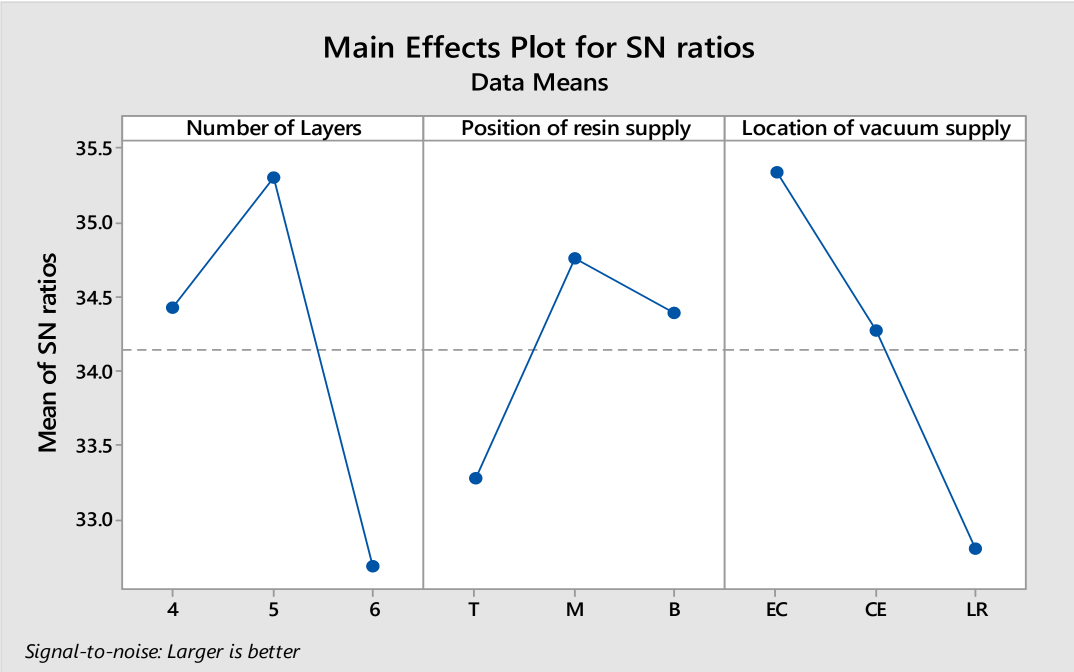


**Figure 6.1** Effect of parameters on tensile strength

**The maximum tensile strength was observed when numbers of layers were 5, position of resin supply from middle and vacuum supply location was from edge.**

- The tensile strength is the resistance of a material to break in the direction of applied force. Normally it is found that as the number of layer increases, tensile strength also increases, because reinforcement is a load bearing member in a composite.
- One of the reasons why tensile strength is found to be more in 5 layers may be due to the effect of other parameters. For low thickness and high fiber volume fraction tensile strength is observed more. This ensures effect of vacuum on tensile strength
- From this set of experiment middle supply resin is a better option; this may be due to the reduction in resin travel distance. All future resin supply location has been kept from middle.
- The effect of vacuum on laminate quality has been studied by many authors and it has been found that more the compactions better the mechanical property which is in line with our result for jute polyester resin.

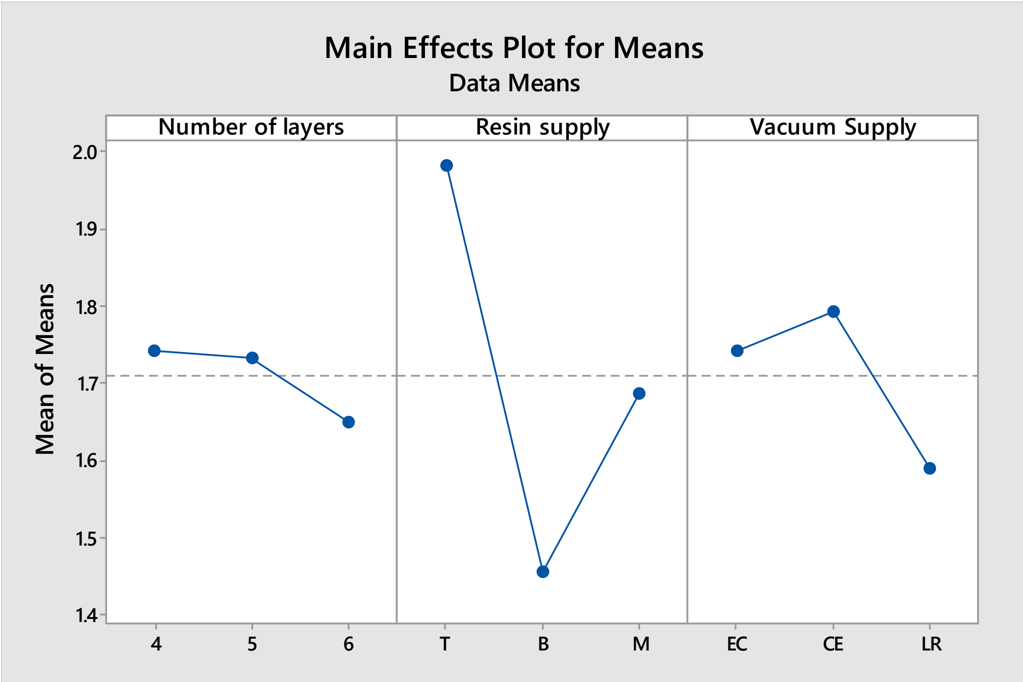


**Figure 6.2** Effect of parameters on flow velocity

The maximum flow velocity was observed when number of layers was 4, resin supply was from top and vacuum supply was from centre to edge**.**

- The flow velocity will be more for less number of layers as the flow will travel through smaller cross section area. Hence for 4 layers flow velocity was observed more.
- As resin supply at top position, will increase pressure head, thus the supply resin pressure will increase; this will create more differential pressure between inlet and outlet. Due to this the flow velocity would have increased. This was in agreement with experiments performed by Rigas et al. (2001) who concluded that elevation of resin feed source in relation to part has significant effect on infusion time.
- Similarly, when the vacuum was at centre and resin was supplied from all the edges due to this, radial flow took place, more resin at same time can penetrate inside laminate, the travel time of resin reduced, pressure gradient increased and the flow velocity increased.
- However, high velocity does not mean high strength. As strength depends on bonding of resin with reinforcement.

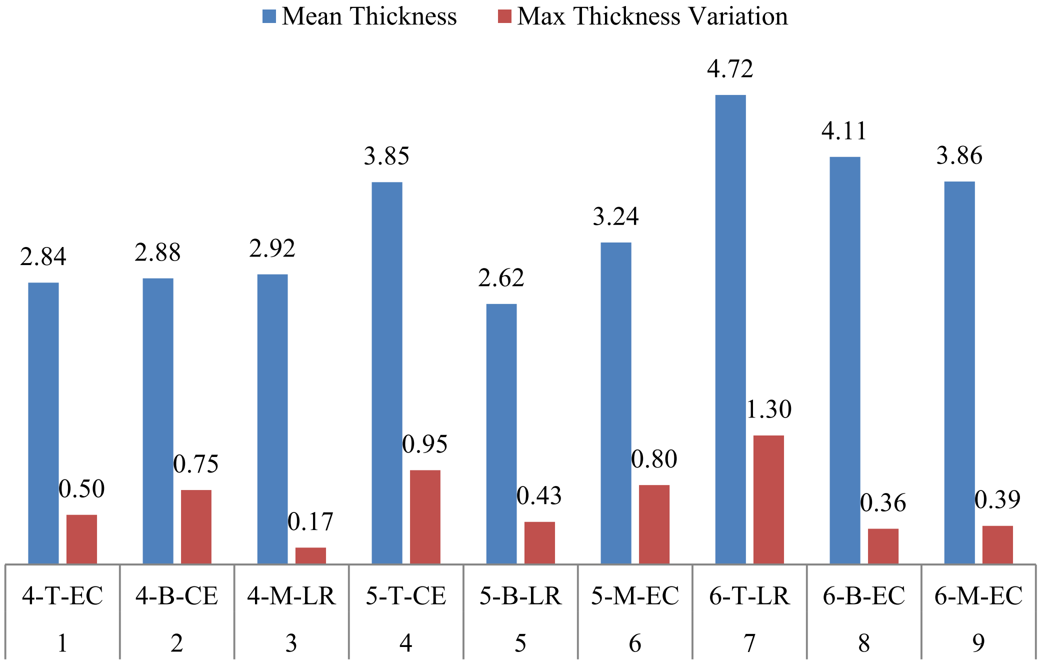


**Figure 6.3** Laminate average thickness and thickness variation

- The minimum variation of 0.17 mm in four layers and maximum variation of 1.3 mm in six layers has been observed over the entire thickness of laminate. This shows that as we increase number of layers the variation in thickness also increases.

- Solvent method was used to find fiber weight fraction for jute laminate and up to 70% fiber weight fraction was achieved.

- Though the radial flow is better but for future sets of experiments linear flow was preferred considering practical difficulties while performing experiments.

## 6.2 INVESTIGATIONS ON NUMBER OF LAYERS AND DEGASSING FOR VARTM PROCESS

Effect of degassing was studied performing six experiments as mentioned in Table 6.2. For each laminate 1) flow velocity 2) tensile strength 3) flexural strength 4) weight fraction 5) thickness variation in laminate and 6) microscopic examination was measured. Jute fabric with polyester resin was used to perform experiments.

**Table 6.2** Effect of vacuum degassing and number of layers on fraction weight, flow velocity, tensile strength and flexural strength

| Laminate Identification | Laminate Detail | Fabric Weight fraction (%) | Tensile Strength (MPa) | Flexural Strength (MPa) |
|---|---|---|---|---|
| 5LWOD | 5 Layers, without degassing | 36.5 | 47.7 | 104.4 |
| 10LWOD | 10 Layers, without degassing | 34.2 | 47.93 | 95.67 |
| 15LWOD | 15 Layers, without degassing | 31.6 | 60.92 | 85.18 |
| 5LWID | 5 Layers, with degassing | 39.3 | 50.60 | 115.12 |
| 10WID | 10 Layers, with degassing | 37.2 | 59.10 | 99.83 |
| 15LWID | 15 Layers, with degassing | 39.8 | 61.53 | 91.06 |

- Weight fraction of fabric had improved after degassing. Flow velocity was reduced after degassing as viscosity of resin increased. The flow velocity was high at supply location and gradually reducing at vacuum supply location as resin pressure reduces over flow length. Flow gradient was observed between top and bottom layer in higher layered laminates. At top layer HPM increases flow velocity. As number of layer increased, flow velocity decreased due to through thickness flow. For lesser number of layers this phenomenon was not observed. This observation was in line with observations found by Rigas et al. (2001).

- Figure 6.4 shows effect of number of layers and degassing on tensile strength. It has been observed that the tensile strength has increased by 6%, 23% and 1% for 5, 10 and 15 layers with degassing. This is in line with observations made by Li, W. et al. (2004). Tensile strength increases if fiber weight fraction increases and thickness variation reduces, as more force can be applied for less cross section area.

- After degassing, the void content reduced, the thickness and its variation of laminate also reduced, due to this, the cross section area was reduced and was uniform while applying tensile load and due to this better tensile strength was achieved.

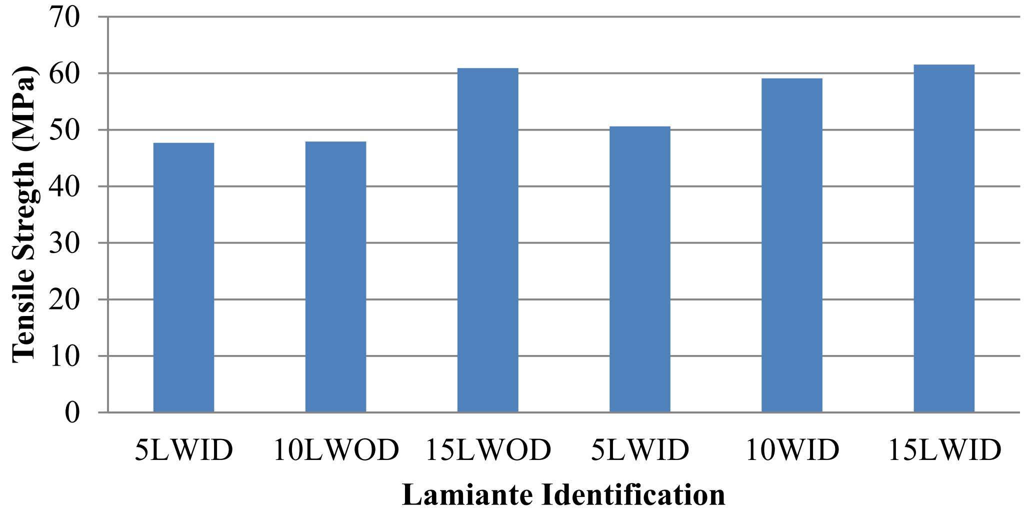


**Figure 6.4** Tensile strength of laminates with and without degassing

Figure 6.5 shows effect of degassing and number of layers on flexural strength. Flexural strength increased by 10%, 4% and 7% for 5, 10 and 15 layers respectively with degassing.

- Voids can affect the mechanical properties and lifespan of the composite. They degrade mainly the matrix-dominated properties such as inter-laminar shear strength, longitudinal compressive strength, and transverse tensile strength.
- By degassing the flexural strength increased which mean inter-laminar shear strength improved. That means the resin could bond with fiber in better way and improved the flexural strength.
- Flexural strength of jute is observed more than tensile strength.

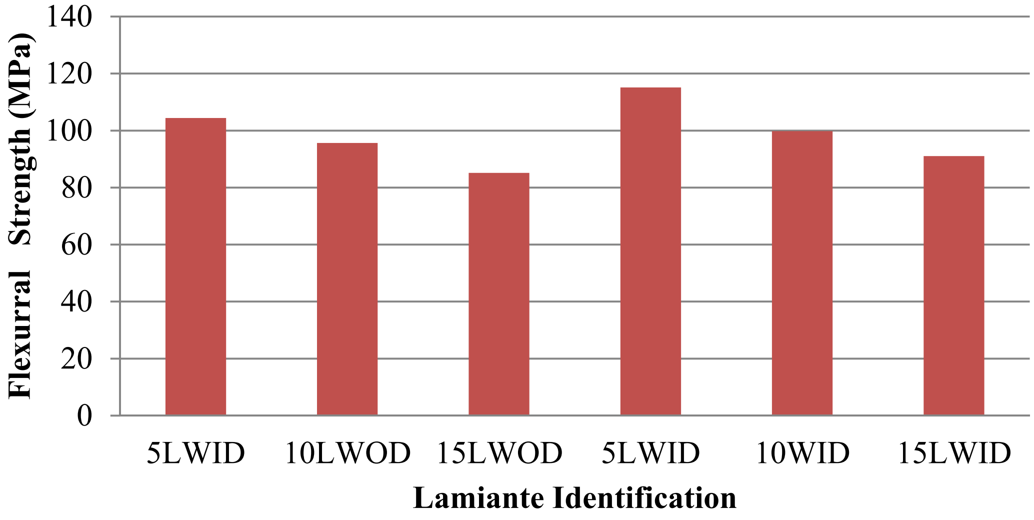


**Figure 6.5** Flexural strength of laminates with and without degassing

Thickness variation in laminate during resin flow was observed in higher number of layers. Thickness variation in cured laminate increases, as number of fabric layers increases, which is shown in Figure 6.6. Effect of degassing was not observed on thickness variation.

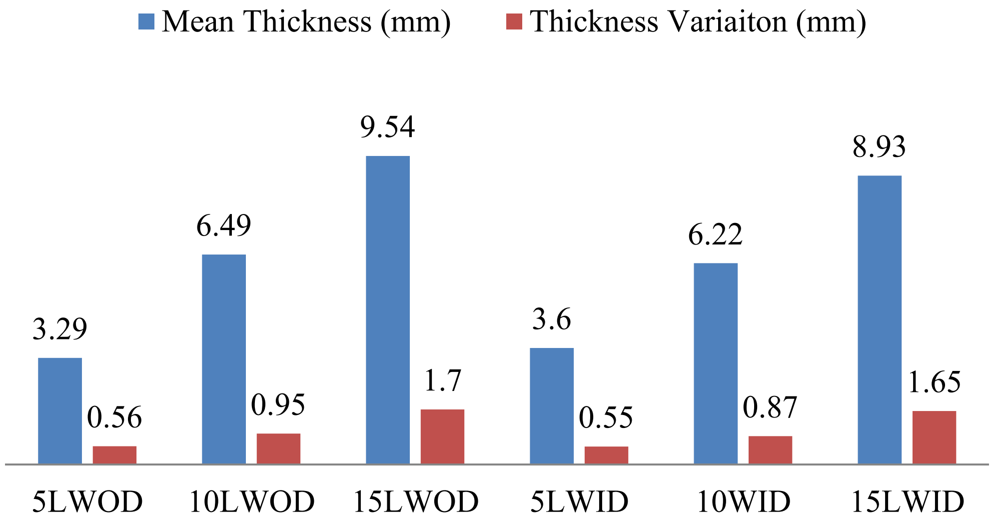


**Figure 6.6** Average laminate thickness variations (mm) with and without degassing

Void inside the laminate was reduced significantly after degassing, which was observed by 180X microscope. Figure 6.7 depicts the picture showing void content for various laminates. It is evident from Figure 6.7 that void content reduced considerably after degassing which was in line with observations found by Yalcinkaya, Sozer, and Altan (2017).

The amount of void content reduced and properties increased after degassing which proves jute polyester resin composite should be prepared with degassing. It will help to increase strength of laminate

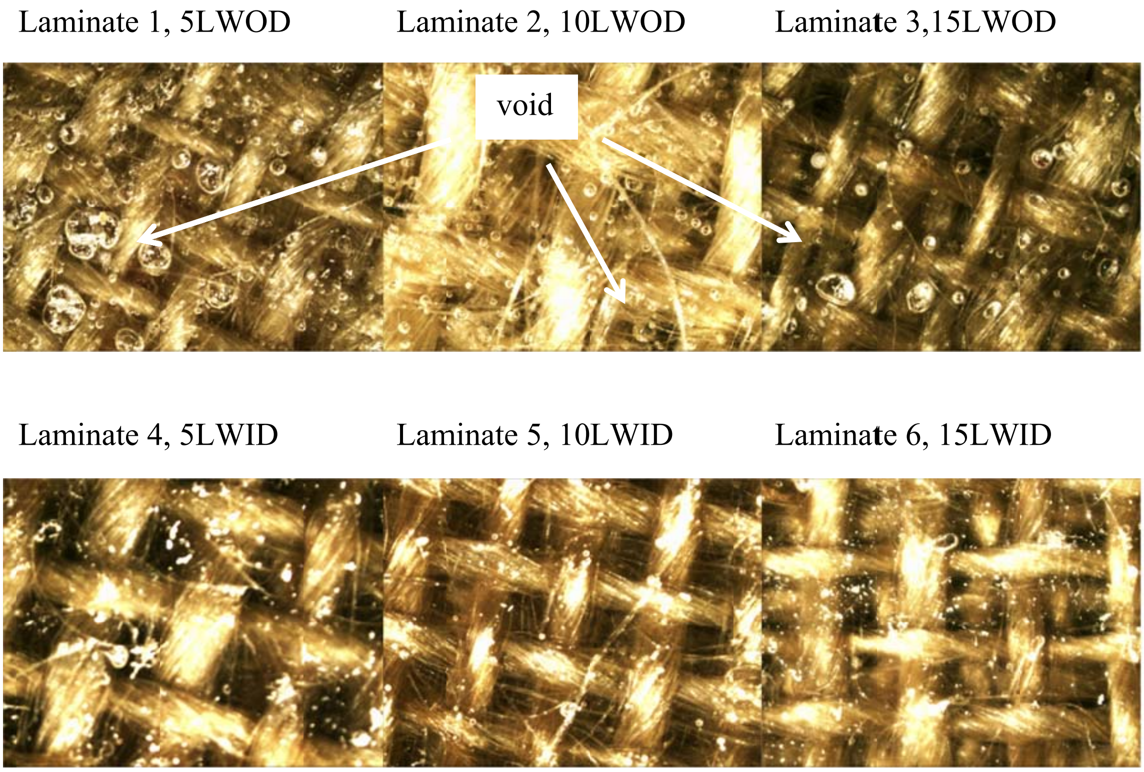


**Figure 6.7** Air entrapments before and after degassing in laminates


**Figure 6.8** Color of laminate with and without degassing

As shown in Figure 6.8, there was change in colour of laminate before and after degassing. Degassing reduces air content and gives dark colour to the resin, without degassing it seems hazy in colour. As you degas resin the resin colour changes and the same difference was observed in jute polyester laminate colours for with and without degassing, so one can easily identify the laminate with and without degassing.

## 6.3 INVESTIGATIONS ON NUMBER OF LAYERS, INCLINATION OF TABLE AND AMOUNT OF VACUUM SUPPLY FOR VARTM PROCESS

This set of experiments was performed with jute fabric and polyester resin. Experiments were performed to study the effect of gravity in response to change in inclination of table, number of layers and varying amount of vacuum supply. Taguchi $L_9$ orthogonal array was used to design experiments. 1) Tensile strength 2) flexural test 3) thickness variation 4) fiber weight fraction and 5) flow velocity study was measured to find effect of input parameters as shown in Table 6.3.

**Table 6.3** Effect of varying number of layers, inclination of table and vacuum on tensile strength, flexural strength, thickness variation, fiber weight fraction and flow velocity

| Laminate Identification | Parameters (Number of layers, inclination of table, amount of vacuum supply) | Average Tensile strength (MPa) | Average Flexural strength (MPa) | Average Thickness (mm) | Thickness variation (mm) | Fiber weight fraction (%) | Flow velocity (mm/s) |
|---|---|---|---|---|---|---|---|
| 4P0I29V | 4-0-29 | 50.30 | 81.92 | 2.39 | 0.1 | 0.35 | 10.00 |
| 4P20I22V | 4-20-22 | 52.04 | 87.40 | 2.65 | 0.1 | 0.35 | 2.50 |
| 4P40I15V | 4-40-15 | 48.14 | 74.84 | 2.83 | 0.2 | 0.34 | 4.30 |
| 8P0I22V | 8-0-22 | 59.70 | 80.28 | 5.06 | 0.3 | 0.38 | 5.70 |
| 8P20I15V | 8-20-15 | 56.34 | 79.34 | 5.31 | 0.2 | 0.37 | 2.70 |
| 8P40I29V | 8-40-29 | 58.90 | 80.64 | 5.01 | 0.1 | 0.38 | 7.50 |
| 12POI15V | 12-0-15 | 60.28 | 92.50 | 8.38 | 0.2 | 0.35 | 2.50 |
| 12P20I29V | 12-20-29 | 58.54 | 60.00 | 7.31 | 0.2 | 0.44 | 10.70 |
| 12P40I22V | 12-40-22 | 42.36 | 47.73 | 9.00 | 0.5 | 0.41 | 5.00 |

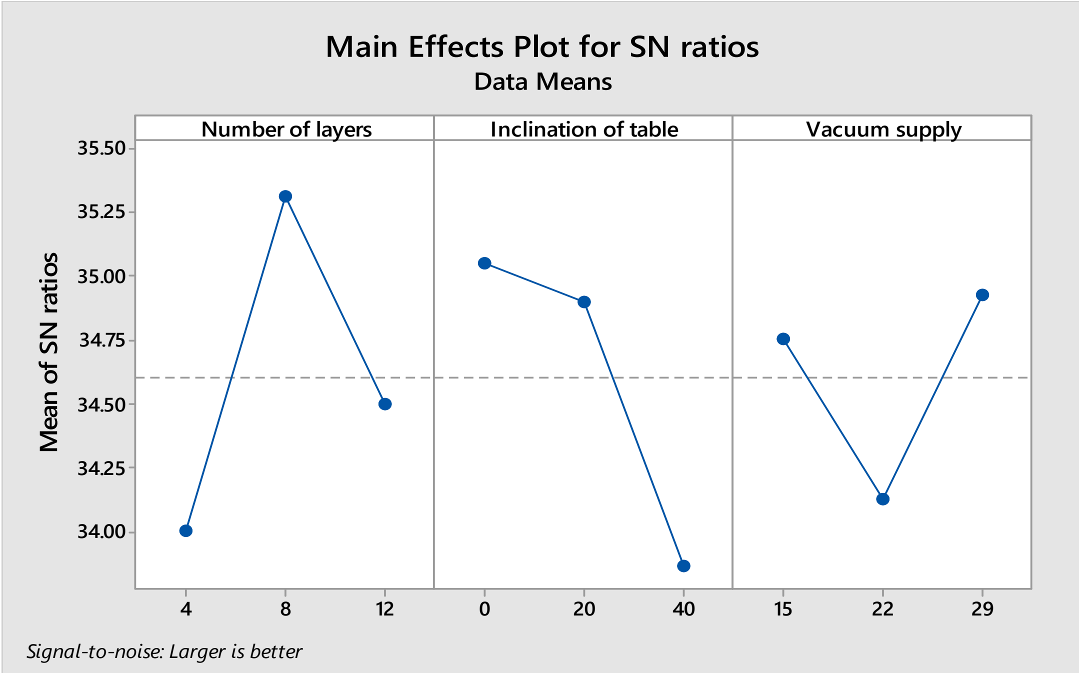


**Figure 6.9** Main plots for tensile strength (MPa)

It was observed from Figure 6.9, that tensile strength was high with 8 number of fabric layers, 0° inclination of table and at 29 in Hg vacuum. High tensile strength at high vacuum was also observed by Chokka, Ben, and Srinadh (2019). For higher layers, more leak rate was observed near sealant tape and due to this tensile strength might have reduced at higher layers.

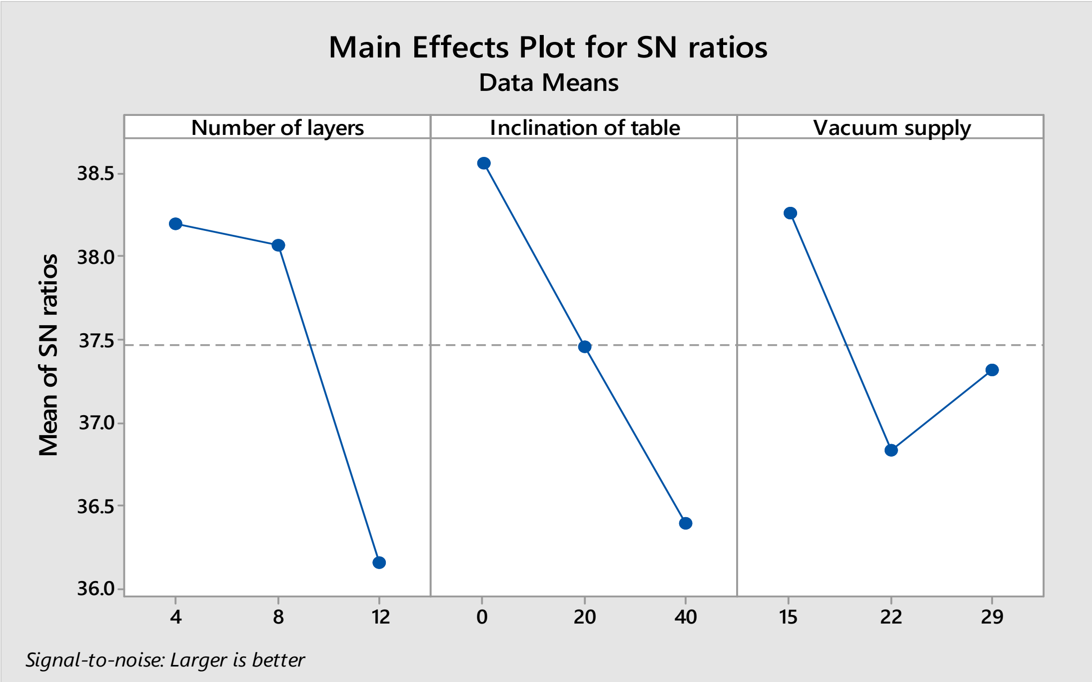


**Figure 6.10** Main plots for flexural strength (MPa)

As shown in Figure 6.10, flexural strength was high with 4 numbers of fabric layers, at 0 ° inclination of table and at 15 in Hg vacuum. As number of layers reduces, flexibility increases and hence flexural strength was found high in 4 layers. It was observed that flow velocity mostly depends on the amount of vacuum supply. It was very high when vacuum was 29 in Hg and low when amount of vacuum supply was 15 in Hg. This concludes that the flow velocity can be controlled by amount of vacuum supply.

For 4 layers and 8 layers, there was no change in the thickness, during resin flow. However, for 12 layers, there was variation in part thickness during the flow of about 0.12 mm, 0.08 mm and 0.08mm in three dials respectively at 0° inclination of glass table.

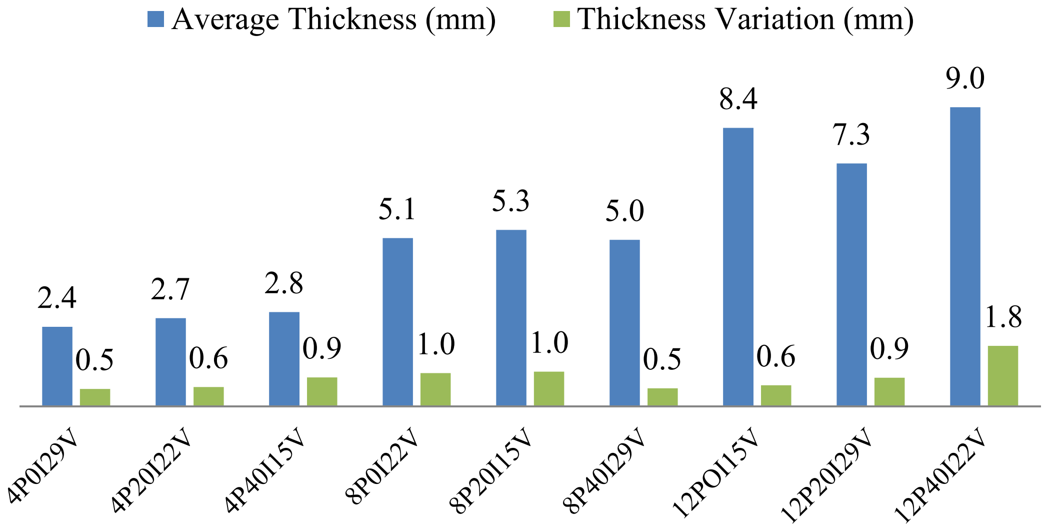


**Figure 6.11** Thickness variations in cured laminate

The thickness variation as shown in Figure 6.11 increased as number of layers increased. The worst case found was for 12P40I22V. This might be due to more layers and high inclination; as proper compaction could not have been achieved. It should be noted that, as number of layers and inclination of table increased, to manufacture the components by VARTM became difficult. Leak rate increased significantly from sealant tape and to hold the required vacuum became challenging. Amount of vacuum played a major role in flow during impregnation. Fiber weight fraction increased as number of layers increased.

## 6.4 INVESTIGATIONS ON VARIATION IN GSM OF GLASS FABRIC, RPM OF PERISTALTIC PUMP AND AMOUNT OF VACUUM SUPPLY FOR VARTM PROCESS

Experiments were performed to study effect of areal weight of fabric, RPM of peristaltic pump and amount of vacuum supply. Glass fabric along with polyester resin was chosen as material for conducting experiments. Full factorial design approach was considered while designing the experiments. Total 27 experiments were performed with three variables and three levels. Result of 1) flow velocity 2) tensile strength 3) flexural strength 4) thickness variation and 5) volume fraction is depicted in Table 6.4.

Flow velocity varied from 8.1 to 2.1 mm/sec. There may be multiple reasons why such variation was seen in flow velocity. The prominent reasons might be resin viscosity, after mixing and before gelation there is a viscosity window within which, if resin is impregnated it will flow within and between tow. However it was difficult to control exact timing after mixing, after degassing and before impregnation. Hence specific conclusion for flow velocity was not achieved as planned.

**Table 6.4** Results of full factorial design with varying GSM, RPM and vacuum

| Laminate Id. | GSM | RPM | Vacuum (in mg) | Flow Velocity (mm/sec) | Tensile strength (MPa) | Flexural Strength (MPa) | Average thickness (mm) | Range (mm) | Volume Fraction (%) |
|---|---|---|---|---|---|---|---|---|---|
| 2G7R15V | 200 | 70 | 15 | 3.6 | 305 | 163 | 1.0 | 0.28 | 0.43 |
| 2G7R22V | 200 | 70 | 22 | 8.1 | 309 | 180 | 1.0 | 0.37 | 0.44 |
| 2G7R29V | 200 | 70 | 29 | 4.9 | 276 | 130 | 1.0 | 0.36 | 0.52 |
| 2G9R15V | 200 | 90 | 15 | 2.1 | 253 | 148 | 1.0 | 0.5 | 0.41 |
| 2G9R22V | 200 | 90 | 22 | 6.7 | 285 | 168 | 1.0 | 0.33 | 0.44 |
| 2G9R29V | 200 | 90 | 29 | 6.8 | 276 | 141 | 1.0 | 0.41 | 0.46 |
| 2G11R15V | 200 | 110 | 15 | 5.9 | 273 | 138 | 1.0 | 0.16 | 0.44 |
| 2G11R22V | 200 | 110 | 22 | 3.1 | 274 | 165 | 1.0 | 0.37 | 0.45 |
| 2G11R29V | 200 | 110 | 29 | 5.7 | 266 | 157 | 0.9 | 0.32 | 0.45 |
| 4G7R15V | 400 | 70 | 15 | 4.1 | 357 | 222 | 1.6 | 0.42 | 0.5 |
| 4G7R22V | 400 | 70 | 22 | 2.8 | 313 | 189 | 1.6 | 0.46 | 0.34 |
| 4G7R29V | 400 | 70 | 29 | 7.2 | 449 | 172 | 1.6 | 0.46 | 0.53 |
| 4G9R15V | 400 | 90 | 15 | 5.4 | 359 | 189 | 1.5 | 0.27 | 0.53 |
| 4G9R22V | 400 | 90 | 22 | 3.6 | 363 | 200 | 1.6 | 0.42 | 0.51 |
| 4G9R29V | 400 | 90 | 29 | 3.8 | 362 | 209 | 1.5 | 0.34 | 0.5 |
| 4G11R15V | 400 | 110 | 15 | 5.6 | 344 | 154 | 1.6 | 0.45 | 0.52 |
| 4G11R22V | 400 | 110 | 22 | 6.4 | 375 | 160 | 1.5 | 0.27 | 0.52 |
| 4G11R29V | 400 | 110 | 29 | 2.6 | 352 | 190 | 1.5 | 0.46 | 0.54 |
| 6G7R15V | 600 | 70 | 15 | 3.6 | 419 | 149 | 2.3 | 0.77 | 0.57 |
| 6G7R22V | 600 | 70 | 22 | 4.8 | 327 | 132 | 2.3 | 0.65 | 0.57 |
| 6G7R29V | 600 | 70 | 29 | 5 | 415 | 111 | 2.7 | 0.87 | 0.45 |
| 6G9R15V | 600 | 90 | 15 | 5.5 | 349 | 110 | 2.8 | 0.86 | 0.44 |
| 6G9R22V | 600 | 90 | 22 | 5.9 | 328 | 126 | 2.2 | 1.03 | 0.56 |
| 6G9R29V | 600 | 90 | 29 | 6.5 | 409 | 148 | 2.2 | 0.45 | 0.55 |
| 6G11R15V | 600 | 110 | 15 | 6.1 | 367 | 125 | 2.2 | 0.52 | 0.57 |
| 6G11R22V | 600 | 110 | 22 | 7.4 | 375 | 173 | 2.4 | 0.71 | 0.54 |
| 6G11R29V | 600 | 110 | 29 | 4.6 | 381 | 123 | 2.2 | 0.55 | 0.44 |

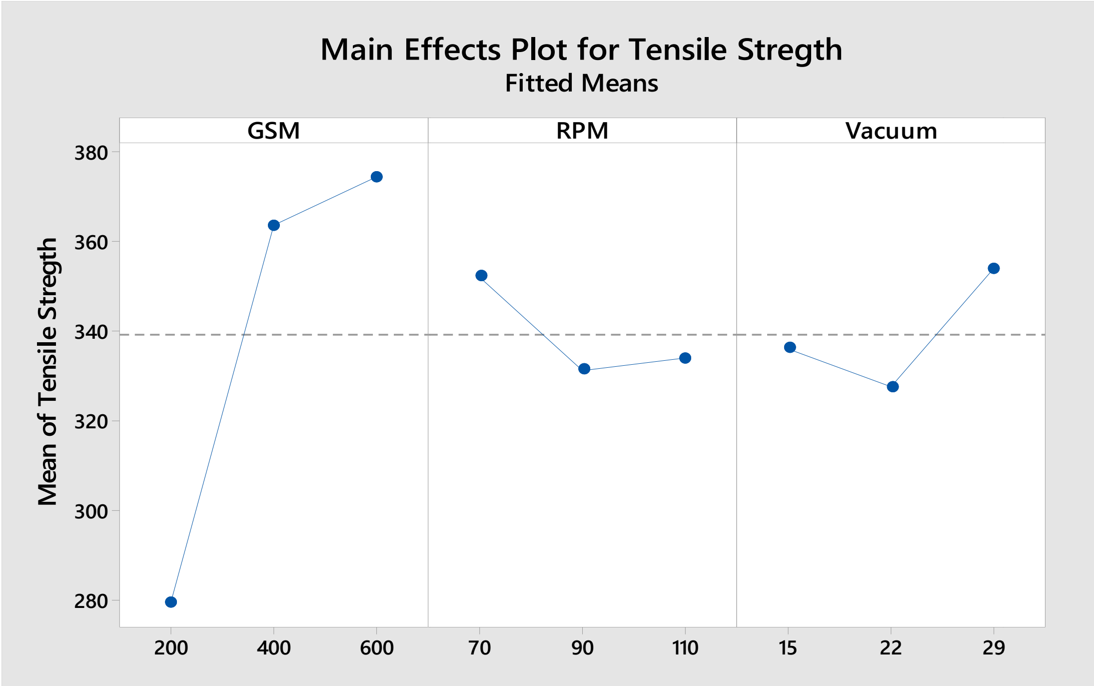


**Figure 6.12** Main plot for tensile strength (MPa)

As shown in Figure 6.12, GSM of fabric is the most significant parameter for achieving high tensile strength. Also as RPM reduced, tensile strength increased and as vacuum increased tensile strength increased. As per interaction plot, shown in Figure 6.13, there is interaction with each other.

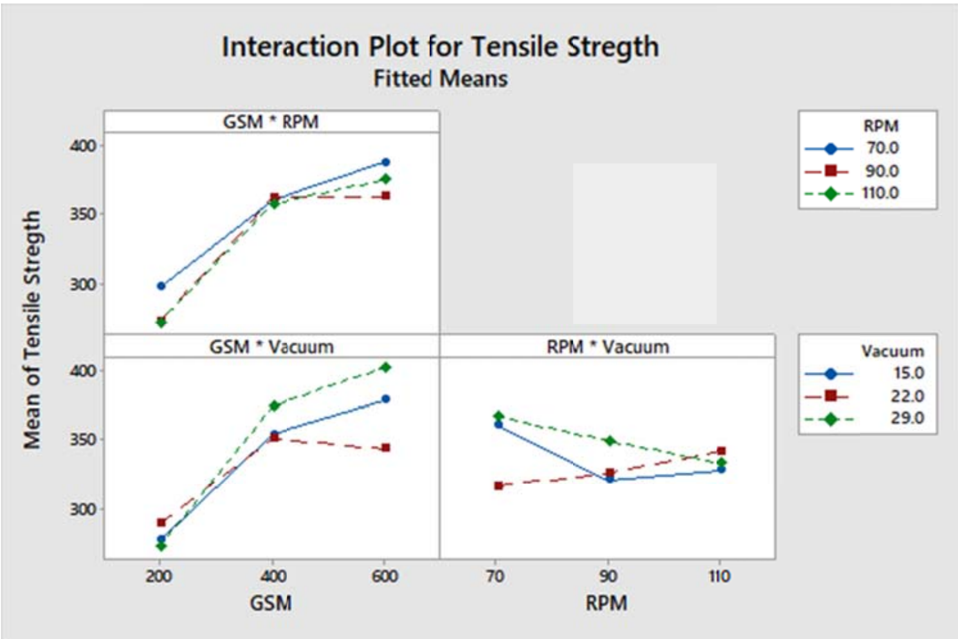


**Figure 6.13** Interaction plot for effect of tensile strength (MPa)

ANOVA analysis has been performed to identify significant input parameters and their interaction affecting the VARTM process. As shown in Table 6.5, P value is less than 0.005 for 95% confidence interval for GSM and GSM *Vacuum.

**Table 6.5** Analysis of variance for tensile strength (MPa)

| Source | DF | Adj SS | Adj MS | F-Value | P-Value |
|---|---|---|---|---|---|
| Regression | 6 | 44401.7 | 7400.28 | 27.28 | 0.000 |
| GSM | 1 | 117.7 | 117.68 | 0.43 | 0.003 |
| RPM | 1 | 104.0 | 103.97 | 0.38 | 0.543 |
| Vacuum | 1 | 239.0 | 239.02 | 0.88 | 0.359 |
| GSM*RPM | 1 | 180.2 | 180.18 | 0.66 | 0.425 |
| GSM*Vacuum | 1 | 2726.9 | 2726.93 | 10.05 | 0.005 |
| RPM*Vacuum | 1 | 5.5 | 5.49 | 0.02 | 0.888 |
| Error | 20 | 5425.3 | 271.26 | | |
| Total | 26 | 49826.9 | | | |

Model Summary:

| S | R-sq | R-sq(adj) | R-sq(pred) |
|---|---|---|---|
| 16.4701 | 89.11% | 85.85% | 80.59% |

Regression Equation:

$$\text{Tensile Strength} = 372.8 - 0.087\,GSM - 0.561\,RPM - 3.18\,Vacuum + 0.00097\,GSM * RPM + 0.01077\,GSM * Vacuum - 0.0048\,RPM * Vacuum \tag{6.1}$$

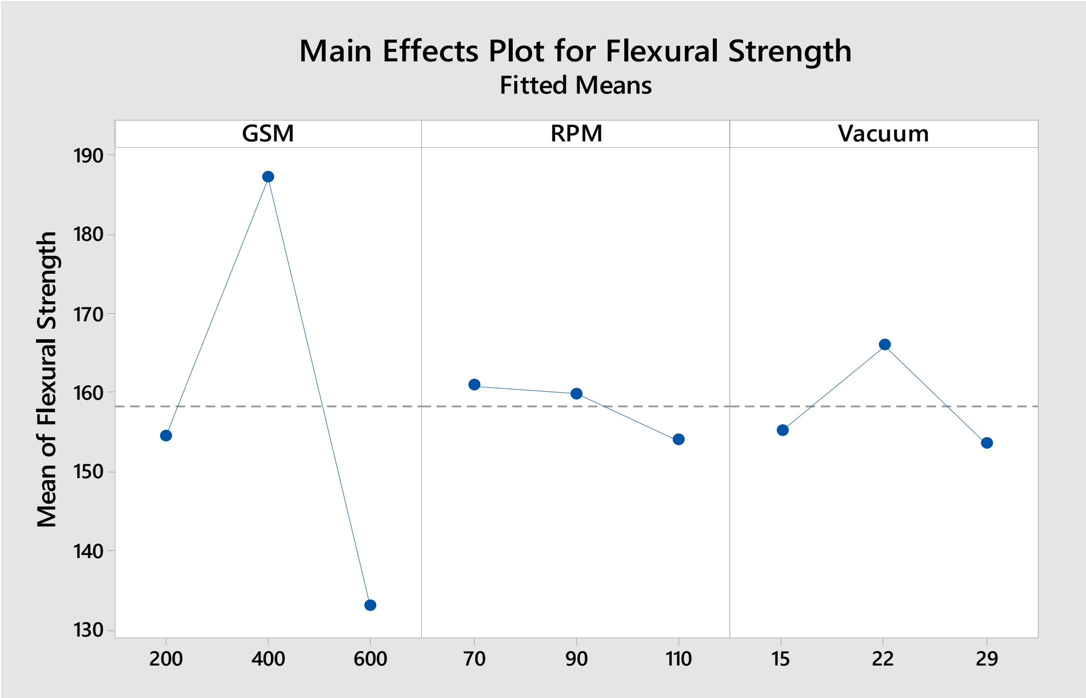


**Figure 6.14** Main plot for effect of flexural strength (MPa)

Major parameter contributing to flexural strength was GSM of fabric. Flexural strength was high for 400 GSM, as shown in Figure 6.14. Less variation in flexural strength was observed for RMP and vacuum. Interaction was found between all parameters as shown in Figure 6.15. Effect of interaction was found between RPM - GSM and RPM - Vacuum as shown in ANOVA Table 6.6

For this set of experiments, glass fabric was used, the flexural strength was less than tensile strength, but for all other sets of experiments where jute fabric was used the flexural strength was higher than tensile strength. This shows that the jute fabric laminate have more flexural strength than tensile strength. The fiber volume fraction increased as fiber GSM increased. Fiber volume fraction varied from 34% to 57 % with increased GSM

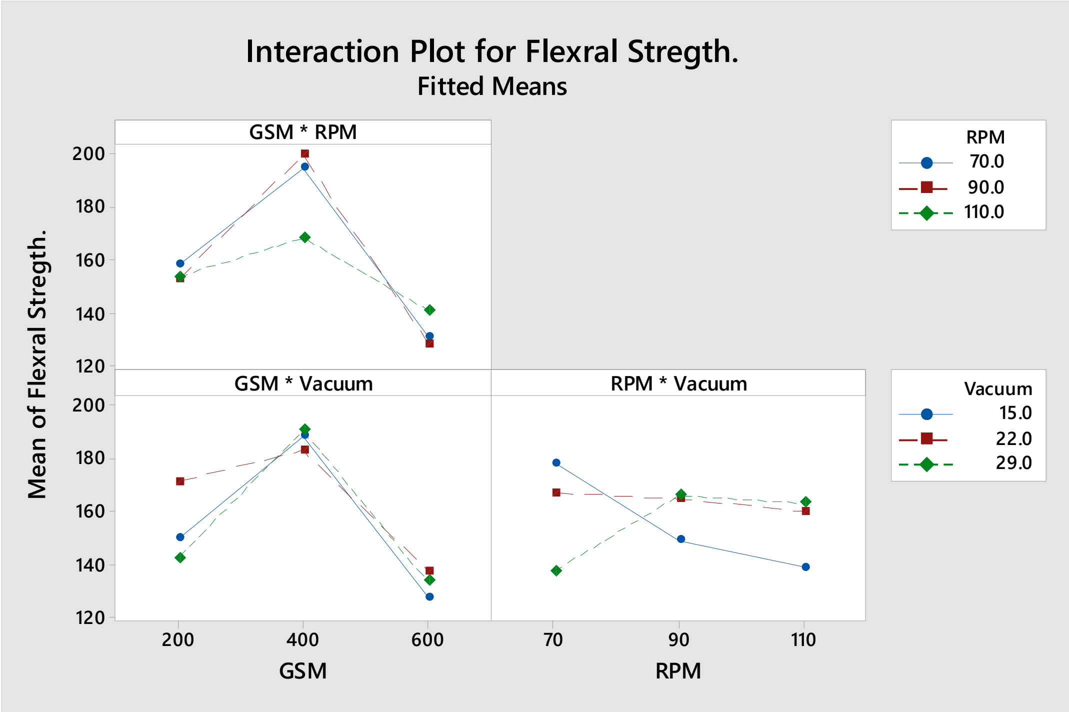


**Figure 6.15** Interaction effect of flexural strength (MPa)

**Table 6.6** Analysis of variance for flexural strength (MPa)

| Source | DF | Adj SS | Adj MS | F-Value | P-Value |
|---|---|---|---|---|---|
| Model | 18 | 20665.6 | 1148.1 | 9.82 | 0.001 |
| Linear | 6 | 14050.0 | 2341.7 | 20.02 | 0.000 |
| GSM | 2 | 13372.5 | 6686.3 | 57.17 | 0.000 |
| RPM | 2 | 249.4 | 124.7 | 1.07 | 0.389 |
| Vacuum | 2 | 428.1 | 214.0 | 1.83 | 0.222 |
| 2-Way Interactions | 12 | 6615.6 | 551.3 | 4.71 | 0.018 |
| GSM*RPM | 4 | 1766.6 | 441.6 | 3.78 | 0.052 |
| GSM*Vacuum | 4 | 1106.6 | 276.6 | 2.37 | 0.140 |
| RPM*Vacuum | 4 | 3742.4 | 935.6 | 8.00 | 0.007 |
| Error | 8 | 935.6 | 117.0 | | |
| Total | 26 | 21601.2 | | | |

Model Summary

| S | R-sq | R-sq(adj) | R-sq(pred) |
|---|---|---|---|
| 10.8145 | 95.67% | 85.92% | 50.66% |

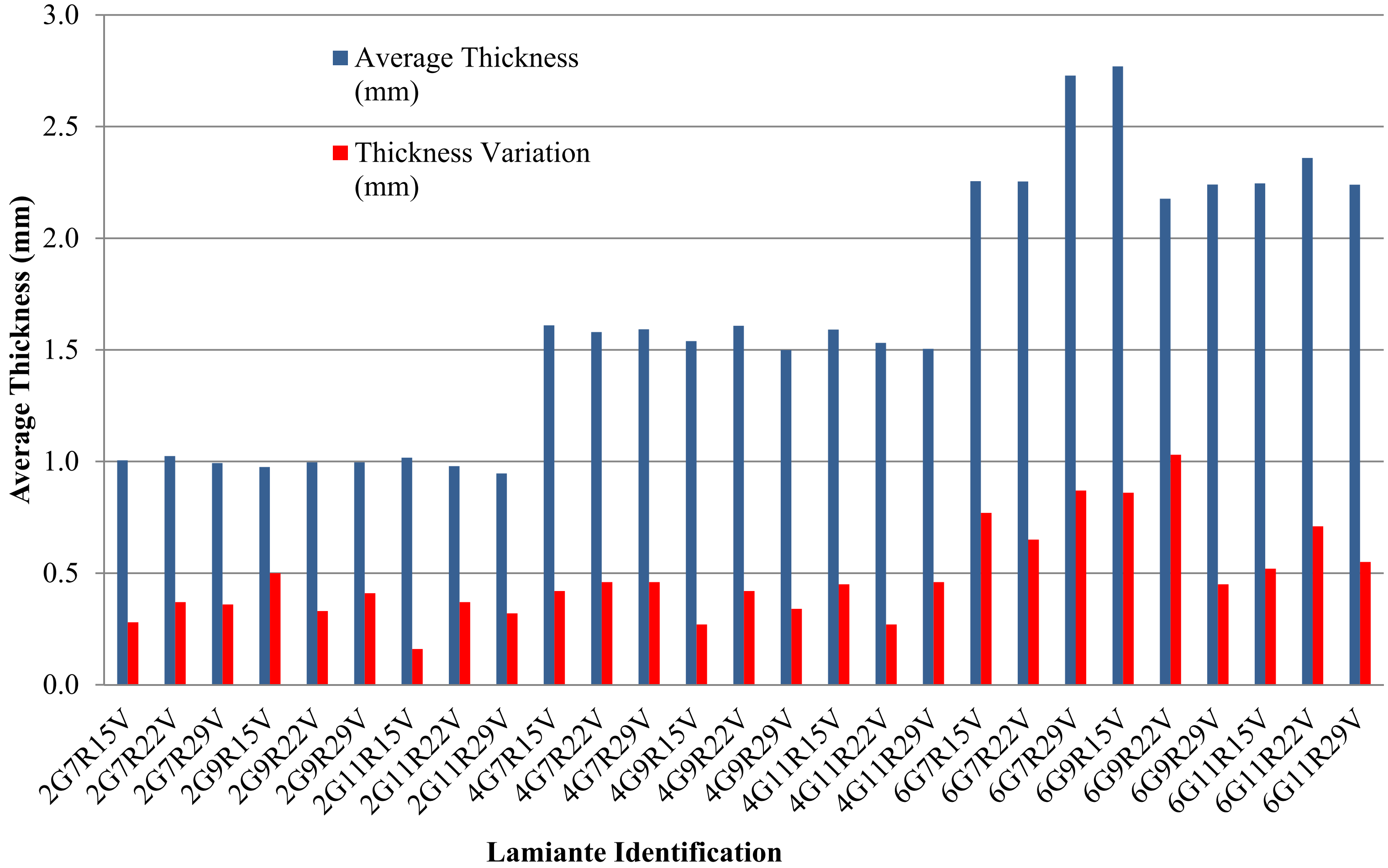


**Figure 6.16** Average thickness and thickness variation of all laminates