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The Optimization of Vacuum-Bagging Processing in Oven Cure for Tensile Strength in Composite Laminate

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ABSTRACT

The implementation of autoclaves has been limited due to high production costs and an excess of residual stress. These drawbacks have led to the exploration and development of an alternative method known as out-of-autoclave (OoA) manufacturing process. This research study was proposed to enhance the production of high tensile strength in composite laminate by optimizing the vacuum-bagging-only (VBO) pre-forming process. The impacts of both individual and combined pre-forming parameters in VBO-oven cure processing were measured for traditional low-cost glass/epoxy composite material with respect to the tensile strength of the cured laminates. Twenty composite panels were produced according to specified parameter combinations using central composite design in a fractional factorial approach for creating a response surface model. The study examined three variables, namely the duration of vacuum debulking, the number of sides with edge breather, and the weight of the intensifier. Two laminates were manufactured without additional processing parameters using both the oven (baseline) and autoclave methods for validation purpose. Subsequently, a tensile test was carried out following ASTM D 3039. The interaction among the combined parameters was examined using analysis of variance (ANOVA). The laminates exhibited the lowest tensile strength when the intensifier was not present, while the highest tensile strength was recorded when edge breather, debulk, and intensifier were applied at varying levels. An ideal processing configuration of 30 minute-debulk, each side of edge breather and 1kg-intensifier had resulted in the production of laminate with the highest tensile strength, measuring 407.44 MPa. This value was roughly 17.2% higher than that of the baseline laminate and 3.77% higher than the autoclave laminate.

1. Introduction

The aircraft industry has shown considerable interest in laminated composite materials, seeking components with a high strength-to-weight ratio and minimal environmental impact to improve the performance capacity of the vehicles [1]. In general, prepregs were employed to manufacture these composite structures, with the fabrication processes primarily divided into two phases: pre-forming

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and curing. Various preforming processing techniques, including liquid moulding, filament winding, vacuum bagging (VBO), and others, were utilized. The curing process could take place in an autoclave or through an out-of-autoclave (OoA) method such as microwave, oven, Quickstep, room temperature, and so on [2,3]. Utilizing vacuum bagging with autoclave curing emerged as the prevalent and efficient processing method for producing composite structures with minimal void content, particularly in applications demanding high performance, such as the aerospace industry [4,5].

However, autoclave curing came with disadvantages, including approximately 30 to 50% longer processing time, heightened residual stress leading to issues like composite core crush, skin pillowing, and dimpling, as well as approximately 30 to 50% higher costs encompassing capital, production, and operational expenses [6-8]. Therefore, the lower cost associated with out-of-autoclave (OOA) curing processes, particularly vacuum-bagging-only with oven curing (VBO-oven cure), presented an appealing and closely comparable alternative to autoclave, eliminating the need for high-pressure application and the associated steep costs [9-11]. Even with the cost advantage offered by the VBO-oven cure method, the composite components struggled to attain the necessary mechanical properties comparable to those achieved with autoclave processes. This shortfall was attributed to inadequate compaction pressure, resulting in increased void content [12]. Consequently, the void content was identified as a significant factor influencing the mechanical characteristics of the composite, critically impacting the performance of structural components. It was observed that an insufficient and suboptimal manufacturing profile led to a reduction in the mechanical properties of structural components, particularly in terms of shear strength, tensile strength, compressive strength, and other related attributes [13].

The primary challenge linked with VBO processing was the need to devise techniques for enhancing the permeability of the prepreg. This enhancement aimed to facilitate the optimal evacuation of entrapped air and volatiles before resin gelation. It was observed that the air permeability exhibited an inversely proportional relationship with the magnitude of compaction pressure, with the property decreasing as the pressure increased [14]. Hence, some researchers suggested that debulking should be performed on each individual prepreg layup for 20 minutes at room temperature, applying a vacuum pressure of 100 kPa. This process ensures an optimal evacuation of voids between prepreg plies [15,16].

The impact of heat treatment in conjunction with debulking on carbon/epoxy laminates was examined, revealing that heated debulking led to a reduction in the manufacturing cycle time by 26-71%. Debulking for 120 minutes at 48 ºC resulted in a lower void content of 2.44%, in comparison to 2.88% in its counterparts subjected to 16 hours of room temperature debulking [17]. Besides, utilizing a rubber seal as an intensifier, positioned beneath the steel plate, effectively enhanced the uniform distribution of compaction pressure during the curing process [18]. On the flip side, the successful implementation of the VBO-oven cure involved the use of dry glass fibres as a breather or bleeder at the edges of the laminate within the bagging setup. The edge breather was proven effective in enhancing air permeability, facilitating the evacuation of entrapped air within the laminate [19].

It was substantiated that air permeability remained optimal and adequate even when at least one edge of the laminate was connected to the edge breathing system. This contributed to a decrease in void distribution and an enhancement in thickness uniformity [20]. The edge breather was employed to facilitate the extraction of in-plane air and reduce porosity in the transverse direction. However, for larger and thicker composite laminates, a longer processing time was required, as the air flow path became more intricate [21,22]. Therefore, an optimum edge breathing mechanism was crucial, as an improper setup could directly impact the ply-slippage in the laminate, leading to an undesirable increase in compressive hoop stress within the fibre of the laminate [23].

Previous research findings highlighted the significance of VBO pre-forming processes on the final properties of the cured composite. Surprisingly, the optimization technique for VBO-oven cure of the conventional prepreg material towards the composite tensile property has not yet been extensively studied. Hence, an experimental study to examine the impact of each individual and combined vacuum-bagging only (VBO) pre-forming parameter on the tensile strength of low-cost, conventional material composite laminates for aircraft structural components was proposed. This study utilized a central composite design within a fractional factorial method to create a response surface model, resulting in 20 distinct processing routes. The utilization of a response surface model was chosen for its capability to predict and analyse the correlation between input variables and the output response. This allows for the identification of optimal factors and levels for a given process or system [24,25]. For validation purposes, two laminates were manufactured without any additional processing parameters using an oven (baseline) and an autoclave. Tensile test following the ASTM D 3039 standard was conducted to ascertain the tensile strength of the laminate. The combined parameters were then analysed for interaction using an analysis of variance (ANOVA) tool. The results established an optimal set of processing parameters in the VBO-oven curing technique for achieving the highest tensile strength in composite laminates.

2. Methodology

2.1 Materials

The prepreg employed was a plain weave glass fibre-reinforced epoxy, specifically Cycom 7668/7881-1, provided by Cytec Engineered Materials Inc. This prepreg is designed for structural laminates intended for use in aircraft exteriors, which typically produced via VBO-autoclave processing. The woven fabric saturated with the 7668-epoxy resin was manufactured through the hot-melt process, with a resin flow percentage of 17±5%. It demonstrates favourable tack and drape for a minimum of 15 days at 24 ˚C. After cured, the material demonstrates remarkable resistance to thermal aging, noteworthy flammability attributes, and exceptional tensile and compressive properties throughout its service life.

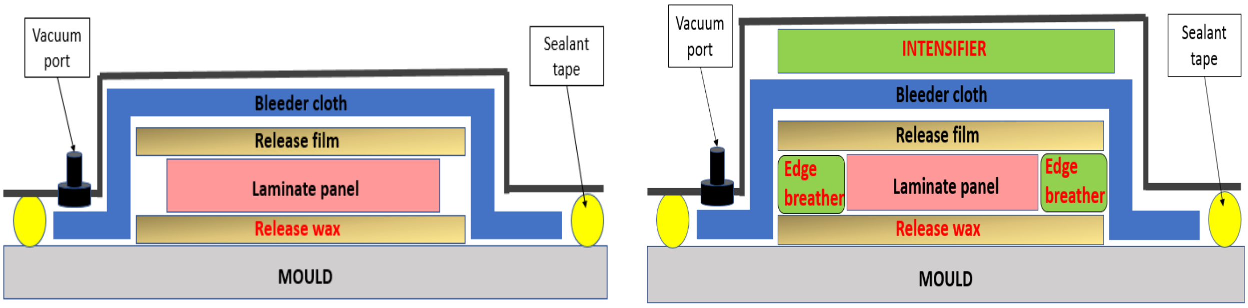
2.2 Manufacturing

Prepregs were precisely cut under controlled conditions of 50% humidity and 24°C temperature. Nine plies of prepreg were arranged into square panels measuring 300mm × 300mm, resulting in a nominal thickness of approximately 2 mm. The VBO process was executed in accordance with various configurations of the bagging setup, following the processing routes outlined in Table 1. Debulk duration, the number of sides with an edge breather, and the weight of the intensifier were analysed at three specific levels using central composite design in a fractional factorial method to create a response surface model, resulting in the production of 20 different composite panels. Laminates without any additional processing parameters were also produced via oven (baseline) and autoclave, for validation purpose.

Table 1
Levels of processing parameters test factors

Symbol	Factors	Level 1	Level 2	Level 3
A	Debulk duration (minutes)	0 min	30 min	60 min
B	Edge breather (no. of sides)	1 side	2 sides	All sides
C	Intensifier (weight, kg)	0 kg	1 kg	2 kg

Figure 1 illustrates the variations in vacuum bagging utilized in the research. In the standard (baseline) bagging method, prepreg plies were arranged on a flat aluminium mould, and a mould release film was positioned between the initial layer and the metallic tool. Additional consumables were arranged above the materials in the sequence; non-perforated release film (RF260 by Tygavac Advanced Materials), Airweave N10 bleeder cloth (Airtech Advanced Materials), and WL7400 vacuum bag (Airtech Advanced Materials). The assembly was enclosed, and the edges of the vacuum bagging were sealed using GS2131/2 sealant tape from General Sealants Inc. A singular vacuum port channel (Airtech Advanced Materials) was utilized to remove air from the sealed bagging.



(a) Baseline oven and autoclave configuration (b) Bagging configurations with additional parameters

Fig. 1. Different configurations in vacuum bagging pre-forming

The bagging configuration with additional processing parameters of Figure 1(b) utilized the use of an intensifier or caul plate to enhance the contact pressure. This addition aimed to reduce the porosity and void content in the cured laminates. 300mm x 300mm of g stainless steel plate of different weight was used as an intensifier and was placed on the laminates, on top of the bleeder. Additionally, dry glass fibre strip of Tygavac Y-0094 measuring 1 cm in thickness and 2.5 cm in width, served as the edge breather, placed beside the laminate plies to assist the in-plane voids evacuation. The breather cloth also functions as the in-plane bleeder material, facilitating the expulsion of voids by drawing entrapped air and excess resin out from the laminate plies via in-plane direction. During the layup process, vacuum debulking was carried out utilizing a JK-VP-3C single-stage vacuum pump, with a hose connecting to the vacuum bagging and the vacuum port. Vacuum pressure was applied for 20 minutes at room temperature after every 3-ply prepreg layup, continuing until a total of 9 prepreg plies were assembled.

The oven-cured laminates underwent curing in an oven with a single dwell section, lasting 120 minutes at a temperature of 180 ± 12 °C, with rates of heating and cooling at 2 °C per minute. A main vacuum pump was linked to the vacuum bag, providing vacuum pressure starting from the initiation of the curing cycle until the laminate panel was taken out, while the temperature gradually decreased to 60 °C. Alternatively, the autoclave-cured laminate experienced a pressure compaction increase from 103 kPa to 310 kPa for a duration of two hours throughout the autoclave curing process, in accordance with the guidelines provided by the prepreg manufacturer.

2.3 Tensile Test

Tensile test was conducted based on ASTM standard of 3039/D 3039 M – 00. Ten specimens per panel were prepared into the dimensions of 180 mm x 12 mm and then polished as required, using 100, 400 and 600 grids of sandpapers. Tabs were also cut from the same composite material, with a size of 25 mm x 12 mm. Tabs was used to reduce the stress concentration on to the specimen; hence avoided any premature damage in the grip area and promoted tensile failure solitary within the gauge section. An epoxy resin was used as adhesive glue between tabs and specimen. Tensile tests were performed under a constant tensile load in an Instron mechanical testing machine, using a test speed of 0.5 mm/min to obtain the ultimate tensile strength of composite panels.

3. Results

3.1 Tensile Strength Analysis

Table 2 shows the tensile strength recorded for the 2^3 orthogonal array, autoclave and baseline laminate panels. From the observation during experiments, it was found that all laminate sample experienced total catastrophic failure without necking and breaking into two pieces, where linear plotted graph was presented. These indicated that the stress was applied successfully to the sample which was directly proportional to the strain until the point of failure. These also suggested that all laminate panels exhibited brittle behaviour with limited ductility, devoid of any significant plastic deformation, which was predicted prior to the nature and features of glass-fibre material used in this research work.

Tensile strength of laminates with additional processing parameters were within the range from 353.07 MPa to 407.44 MPa. In contrast with the panels without any additional processing parameters, lowest tensile strength of 348.18 MPa was obtained for baseline laminate, while autoclave panel yielded tensile strength value of 392.63 MPa. Highest tensile strengths measured with the values of 407.44 MPa, 405.48 MPa and 402.75 MPa with the combination of edge breather, debulk and intensifier at different levels. On the other hand, lowest tensile strengths for the panels with processing parameters were recorded at the value of 353.07 MPa, 358.23 MPa and 364.76 MPa, where there was no intensifier application.

Table 2
Tensile strength of composite panels

Trial	Factor			Tensile strength (MPa)
	A (Debulk)	B (Edge Breather)	C (Intensifier)	
1	1	1	1	358.23
2	1	3	1	365.24
3	2	2	1	367.71
4	3	1	1	353.07
5	3	3	1	364.76
6	1	2	2	388.26
7	2	1	2	369.57
8	2	2	2	384.19
9	2	2	2	380.52
10	2	2	2	382.63
11	2	2	2	380.46
12	2	2	2	384.91
13	2	2	2	373.19
14	2	3	2	407.44
15	3	2	2	405.48
16	1	1	3	371.22
17	1	3	3	389.81
18	2	2	3	402.75
19	3	1	3	400.15
20	3	3	3	392.28
Autoclave				392.63
Baseline (oven)				348.18

Based on the results, it was discovered that tensile strengths were lowest in laminate 1 to 5, where intensifier was absent during cure for those panels. Tensile strength is a measure of the ability to withstand tensile (pulling) forces without breaking and the quality was dependable on the processing conditions during manufacturing. In this study, intensifier supplied additional compaction throughout cure and subsequently facilitated resin flow within the laminate. As a result, this aided in a proper fibre wetting, improved cure uniformity, enhanced fibre-matrix attachment which then improved the tensile properties of composite laminate.

It was observed that the effects of different levels involving factors debulk and edge breather toward tensile strength were scattered. However, in comparison between laminate 14 (highest tensile strength) and laminate 4 (lowest tensile strength), edge breather was utilized in maximum level with lower debulking level for laminate 14, as compared to minimum edge breather and highest debulking level for laminate 4. Edge breather offered several advantages in oven curing composite namely; enhanced permeability in in-plane direction, improved pressure distributions and amplified resin flow, hence improve the tensile strength of laminate.

Conversely, debulking in an improper levels, frequency and conditions was discovered to reduce the tensile strength of oven-cured composite. An inadequate consolidation might occur during debulking since the process was performed during resin B-stage state, where laminate would be partially cured with minimal resin flow, resulting in entrapped air pockets, non-uniform curing and poor tensile property of produced laminate. Nevertheless, debulking processing parameter was undeniably contributed to better tensile property of laminate than the ones without any additional processing parameters. Conclusively, the processing parameter studied in this validation work improved tensile strength since all the laminates cured with additional processing variables attained a higher tensile strength than the baseline laminate. Hence, it is critical to examine specific processing parameters and levels of each factor to optimize the tensile strength, which then demonstrated the importance of proper processing selection to achieve the desired properties in composite laminates.

3.2 Analysis of Variance (ANOVA)

ANOVA analysis was performed to evaluate the significance effects of each and combined input variables to the tensile property, as shown in Table 3. Since the significance level value of 0.1 was selected, the model P-value of 0.036 elucidated that there was strong evidence to reject the null hypothesis and the model fits the data adequately. Factors B and C presented P-values of 0.077 and 0.002, indicating the highest and significant contributions towards the tensile strength, which were further shown in the Pareto chart of Figure 2.

Table 3
ANOVA for tensile strength

Source	Sum of Squares	Df	Mean Square	F-value	P-value
Model	3536.17	9	392.91	3.38	0.036
A	184.73	1	184.73	1.59	0.236
B	452.79	1	452.79	3.89	0.077
C	2166.78	1	2166.78	18.64	0.002
AA	32.1	1	32.1	0.28	0.611
BB	67.34	1	67.34	0.58	0.464
CC	185.98	1	185.98	1.6	0.235
AB	59.3	1	59.3	0.51	0.491
AC	171.5	1	171.5	1.48	0.252
BC	7.96	1	7.96	0.07	0.799

Std. Dev.	Mean	R-Squared	Adj R-Squared
10.7823	381.094	0.7526	0.5299

Figure 2 illustrated the Pareto chart of significant contributing input factors that bestowed effect towards output responses. It was found factors C (intensifier) and B (edge breather) were statistically significant towards tensile strength at 0.1 α level in the model term, crossing the reference line at 1.812. The percentage contribution of factors was computed from Pareto plot with factor C and B had the most significant effect of approximately 35.12% and 16.05%, respectively.

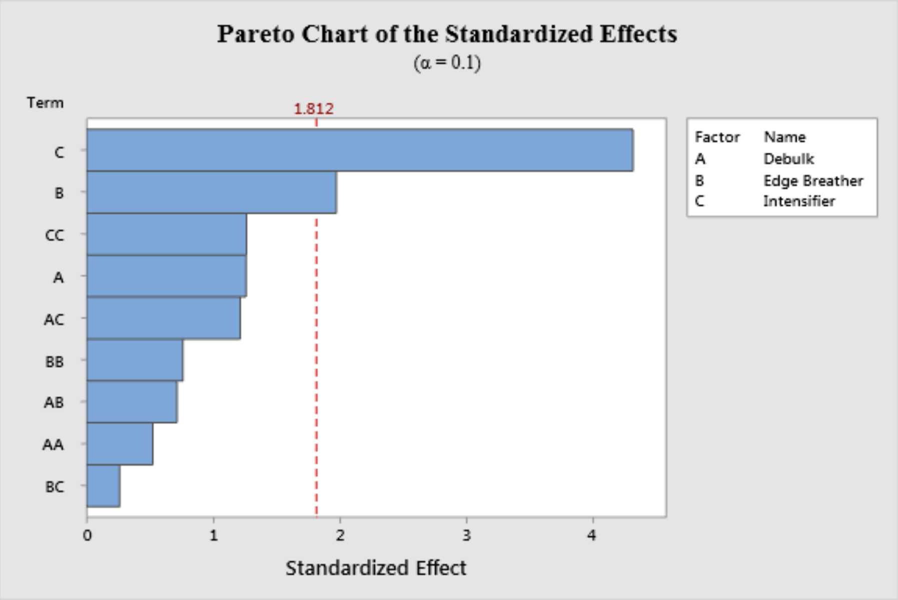


Fig. 2. Pareto chart of standardized effects on tensile strength

Figure 3 depicted the standard plot of standardized effects, also known as the quantile-quantile (Q-Q) plot, for tensile strength. The linear diagonal line following plotted points confirmed that tensile strength values were normally distributed and fitted the model. Conversely, factors C and B which were further from 0 in the x-axis were found to be statistically significant. It was also demonstrated that these factors were located at the positive side of x-axis, representing a positive standardized effect on tensile strength. This indicated that when intensifier and edge breather level was increased, tensile strength would be also increased, and vice versa. Thus, the main and interaction effects analysis of were important and critical in order to examine the trend effects of each factor towards output response in more detail manner.

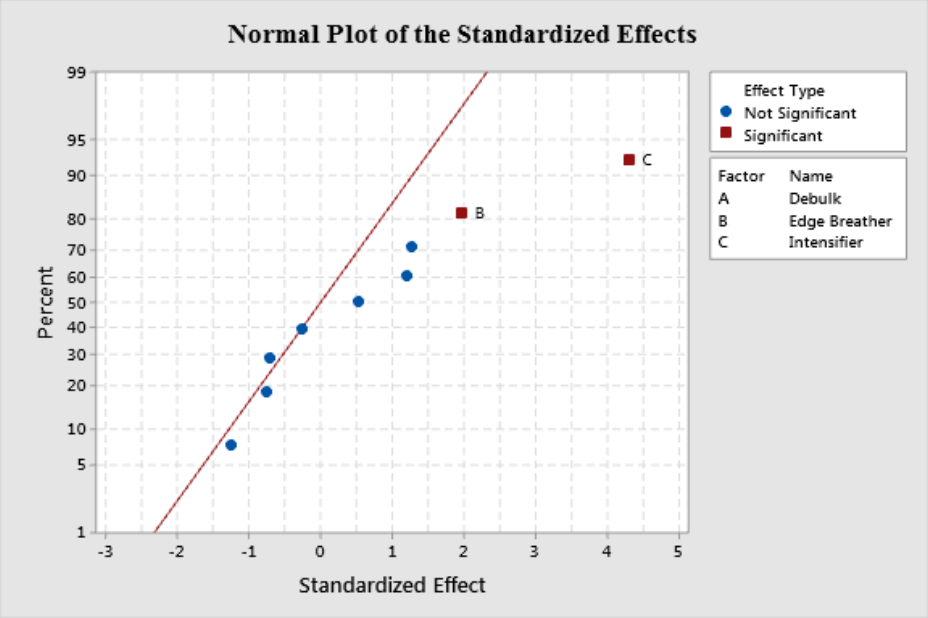


Fig. 3. Normal plot of standardized effects on tensile strength

The main effects of processing parameters towards the tensile strength of laminate panel were exhibited in Figure 4. It was illustrated that the highest tensile strength was associated with level 2 debulk, level 3 debulk and level 3 intensifier when each individual factor was considered. Intensifier was found to have the strongest impact with tensile strength enhancement of approximately 8.27% from no intensifier to level 3 intensifier factor. Contrarily, minimum level of factor debulk, edge breather and intensifier were affiliated with lowest tensile strength, where intensifier level 1 persistently impacted to produce laminate with lowest tensile quality. Based on the reference line in the graphs, input factors no debulk, one-sided edge breather and no intensifier were most unfavourable since tensile strengths were found to be below the average mean.

As illustrated in main effect plot of debulk factor of Figure 4, tensile strength was increased by approximately 2.54% from no debulk to 30 minutes debulk and subsequently reduced by approximately 0.13% with further implementation to 60 minutes debulk. These proved that single processing parameter of debulk at 30 minutes was most favourable in producing best tensile strength in laminate. On the other hand, it was discovered from the edge breather plot that tensile strength was augmented by approximately 4.19% when two laminate sides were attached with edge breathers as compared to single-sided edge breather. Then, tensile strength was reduced by approximately 0.26% with the implementation of edge breather on each laminate side. These showed that debulk and edge breather implementation should be optimal in producing composite panel with best tensile quality.

In view of factor intensifier, tensile strength was steeply increased by approximately 6.34% from no intensifier to 1 kg intensifier application. As the intensifier weight was then augmented to 2 kg, tensile strength was further increased by approximately 1.81%. As resin acted as the stress transfer media between the fibre plies, resin quality affected the value of tensile strength imperceptibly. Hence, the additional dead weight of intensifier was effective in boosting the contact pressure, ensured curing uniformity and resin wetting within laminate and subsequently improving tensile quality of composite panel.

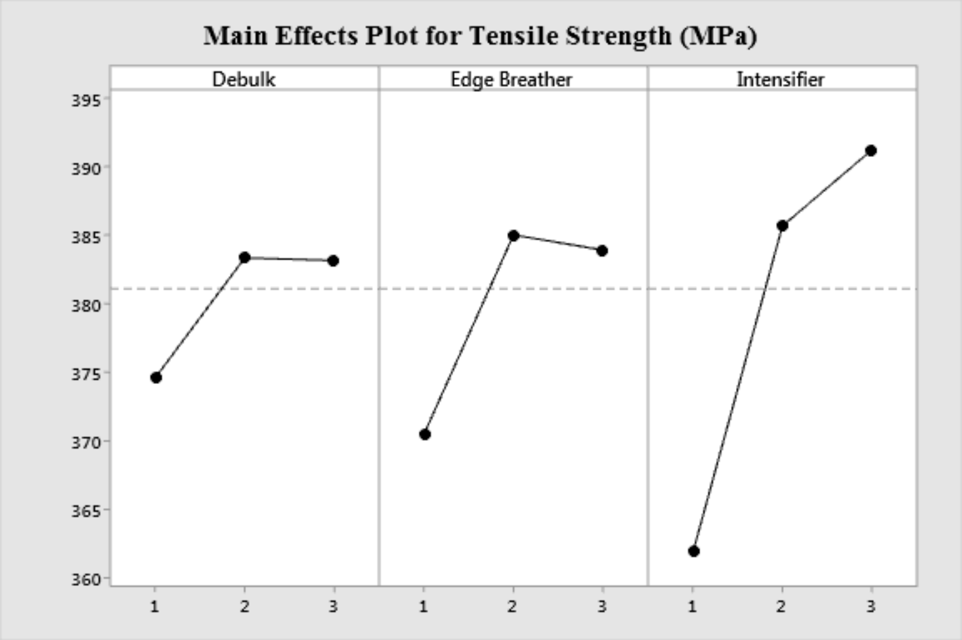


Fig. 4. The main effects plot of processing parameters towards tensile strength

Figure 5 showed significant interactions between two combined factors towards tensile strength due to the non-parallel lines yielded. From the first interaction graph of debulk versus edge breather, it was found that the relationship between tensile strength and debulk factor was dependable on the level of edge breather. For example, if there was no debulk (level 1) employed, single-sided edge breather (level 1) was associated with lowest tensile strength of approximately 365 MPa. Though, if 30 minutes debulk (level 2) was utilized, all-sided edge breather (level 3) was associated with the best tensile strength value of approximately 405 MPa.

Based on debulk versus intensifier graph, it was also illustrated that the relationship of tensile strength and debulk factor was dependable on intensifier level. For instance, poorest tensile strength of approximately 360 MPa was generated when one-hour debulk (level 3) associated with the absent of intensifier (level 1). Whereas, if 1 kg of intensifier (level 2) was utilized, highest tensile strength of approximately 405 MPa was achieved with the similar debulk level. Likewise, according to interaction plot of edge breather versus intensifier, the relationship of edge breather and tensile strength was dependable on intensifier level. Lowest tensile strength of approximately 360 MPa was exhibited with the combination of one-sided edge breather (level 1) along with no intensifier utilization. Nevertheless, when 1 kg intensifier was applied (level 2), all-sided edge breather (level 3) was associated with the greatest tensile strength of approximately 408 MPa.

Ultimately, the optimum combination of debulk, intensifier and edge breather at a certain levels and condition were proved to improve tensile quality of oven-cured glass/epoxy composite laminate. It was discovered that debulking and intensifier factors enhanced the permeability in inter-plane direction, while edge breather acted as the medium perimeter to ensure enhancement in in-plane direction. As a result, each laminate panel with additional processing parameters produced in this study possessed better tensile strength than the baseline laminate. Conclusively, with regards to tensile strength, the combination of these factors was found to be optimum when debulking, edge breather and intensifier were employed for 30 minutes (level 2), on each side (level 3) and weighted at 1 kg (level 2), which was approximately 17.2% and 3.77% higher than the baseline and autoclave laminate, respectively.

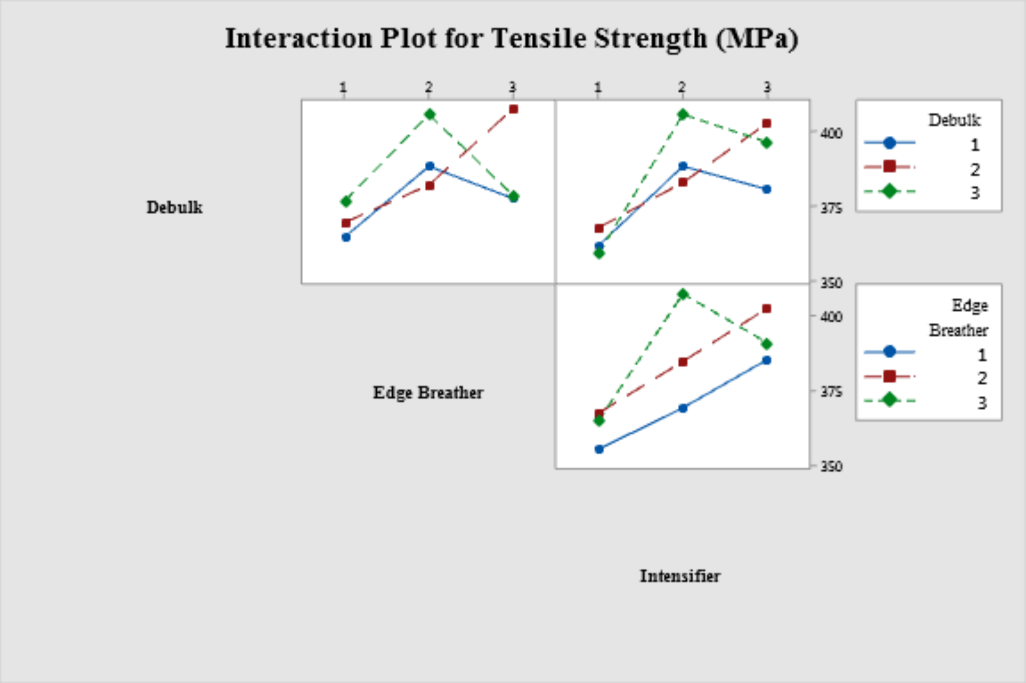


Fig. 5. Interaction plot for combination of two processing parameter towards tensile

4. Conclusion

An experimental investigation was carried out to identify optimal processing parameters for vacuum-bagging preforming in oven curing, specifically focusing on enhancing the tensile strength in glass/epoxy composite laminate. Twenty composite panels were manufactured according to the specified parameter combinations using central composite design in the fractional factorial method for response surface model. Three variables, namely vacuum debulk duration, the number of sides with edge breather, and the weight of the intensifier, were examined. Laminates without additional processing parameters were also produced in oven (baseline) and autoclave for validation purpose. The laminates produced without intensifier in the processing setup exhibited the lowest tensile strength, whereas the highest tensile strength was observed in the configurations where edge breather, debulk, and intensifier were combined at varying levels. Compared to panels without any additional processing parameters, the baseline laminate recorded the lowest tensile strength at 348.18 MPa, whereas the autoclave panel achieved an intermediate tensile strength value of 392.63 MPa. VBO configuration involving 30-minute debulk, edge breather on each side, and 1kg intensifier resulted in the highest tensile strength, which was approximately 17.2% higher than the baseline laminate and 3.77% higher than the autoclave laminate.

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