Optimization of Carbon Fiber Reinforced Plastic Curing Parameters for Aerospace Application

Fareed Ahmad 1,2,* , Mohammed Al Awadh 3, Muhammad Abas 1, Sahar Noor 1 and Asad Hameed 2

1 Department of Industrial Engineering, University of Engineering and Technology, Peshawar 25100, Pakistan; muhammadabas@uetpeshawar.edu.pk (M.A.); sahar@uetpeshawar.edu.pk (S.N.)
2 Aerospace Engineering Department, College of Aeronautical Engineering, National University of Sciences and Technology, Islamabad 44000, Pakistan; asadhameed@cae.nust.edu.pk
3 Department of Industrial Engineering, College of Engineering, King Khalid University, Abha 61411, Saudi Arabia; mohalawadh@kku.edu.sa
* Correspondence: fareedahmad.ind@uetpeshawar.edu.pk

Abstract: The use of carbon fiber reinforced plastic (CFRP) is increasing in engineering applications such as aerospace, automobiles, defense, and construction. Excellent strength-to-weight ratio, high impact toughness, and corrosion resistance make CFRP highly suitable for aerospace applications. Curing temperature, curing time, and autoclave pressure are among the most important curing parameters affecting the properties of CFRP. Tensile strength, impact toughness, and hardness of CFRP were selected as desirable properties for optimization. A $2^3$ full factorial design of experiment (DOE) was employed by varying curing temperature (120 and 140 °C), curing time (90 and 120 min), and autoclave pressure (3 and 7 bar) while keeping the number of experiments to a minimum level. The cured samples were subjected to tensile strength, impact toughness, and hardness tests at room temperature as per relevant ASTM standards. Analysis of variance (ANOVA) was used, and it was found that tensile strength, impact toughness, and hardness were influenced most significantly by temperature and time. The maximum tensile strength and hardness were achieved for curing cycle parameters of 140 °C, 120 min, and 7 bar, and impact toughness was maximized for 140 °C, 120 min, and 3 bar. A concept of composite desirability function was used to achieve simultaneous optimization of conflicting tensile strength and impact toughness properties for the specific application of aircraft skin.

Keywords: autoclave; carbon fiber reinforced plastic; curing process; desirability function; simultaneous optimization

1. Introduction

Carbon fiber reinforced plastics (CFRP’s) have proven to be the most suitable alternative to aluminum alloys for structural applications in the aerospace industry. Due to their superior properties, the use of CFRPs has increased in recent years [1,2]. Some of the properties suitable for aerospace applications are high strength-to-weight ratio, impact toughness, hardness, dimensional stability, corrosion resistance, fatigue resistance, noise reduction, low radar cross-section, and the capability to be molded into large and complex shapes [3–6].

Tensile strength, impact toughness, and hardness are some of the desired properties for the skin of an aircraft. Tensile strength is the most fundamental requirement for the design of any structural component. The structure of commercial and military aircraft is semi-monocoque in construction. The entire skin of the fuselage, wings, and empennage is divided into regular geometric units. Each unit of the skin can be considered as a thin plate...
subjected to aerodynamic pressure. The required strength for most of the aircraft skin can be estimated by Equation (1) [7,8].

\[
\sigma_{\text{max}} = \frac{\beta qb^2}{t^2}
\]

where

\(\sigma_{\text{max}}\) is maximum stress in the skin patch (MPa);
\(\beta\) is a plate dimensions ratio (dimension less);
\(q\) is uniformly distributed aerodynamic pressure on the skin of the selected portion (MPa);
\(b\) is a short dimension of the skin patch (mm);
\(t\) is the thickness of the skin patch (mm).

Besides being dependent on the dimensions, the maximum allowable stress is a function of aerodynamic pressure acting on the skin panel and it must be below the yield strength of the material. Furthermore, a fracture is less likely to occur if the maximum applied stress is below the tensile strength of the skin panel. Adequate impact toughness of composite makes the skin damage tolerant and enables it to sustain normal impact loads such as runway debris [9], bird strikes, gale strikes during normal operation, and tool drops during maintenance [10]. The impact toughness is also correlated with Mode I and II interlaminar crack growth resistance [9,11] (Section 3.2.2) influencing the structural integrity of the material. The hardness of the aircraft skin helps to resist indentation, scratching, and abrasion. Prepreg polymer matrix composites (PMCs) are generally used for the construction of aircraft skin due to the superior quality of the finished product. It is well established that the mechanical properties of prepreg PMCs are strongly dependent on the curing cycle (CC) [12–15]. The CC can be programmed for desired levels of processing parameters. The effect of various CC parameters such as autoclave pressure [16–19], vacuum application time, curing temperature, curing time [20–25], heating/cooling rate [26], and the number of stages for curing [27] has been investigated in the literature. Amongst these, temperature, time, and pressure are the most influential in dictating the mechanical properties of CFRP [20,23–25,28–30]. Temperature and time are interlinked as there is always an optimal temperature for a selected time to obtain an optimum mechanical property. It is often desirable to know those optimum values of temperature and time [31,32]. Autoclave pressure has also been found to heavily influence the volume fractions of the voids in the matrix [17,18]. Increasing the pressure causes a decrease in matrix voids thus increasing mechanical properties. A combination of certain (optimal) values of temperature, time, and autoclave pressure results in optimum values of mechanical properties of composites that have been studied in the literature. For example, Singh et al. investigated the effects of curing parameters on tensile, compressive, and flexural characteristics of CFRP [33]. The authors compared experimental results to find out the optimal curing parameters for the resulting optimized properties. Similarly, the optimization of surface finish, void formation, void distribution, tensile strength, flexural strength, stiffness, and mass has also been investigated in literature [23,32].

DOE is a systematic data collection and analysis tool that is used to determine the effects of curing parameters on the properties. Determination of optimum CFRP properties requires DOE in the curing parameters space followed by experimentation. An efficient DOE helps to minimize the number of experiments and saves time and resources. This was achieved by exploiting available information about the curing process (Section 2) which was then used in selecting the levels of curing parameters. This helped to choose the starting point in the likely vicinity of the optimum property, which made the optimization efficient, requiring a lower number of experiments. In contrast, other advanced optimization techniques such as artificial neural networking (ANN) cannot be used for optimization with a smaller number of experiments. The results predicted by ANN do not always describe the most effective improvement. For example, the main effects of a process parameter cannot be described as statistically significant with clarity. However, these limitations of ANN
can be overcome if used with DOE and response surface methodology (RSM) as a hybrid model [34]. DOE provides a high level of control over the variables, allowing researchers to utilize as many variations as they want without destroying the validity of the research design, leading to excellent results.

Some of the standard design of experiments (DoE) techniques, i.e., full factorial [24], fractional factorial, central composite [35], and Taguchi design [20], were used for experimentation in various optimization schemes. Generally, it is a common practice to develop intricate mathematical objective functions between curing parameters and properties for optimization using numerical methods [23,32,36]. In the case of multiple properties optimization, the mathematical modeling of the objective function becomes even more complex. This requires the use of a heuristic algorithm to find out the optimum parameter at the cost of accuracy and precision [22,36]. However, most of the referred studies are generic and not targeted at a specific engineering application.

For aerospace engineering applications such as the skin of an aircraft (aimed in this work), mechanical properties such as tensile strength and impact toughness have generally conflicting objective functions. Hence, engineering decisions about trade-off amongst various available options becomes a necessity. In this work, an aerospace-specific multiple properties optimization scheme for a CFRP with a minimal number of experiments is presented. A full factorial $2^3$ DoE was used for the design and execution of experiments. A reference CC and seven other CCs were designed using existing knowledge of composite properties. The mechanical tests for tensile strength, impact toughness, and hardness were conducted. ANOVA was used to identify significant curing parameters and interactive terms, with a 95% confidence level [37,38]. Regression equations and three-dimensional surface plots were then developed between significant curing parameters and properties of CFRP. The concept of composite desirability function was used to trade-off between conflicting properties of tensile strength and impact toughness [39–42]. With the existing knowledge of some of the composite properties, the approach presented in this paper can be used to quickly reach optimization point without expanding large experimental resources.

2. Materials and Methods

The composite material used for this research work is a prepreg unidirectional carbon fiber reinforced plastic. The matrix of the understudy composite is a di-glycidyl ether of bisphenol A (DGEBA) epoxy system, a class of thermoset polymer. DGEBA is used as a binding matrix in high-performance fiber-reinforced composites and it is known for excellent mechanical properties, dimensional stability, chemical resistance, and ease of processing [19,43]. During curing, the epoxy converts into a hard rigid solid by chemical cross-linking. A two-stage CC is recommended by the prepreg CFRP manufacturer. The glass transition temperature with the maximum degree of conversion ($T_g \infty$) is 140 °C according to the manufacturer. Stage-1 comprises 1–3 °C/min heating rate from ambient temperature to 80 °C and holding for 30 min. During stage-1, polymerization initiates. Stage-2 recommends increasing curing temperature at the same heating rate from 80 °C to 120 °C for an additional time of 120 min to accelerate the polymerization process under autoclave pressure of 7 bar. After 120 min, a cooling rate of 2–5 °C/min is recommended to bring the laminate to 30 °C. A vacuum (~0.8 bar) is recommended inside the laminate bag during curing. Figure 1 presents a manufacturer-recommended curing cycle (MRCC) comprising curing temperature ($T_c = 120 \degree$ C), curing time ($t_c = 120$ min), and autoclave pressure ($P_{au} = 7$ bar). This research work is confined to the second stage of curing (MRCC) only. It is pertinent to mention that MRCC results in a set of CFRP properties for general-purpose application. The MRCC needed modification to achieve optimum properties for an aircraft skin application.
2.1. Selection of Curing Parameter Levels

To investigate the optimum properties for aircraft skin material, the properties region around MRCC was explored experimentally. For this purpose, one of the levels of the curing parameters was selected as defined in MRCC. The other level was selected either above or below the MRCC level, keeping in view the known relationship of curing parameters with the property.

2.1.1. Curing Temperature Levels

One of the \( T_c \) levels was selected from MRCC, i.e., 120 °C. The second level of \( T_c \) was selected as 140 °C, the glass transition temperature (\( T_{g\infty} \)) of the understudy CFRP matrix epoxy. However, above \( T_{g\infty} \), the resin begins to char which adversely affects the properties of CFRP [44] making \( T_{g\infty} \) a practical constraint for experimentation.

2.1.2. Curing Time Levels

The effect of increasing \( T_c \) and \( t_c \) on the properties of CFRP is similar [21]. Since 140 °C was selected as a higher level of \( T_c \), selection of a longer period of \( t_c \) than MRCC-defined time could likely result in property degradation of the CFRP matrix. Therefore, another level of \( t_c \) was selected as 90 min which is shorter than the MRCC \( t_c \) value (120 min).

2.1.3. Autoclave Pressure Levels

The high level for experimentation was selected according to MRCC, i.e., 7 bar [45]. The first level of \( P_{au} \) was selected lower than MRCC-defined \( P_{au} \), i.e., 3 bar, to explore the probability of improvement in impact toughness, which increases with decreasing \( P_{au} \) [19]. Table 1 shows the summarized designed curing parameters levels for experimentations.
Table 1. Summary of designed curing parameters levels for experimentation.

| Parameters          | Symbols (Units) | Levels |
|---------------------|-----------------|--------|
| Curing temperature  | T_c (°C)        | 120 140|
| Curing time         | t_c (min)       | 90 120 |
| Autoclave pressure  | P_{au} (bar)    | 3 7    |

2.2. Samples Preparation and Experimentations

CFRP UD lamina of thickness 0.125 mm was selected for preparing composite laminate for mechanical testing. Zund 1600 cutting plotter was used to cut laminae at 45° and 0° orientations, as shown in Figure 2. For good strength along the axial direction of a test coupon, stacking sequence [0/+45/0/0/0/−45/0]_3 was selected to prepare laminate for the tensile test coupon, whereas [0/+45/0/0/0/−45/0]_2 laminate was prepared for impact toughness and hardness test coupons. Both these laminates were prepared in the ISO class 8 cleanroom.

![CFRP laminae at 45° and 0° orientation on Zund 1600 cutting plotter.](image1)

The laminates were subjected to eight different CCs according to 2^3 full factorial design as shown in Table 2. It shows all eight combinations of three curing parameters. Vacuum bagging of laminates was carried out to avoid void formation during curing and exposure of epoxy to air, as shown in Figure 3. The curing was performed in an Irop Parma autoclave, as shown in Figure 4a,b.

![Vacuum bagging of the laminate before curing.](image2)
Figure 4. (a) Irop Parma autoclave used for polymerization/curing of CFRP laminates; (b) close-up of vacuum-bagged laminates after curing.

Table 2. $2^5$ full factorial design and mechanical tests results. MRCC parameters and corresponding properties are represented by bold numbers.

| CC | $T_c$ (°C) | $t_c$ (min) | $P_{au}$ (bar) | Tensile Strength (MPa) | Impact Toughness (J) | Hardness (HRB) |
|----|------------|-------------|----------------|-----------------------|---------------------|----------------|
| 1  | 120        | 90          | 3              | 1044.8                | 02.45               | 46.0           |
| 1  | 120        | 90          | 3              | 1078.4                | 02.42               | 48.2           |
| 1  | 120        | 90          | 3              | 1060.8                | 02.53               | 44.8           |
| 2  | 140        | 90          | 3              | 1083.2                | 03.61               | 52.4           |
| 2  | 140        | 90          | 3              | 1153.6                | 05.84               | 50.7           |
| 2  | 140        | 90          | 3              | 1137.6                | 03.93               | 50.2           |
| 3  | 120        | 120         | 3              | 1041.6                | 08.08               | 48.4           |
| 3  | 120        | 120         | 3              | 1142.4                | 07.19               | 48.2           |
| 3  | 120        | 120         | 3              | 1224.0                | 08.52               | 51.5           |
| 4  | 140        | 120         | 3              | 1364.8                | 17.43               | 56.2           |
| 4  | 140        | 120         | 3              | 1417.6                | 16.97               | 54.5           |
| 4  | 140        | 120         | 3              | 1384.0                | 17.80               | 56.1           |
| 5  | 120        | 90          | 7              | 1110.4                | 03.37               | 45.5           |
| 5  | 120        | 90          | 7              | 1177.6                | 03.10               | 49.2           |
| 5  | 120        | 90          | 7              | 1148.8                | 03.20               | 48.4           |
| 6  | 140        | 90          | 7              | 1212.8                | 05.20               | 52.9           |
| 6  | 140        | 90          | 7              | 1094.4                | 05.85               | 53.1           |
| 6  | 140        | 90          | 7              | 1048.0                | 05.86               | 55.4           |
| 7  | 120        | 120         | 7              | 1204.8                | 11.19               | 48.2           |
| 7  | 120        | 120         | 7              | 1345.6                | 11.00               | 49.5           |
| 7  | 120        | 120         | 7              | 1327.5                | 12.03               | 52.0           |
| 7  | 120        | 120         | 7              | 1446.4                | 16.40               | 59.1           |
| 8  | 140        | 120         | 7              | 1422.4                | 16.97               | 56.8           |
| 8  | 140        | 120         | 7              | 1432.0                | 16.19               | 60.8           |
| 8  | 140        | 120         | 7              | 1432.0                | 16.19               | 60.8           |

* MRCC/CC7.

A total of 3 coupons were prepared from each of the laminate cured at 8 different CCs. Thus, 24 coupons for mechanical tests, i.e., tensile test (ASTM D3039), Charpy impact test (ASTM D6110), and Rockwell hardness test (ASTM D785), were prepared. The tensile test was conducted on a 300 kN UTM at a strain rate of 2 mm/min (Figures 5a and 6a), impact toughness was conducted on Charpy impact testing machine model JBS300 (Figures 5b and 6b), whereas hardness tests were conducted on a Rockwell hardness testing machine model TH300 (Figures 5c and 6c). The mechanical test results are summarized in Table 2.
impact toughness was conducted on Charpy impact testing machine model JBS300 (Figures 5b and 6b), whereas hardness tests were conducted on a Rockwell hardness testing machine model TH300 (Figures 5c and 6c). The mechanical test results are summarized in Table 2.

Figure 5. (a) Universal tensile testing machine M/s Hualong, Shanghai, China HLE 300 kN. (b) Charpy impact toughness testing machine M/s Time Group Inc., Beijing, China Model No. JBS300. (c) Rockwell hardness testing machine M/s Time Group Inc., Beijing, China Model No. TH300 used for mechanical testing.

Figure 6. Test coupons for (a) tensile strength testing, (b) impact toughness test, (b,c) Rockwell hardness test.

3. Results and Discussions
3.1. Analysis of Variance (ANOVA)

ANOVA was performed at a 95% confidence interval [46] to study the influence of curing parameters on tensile strength, impact toughness, and hardness. ANOVA results, summarized in Tables 3–5, were further used for the development of prediction models.
and optimization. Prediction models for individual responses were developed using the backward elimination method ($\alpha = 0.1$). F-value shows the most contributory curing parameters towards the response variable. A $p$-value less than 0.05 shows the statistical significance of curing parameters on the response variable. The results showed that the individual factors $T_c$, $t_c$, and $P_{au}$, and their interaction ($T_c \times t_c$) and ($T_c \times P_{au}$), have a significant effect on tensile strength.

Table 3. ANOVA results for tensile strength. The table shows the significance ($p$-value < 0.05) of individual factors $T_c$, $t_c$, and $P_{au}$, and their interaction ($T_c \times t_c$) and ($T_c \times P_{au}$) on the property of tensile strength.

| Source         | DF | Adj SS  | Adj MS  | F-Value | p-Value |
|----------------|----|---------|---------|---------|---------|
| Model          | 5  | 402,449 | 80,490  | 25.85   | 0.000   |
| Linear         | 3  | 339,145 | 113,048 | 36.30   | 0.000   |
| $T_c$          | 1  | 69,346  | 69,346  | 22.27   | 0.000   |
| $t_c$          | 1  | 240,544 | 240,544 | 77.24   | 0.000   |
| $P_{au}$       | 1  | 29,255  | 29,255  | 9.39    | 0.007   |
| 2-way inter    | 2  | 63,304  | 31,652  | 10.16   | 0.001   |
| $T_c \times t_c$ | 1  | 47,926  | 47,926  | 15.39   | 0.001   |
| $T_c \times P_{au}$ | 1  | 15,378  | 15,378  | 4.94    | 0.039   |
| Error          | 18 | 56,054  |         |         |         |
| Lack-of-Fit    | 2  | 5895    |         | 0.94    | 0.411   |
| Pure Error     | 16 | 50,159  |         |         |         |
| Total          | 23 | 458,503 |         |         |         |

R-sq = 88%, R-sq(adj) = 84%, R-sq(pred) = 78%

For impact toughness, all main effects, as well two- and three-way interactions, were found significant, except ($t_c \times P_{au}$). For hardness, only the main effect of $T_c$, $t_c$, and $P_{au}$ had a significant effect. The $T_c$, $t_c$, and $P_{au}$ has also been indicated as significant curing parameters in the literature [20,22,27,36,44].

Table 4. ANOVA results for impact strength. It was observed that all main effects and three-way interactions were found significant ($p$-value < 0.05) for the impact toughness of the CFRP.

| Source         | DF | Adj SS  | Adj MS  | F-Value | p-Value |
|----------------|----|---------|---------|---------|---------|
| Model          | 7  | 722,798 | 103,257 | 304.35  | 0.000   |
| Linear         | 3  | 669,428 | 223,143 | 657.72  | 0.000   |
| $T_c$          | 1  | 135,233 | 135,233 | 398.60  | 0.000   |
| $t_c$          | 1  | 526,500 | 526,500 | 1551.88 | 0.000   |
| $P_{au}$       | 1  | 7,695   | 7,695   | 22.68   | 0.000   |
| 2-Way inter    | 3  | 44,813  | 14,938  | 44.03   | 0.000   |
| $T_c \times t_c$ | 1  | 38,837  | 38,837  | 114.47  | 0.000   |
| $T_c \times P_{au}$ | 1  | 5,812   | 5,812   | 17.13   | 0.001   |
| $t_c \times P_{au}$ | 1  | 0.165   | 0.165   | 0.49    | 0.496   |
| 3-Way inter    | 1  | 8,556   | 8,556   | 25.22   | 0.000   |
| $T_c \times t_c \times P_{au}$ | 1  | 8,556   | 8,556   | 25.22   | 0.000   |
| Error          | 16 | 5,428   | 0.339   |         |         |
| Total          | 23 | 728,226 |         |         |         |

R-sq = 99%, R-sq(adj) = 99%, R-sq(pred) = 98%
Table 5. ANOVA results for hardness. It was observed that only the main effect of \( T_c \), \( t_c \), and \( P_{au} \) had a significant effect on the hardness of the CFRP.

| Source    | DF | Adj SS | Adj MS | F-Value | p-Value |
|-----------|----|--------|--------|---------|---------|
| Model     | 3  | 361.37 | 120.456| 41.20   | 0.000   |
| Linear    | 3  | 361.37 | 120.456| 41.20   | 0.000   |
| \( T_c \) | 1  | 255.45 | 255.454| 87.37   | 0.000   |
| \( t_c \) | 1  | 82.51  | 82.51  | 28.22   | 0.000   |
| \( P_{au} \) | 1  | 23.4   | 23.404 | 8.00    | 0.010   |
| Error     | 20 | 58.48  | 2.924  |         |         |
| Lack-of-Fit | 4  | 14.25  | 3.561  | 1.29    | 0.316   |
| Pure Error | 16 | 44.23  | 2.765  |         |         |
| Total     | 23 | 419.85 |        |         |         |

R-sq = 86.1%, R-sq(adj) = 84%, R-sq(pred) = 80%

Equations (2)–(4) show the prediction model developed for tensile strength (\( TS \)), impact toughness (\( IT \)), and hardness (\( HD \)) of understudy CFRP. The equations adequacy was analyzed by a lack-of-fit test. The coefficient of determination, i.e., R-square (R-sq), adjusted R-square (R-sq(adj)), and predicted R-square (R-sq(pred)), are summarized in Tables 3–5. The lack-of-fit test shows the adequacy of the relationship between modeled curing parameters and responses/properties. The \( p \)-value of lack-of-fit is an indicator of the regression model adequacy. As the \( p \)-values of lack-of-fit for \( TS \), \( IT \), and \( HD \) are greater than 0.05, it shows that lack-of-fit is insignificant. In other words, prediction models are properly formulated, and the important parameters and their interaction terms are included. The R-sq, R-sq(adj), and R-sq(pred) of \( TS \), \( IT \), and \( HD \) equations show that the regression model describes the experimental values with good approximation. The validation of the regression models is appended in Appendix A to this article. Validation was carried out by selecting curing parameters other than those used in Table 2, and the regression models output was compared with that of experimental results [47].

\[
TS = 2970 - 19.58T_c - 32.05t_c + 182P_{au} + 0.2979T_c t_c - 1.266T_c P_{au} \quad (2)
\]
\[
IT = 180.6 - 2.098t_c - 1.575T_c - 23.98P_{au} + 0.01843T_c t_c + 0.18445T_c P_{au} + 0.2615P_{au} t_c - 0.00199T_c P_{au} t_c \quad (3)
\]
\[
HD = -6.27 + 0.3263T_c + 0.1236t_c + 0.494P_{au} \quad (4)
\]

Adequacy of ANOVA depends upon normal distribution and constant variance of residuals for each response/property. The normal probability plots of residuals for each property (\( TS \), \( IT \), and \( HD \)) are shown in Figure 7a–c, respectively. For all responses, the residuals data fall near the fitted line, which indicates a normal distribution of the data. Further, the normal distribution of the residuals is validated by Ryan–Joiner (RJ) normality test. A \( p \)-value of the test greater than the alpha value of 0.05 shows that the data follow a normal distribution. As the \( p \)-value of the RJ test for \( TS \), \( IT \), and \( HD \) are greater than 0.05, it further supports the assumption that residuals are normally distributed. The residuals are spread randomly above and below the fitted line for all responses with no recognizable patterns (uneven distribution and curve patterns), therefore it also satisfies the assumption of constant variance of the data points (Figure 8a–c).
Figure 7. Normal probability plot of residuals for (a) tensile strength, (b) impact toughness, and (c) hardness data. p-values > 0.05 indicate that residuals are normally distributed.

Figure 8. Residuals of properties vs. fitted value for (a) tensile strength, (b) impact toughness, and (c) hardness data. The uneven distribution indicates the constant variance of the data points.
3.2. Surface Plots

The surface plot conveniently expresses the relationship between curing parameters and responses/properties. The surface plots between properties (TS, IT, and HD) and curing parameters (Tc, tC, and Pau) were generated based upon regression Equations (2)–(4). There are three curing parameters for each of the properties. Therefore, two surface plots were drawn for each of the properties at two constant values of Pau (3 and 7 bar), to elaborate the complete behavior of each property.

3.2.1. Optimum Tensile Strength

The experimental results of the understudy CFRP tensile strength (Table 2) were transformed into regression Equation (2) and surface plots (Figure 9). Equation (2) was used to predict TS within the upper and lower limit of curing parameters (Tc, tC, and Pau).

The two surface plots of tensile strength at constant Pau of 3 and 7 bar are shown in Figure 9. It was observed from the surface plots of Figure 9b that the MRCC resulted in tensile strength of 1274.8 MPa at CC7 (120 °C, 120 min, 7 bar), whereas the enhanced tensile strength of 1420 MPa was achieved at CC8 (140 °C, 120 min, 7 bar) in our study. With increasing Tc, more epoxide rings of the CFRP matrix open and larger molecules are formed [48], giving rise to a higher degree of cross-linking [49]. During cross-linking, the unordered amorphous state of the CFRP matrix transforms into an ordered glassy state which results in a higher tensile strength [49,50] of the epoxy matrix. On the contrary, for insufficiently high values of Tc, matrix resin would not cure fully, resulting in reduced mechanical properties [51]. As we used a high Tc of 140 °C (equal to Tg∞), an increase of 11.4% in strength was observed as compared to the tensile strength at MRCC. The result of optimal curing parameters along with optimum tensile strength is summarized in Table 6.

Table 6. A comparative summary of non-optimum and optimum properties. This table compares MRCC (non-optimal) curing parameters and non-optimum properties with optimal curing parameters and optimum properties.

| Properties       | Non-Optimal Curing Parameters | Non-Optimum Properties | Optimal Curing Parameters | Optimum Properties | Improvement (%) |
|------------------|-------------------------------|------------------------|---------------------------|--------------------|-----------------|
| Tensile Strength | 120 °C, 120 min, 7 bar (MRCC/CC7) | 1274.8 MPa             | 140 °C, 120 min, 7 bar (CC8) | 1420 MPa           | 11.4%           |
| Impact Toughness | 10.9 J                        |                        | 140 °C, 120 min, 3 bar (CC4) | 17.4 J             | 59.6%           |
3.2.2. Optimum Impact Toughness

Similar to the experimental results of understudy CFRP tensile strength, the results of impact toughness (Table 2) were transformed into regression Equation (3) and the surface plots (Figure 10). This equation and the surface plot were used to predict impact toughness within the upper and lower limit of curing parameters ($T_c$, $t_c$, and $P_{au}$) of experiments.

Figure 10. Surface plots of impact toughness (IT) at a constant pressure of (a) 3 bar; (b) 7 bar. The optimum impact toughness was observed at CC4 (140 °C, 120 min, 3 bar), represented by a black dot.

It was observed from the surface plots of Figure 10b that MRCC produced an average impact toughness of 10.9 J. However, the maximum impact toughness of 17.4 J was produced at CC4 (140 °C, 120 min, 3 bar), as shown in Figure 10a. Unlike the result of the maximum tensile strength, the maximum impact toughness was achieved at a different set of curing parameters. The increased void and resin content of the CFRP matrix at lower $P_{au}$ (3 bar) was the likely reason for the maximum impact toughness. The increased void content, at lower $P_{au}$ promotes multiple cracking mechanisms, which raises the impact toughness of CFRP [11,20,52]. The higher impact toughness is related to a higher Mode I and II interlaminar crack growth resistance due to multiple crack failure mechanisms as a result of increased void contents at lower $P_{au}$ [9,11]. This improves the structural integrity and damage tolerance of the material, which is a fundamental requirement for material used in aircraft. As we used a smaller cure $P_{au}$ value of 3 bar, an increase of 59.6% in impact toughness was observed, as compared to the impact toughness at MRCC. A similar set of values of impact toughness (5–13 J) has been observed for CFRP laminate in the literature [33]. The summary of optimal curing parameters along with optimum impact toughness is provided in Table 6.

3.2.3. Optimum Hardness

The experimental results of the understudy CFRP hardness (Table 2) were transformed into regression Equation (4) and the surface plot (Figure 11). The equation and the surface plot were used to predict hardness within the upper and lower limit of curing parameters ($T_c$, $t_c$, and $P_{au}$) of experiments.

The MRCC (120 °C, 120 min, 7 bar) produced a hardness of 51.2 HRB, whereas the maximum hardness of 57.6 HRB was observed at CC8 (140 °C, 120 min, 7 bar) (Figure 11b). A similar trend of increasing hardness with an increase in either $T_c$ or $t_c$ is found in the literature for CFRP [21]. Both tensile strength and hardness were maximum at the same
curing condition, i.e., CC8. Hardness is resistant to plastic deformation and is somewhat related to the highest point in the stress–strain curve. Since both tensile strength and hardness address the same physical phenomenon, maximum hardness was also observed under the same curing conditions as tensile strength. As we used a higher \( T_c \) of 140 °C, an increase of 12.5% in hardness was observed, as compared to hardness at MRCC. The result of optimal curing parameters along with optimum hardness is summarized in Table 6.

![Figure 11](image_url)

**Figure 11.** Surface plots of hardness (HD) at a constant pressure of (a) 3 bar; (b) 7 bar. Hardness was observed to increase with temperature, time, and pressure. The optimum hardness was observed at CC8 (140 °C, 120 min, and 7 bar), represented by a black dot.

### 3.3. Multi-Response Optimization of CFRP Mechanical Properties

The outcome of experimental results shows that maximum tensile strength and impact toughness was achieved at two different CCs. To solve such issues of multiple responses, the desirability function was introduced by Harrington [41]. Derringer and Suich [39] further modified the concept later and suggested using a composite desirability function to solve multiple response optimization problems [10,40,54–56]. According to this approach, each of the properties was converted into an individual desirability value “\( d_i \)” which varied over a range of 0 to 1, \( 0 \leq d_i \leq 1 \). The value of \( d_i \) increased with the desirability of the corresponding property. For the maximization of three properties (tensile strength, impact toughness, and hardness), Equation (5) was used to calculate the desirability of an individual property.

\[
d_i = \begin{cases} 
0; & y_i < L \\
\left(\frac{y_i - L}{T - L}\right)^{w_i}; & L \leq y_i \leq T \\
1; & y_i > T 
\end{cases} 
\]  

(5)

where

- \( d_i \) is the desirability of an individual response,
- \( y_i \) is the actual property value,
- \( L \) is the lower bound of the property,
- \( T \) is the target property value,
- \( w_i \) is the weight of the desirability function.

The individual desirability \( d_i \) was then combined by using the geometric mean, as expressed in Equation (6):

\[
D = \left(\prod_{i=1}^{n} d_i\right)^{\frac{1}{n}}
\]  

(6)

where

- \( D \) is the composite desirability,
- \( n \) is the number of responses.

The results are summarized in Table 7. The highest desirability values obtained for \( TS \) are at CC8 (140 °C, 120 min, 7 bar), i.e., 1.064, and 0.964, with the maximum \( TS \) of 1420 MPa. For \( IT \), the highest desirability values are at CC4 (140 °C, 120 min, 3 bar), i.e., 1, 0.947, and 0.977, with the maximum \( IT \) of 17.4 J. For hardness, optimal CC was found to
be the same as for $TS$, with desirability values of 1, 0.894, and 0.750. The maximum $HD$ value obtained at optimal CC8 is 57.6 HRB. Optimization of $TS$ and $IT$ at different CCs is consistent with the findings of Odian and d’Almeida [49,50].

Table 7. Desirability and composite desirability values of the three responses. The highest desirability value of $IT$ was observed at CC4, whereas the highest desirability value of TS, HD and composite desirability values were observed at CC8 (represented by bold letters).

| CCs | Desirability Value of $TS$ | Desirability Value of $IT$ | Desirability Value of $HD$ | Composite Desirability Value |
|-----|--------------------------|---------------------------|---------------------------|------------------------------|
| 1   | 0.008                    | 0.002                     | 0.075                     | 0.000                        |
| 1   | 0.091                    | 0.000                     | 0.213                     | 0.000                        |
| 2   | 0.047                    | 0.007                     | 0.000                     | 0.000                        |
| 2   | 0.103                    | 0.077                     | 0.475                     | 0.001                        |
| 2   | 0.277                    | 0.222                     | 0.369                     | 0.008                        |
| 3   | 0.237                    | 0.098                     | 0.338                     | 0.003                        |
| 3   | 0.000                    | 0.368                     | 0.225                     | 0.000                        |
| 3   | 0.249                    | 0.310                     | 0.213                     | 0.005                        |
| 3   | 0.451                    | 0.397                     | 0.419                     | 0.025                        |
| 4   | 0.798                    | 0.976                     | 0.713                     | 0.185                        |
| 4   | 0.929                    | 0.946                     | 0.606                     | 0.178                        |
| 4   | 0.846                    | 1.000                     | 0.706                     | 0.199                        |
| 5   | 0.170                    | 0.062                     | 0.044                     | 0.000                        |
| 5   | 0.336                    | 0.044                     | 0.275                     | 0.001                        |
| 5   | 0.265                    | 0.051                     | 0.225                     | 0.001                        |
| 6   | 0.423                    | 0.181                     | 0.506                     | 0.013                        |
| 6   | 0.130                    | 0.223                     | 0.519                     | 0.005                        |
| 6   | 0.016                    | 0.224                     | 0.663                     | 0.001                        |
| 7   | 0.403                    | 0.570                     | 0.213                     | 0.016                        |
| 7   | 0.751                    | 0.358                     | 0.294                     | 0.041                        |
| 7   | 0.706                    | 0.625                     | 0.450                     | 0.066                        |
| 8   | 1.000                    | 0.909                     | 0.894                     | 0.271                        |
| 8   | 0.941                    | 0.946                     | 0.750                     | 0.222                        |
| 8   | 0.964                    | 0.895                     | 1.000                     | 0.288                        |

* MRCC/CC7.

To overcome the issue of two different optimal CC, and simultaneous optimization of mechanical properties, the concept of composite desirability was applied using Equation (6). The results are tabulated in Table 7.

There were two CCs at which maximum properties were achieved, i.e., CC4, where maximum $IT$ was achieved, and CC8, where maximum $TS$ and $HD$ were achieved. Hence, the composite desirability function at these two CCs was compared. The largest composite desirability values (i.e., 0.271, 0.222, and 0.288 (avg = 0.260)) were obtained at CC8, with $TS$ of 1420 MPa, $IT$ of 16.5 J, and $HD$ of 57.6 HRB. The summary of the composite desirability function is appended in Table 8.

Table 8. Composite desirability function value for two options of CCs.

| Option | $T_c$ (°C) | $t_c$ (min) | $P_{au}$ (bar) | Tensile Strength (MPa) | Impact Toughness (J) | Hardness (HRB) | Average Composite Desirability |
|--------|------------|-------------|----------------|------------------------|----------------------|---------------|-------------------------------|
| CC8    | 140        | 120         | 7              | 1420 $^{\dagger\dagger}$ | 16.5 $^\dagger$     | 57.6 $^{\dagger\dagger}$ | 0.260                         |
| CC4    | 140        | 120         | 3              | 1400                   | 17.4 $^\dagger$      | 55.7          | 0.187                         |

* Optimal CC. $^\dagger$ Optimum property. $^{\dagger\dagger}$ Maximum property.

4. Conclusions

The experimental work resulted in improved properties at the designed CC8, as compared to properties observed at MRCC/CC7. The $TS$ and $HD$ were maximized to
1420 MPa (11.4% improvement) and 57.6 HRB (12.5% improvement) when cured at CC8 (140 °C, 120 min, 7 bar), but the IT was maximized to 17.4 J (59.6% improvement) at CC4 (140 °C, 120 min, 3 bar).

Due to the detection of two different optimal CC (CC4 and CC8) for optimum properties (TS, IT, and HD), a composite desirability function was used to determine simultaneous optimum properties. The composite desirability function yielded TS of 1420 MPa, IT of 16.5 J, and HD of 57.6 HRB as optimum properties at CC8 as optimal CC for understudy CFRP, suitable for aircraft skin application.

The statistical analysis (ANOVA) concluded that \( T_c \) and \( t_c \) are the most significant curing parameters for influencing TS, IT, and HD of CFRP.

5. Future Work

The porosity in the CFRP has a remarkable effect on the tensile strength, impact toughness, and hardness as well the Mode I and II interlaminar crack growth resistance of CFRP laminate. For aerospace application, structural integrity and damage tolerance of the used material matters a lot. It is therefore suggested to include microstructural analysis of CFRP laminate to validate the effect of porosity on the understudy properties of CFRP.

Author Contributions: Conceptualization, F.A. and M.A.A.; methodology, F.A. and M.A.A.; software, M.A.; validation, M.A.; formal analysis, F.A. and M.A.; investigation, F.A.; resources, S.N.; data curation, F.A.; writing-original draft preparation, F.A.; writing-review and editing, A.H.; visualization, M.A.A.; supervision, S.N.; project administration, S.N.; funding acquisition, S.N. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by King Khalid University of Saudi Arabia grant number RGP2/163/43.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Acknowledgments: The authors extend their appreciation to the Deanship of Scientific Research, the King Khalid University of Saudi Arabia, for funding this work through the General Research Project under grant number (RGP2/163/43).

Conflicts of Interest: The authors declare no conflict of interest.

Acronyms

- CFRP: Carbon fiber reinforced plastic
- PMC: Polymer matrix composite
- DGEBA: Di-glycidyl ether of bisphenol A
- DOE: Design of experiments
- RSM: Response surface methodology
- ANN: Artificial neural networking
- UD: Uni-directional
- ANOVA: Analysis of variance
- \( \alpha \): Significance level
- CC: Curing cycle
- MRCC: Manufacturer-recommended cure cycle
- Adj SS: Adjusted sum of squares
- Adj MS: Adjusted mean of squares
- DF: Degree of freedom
- \( p \)-value: Probability value
Appendix A

Model Validation

The experimental work for this research work was carried out in two phases. In Phase I, limited experiments were carried out by selecting curing parameters $T_c$, $t_c$, and $P_{au}$ in the light of the literature review. Based upon the outcome of Phase I experiments, and knowledge available in the literature, DOE was finalized to conduct Phase II experiments. Validation of the regression model was carried out by using Phase I experiment data and comparing the results with those of regression models [47]. The experimental error found between regression and Phase I experimental results varied between 2.1 to 5.9%, (Table A1) which is within acceptable experimental error.

Table A1. Comparison of Phase I experiments result with the regression model. The percentage of experimental error was found between 2.02 to 5.87%, which is an acceptable error.

| Curing Parameters | Regression Results | Experimental Results | % Experimental Error |
|-------------------|--------------------|----------------------|---------------------|
| Phase I CC | $T_c$ (°C) | $t_c$ (min) | $P_{au}$ (bar) | Tensile Strength (MPa) | Impact Toughness (J) | Hardness (HRB) | Tensile Strength (MPa) | Impact Toughness (J) | Hardness (HRB) |
| 1 | 130 | 100 | 4 | 1161.98 | 6.75 | 50.48 | 1122.56 | 6.91 | 52.84 | 4.25 | 2.30 | 4.66 |
| 2 | 130 | 100 | 5 | 1179.40 | 7.03 | 50.97 | 1204.56 | 6.89 | 52.06 | 2.13 | 2.02 | 2.12 |
| 3 | 130 | 100 | 6 | 1196.82 | 7.31 | 51.47 | 1216.51 | 7.11 | 49.57 | 5.87 | 2.74 | 3.69 |
| 4 | 135 | 110 | 4 | 1269.37 | 11.41 | 53.35 | 1211.21 | 11.04 | 56.37 | 4.58 | 3.30 | 5.65 |
| 5 | 135 | 110 | 5 | 1280.46 | 11.55 | 53.84 | 1214.59 | 11.2 | 51.85 | 5.14 | 3.04 | 3.70 |
| 6 | 135 | 110 | 6 | 1291.55 | 11.68 | 54.34 | 1333.58 | 12.15 | 52.62 | 3.23 | 3.97 | 3.16 |
| 7 | 140 | 120 | 4 | 1405.56 | 17.12 | 56.22 | 1335.79 | 16.34 | 54.81 | 3.53 | 4.60 | 2.50 |
| 8 | 140 | 120 | 5 | 1413.32 | 16.91 | 56.71 | 1347.65 | 16.46 | 53.99 | 4.51 | 2.71 | 4.80 |
| 9 | 140 | 120 | 6 | 1416.08 | 16.71 | 57.20 | 1460.18 | 17.47 | 59.57 | 3.11 | 4.54 | 4.12 |

References
1. Chandrathilaka, E.; Gamage, J.; Fawzia, S. Mechanical characterization of CFRP/steel bond cured and tested at elevated temperature. Compos. Struct. 2018, 207, 471–477. [CrossRef]
2. Kim, K.W.; Kim, D.K.; Kim, B.S.; An, K.H.; Park, S.J.; Rhee, K.Y.; Kim, B.J. Cure behaviors and mechanical properties of carbon fiber-reinforced nylon6/epoxy blended matrix composites. Compos. Part B Eng. 2017, 112, 15–21. [CrossRef]
3. Nayak, N.V. Composite Materials in aerospace applications. Int. J. Sci. Res. Publ. 2014, 4, 1–10.
4. Yu, Z.; Li, R.; Peng, Z.; Tang, Y. Carbon Fiber Reinforced Epoxy Resin Matrix Composites. Mater. Sci. Adv. Compos. Mater. 2017. [CrossRef]
5. Mrazova, M. Advanced composite materials of the future. INCAS Bull. 2013, 5, 139–150.
6. Kalanchiam, M. Advantages of composites materials in aircraft structures. Int. J. Aerosp. Mech. Eng. 2012, 6, 2428.
7. Young, W.C.; Budynas, R.G. Roark's Formulas for Stress and Strains, 7th ed.; McGraw Hill: New York, NY, USA, 2002.
8. Niu, M.C.Y. Airframe Stress Analysis and Sizing, 2nd ed.; Hong Kong Conmilit Press Ltd.: Hong Kong, 1999.
9. Cantwell, W.; Morton, J. The impact resistance of composite materials—A review. Composites 1991, 22, 347–362. [CrossRef]
10. Hong, S.W.; Ahn, S.S. Charpy impact fracture characteristics of CFRP composite materials according to variations of fiber array direction and temperature. Int. J. Precis. Eng Manuf. 2013, 14, 253–258. [CrossRef]
11. Hou, M.; Ye, L.; Mai, Y.-W. Effect of Moulding Temperature on Flexure, Impact Strength and Interlaminar Fracture Toughness of CF/PEI Composite. J. Reinf. Plast. Compos. 1996, 15, 1117–1130. [CrossRef]
12. Gao, L.; Zhang, Q.; Guo, J.; Li, H.; Wu, J.; Yang, X. Effects of the amine/epoxy stoichiometry on the curing behavior and glass transition temperature of MWCNTs-NH2/epoxy nanocomposites. Thermochim. Acta 2016, 639, 98–107. [CrossRef]
13. Fu, Y.; Zhong, W.-H. Cure kinetics behavior of a functionalized graphitic nanofiber modified epoxy resin. *Thermochim. Acta* **2011**, *516*, 58–63. [CrossRef]

14. Johnson, J.B.; Owston, C.N. The Effect of Cure Cycle on the Mechanical Properties of CFRP. *Composites** **1973**, *4*, 111–117. [CrossRef]

15. Esposito, L.; Sorrentino, L.; Penta, F.; Bellini, C. Effect of curing overheating on interlaminar shear strength and its modelling in thick FRP laminates. *Int. J. Adv. Manuf. Technol.** **2016**, *87*, 2213–2220. [CrossRef]

16. Boey, F.; Lye, S. Void reduction in autoclave processing of thermoset composites: Part 2: Void reduction in a microwave curing process. *Composites** **1992**, *23*, 266–270. [CrossRef]

17. Guo, Z.-S.; Liu, L.; Zhang, B.-M.; Du, S. Critical Void Content for Thermoset Composite Laminates. *J. Compos. Mater.** **2006**, *43*, 1775–1790. [CrossRef]

18. Olivier, F.; Cottu, J.P.; Ferret, B. Effects of cure cycle pressure and voids on some mechanical properties of carbon/epoxy laminates. *Compos. Part A. Appl. Sci. Manuf.** **1995**, *26*, 500–515.

19. Li, W. Effect of Cure Pressure on Woven Carbon Fibre Epoxy Composite. Ph.D. Thesis, The University of New South Wales, Sydney, Australia, 2003.

20. Davies, L.; Day, R.; Bond, D.; Nesbitt, A.; Ellis, J.; Gardon, E. Effect of cure cycle heat transfer rates on the physical and mechanical properties of an epoxy matrix composite. *Compos. Sci. Technol.** **2007**, *67*, 1892–1899. [CrossRef]

21. Pittroff, R.R. Relationship between the Physical Properties and Curing System of an Epoxy Matrix. Master’s Thesis, Tshwane University of Technology, Pretoria, South Africa, 2007.

22. Seretis, G.; Kouzilos, G.; Manolakos, D.; Provatidis, C. Multi-Objective Curing Cycle Optimization for Glass Fabric/Epoxy Composites Using Poisson Regression and Genetic Algorithm. *Mater. Res.** **2018**, *21*. [CrossRef]

23. Sultania, M.; Rai, J.; Srivastava, D. Process modeling, optimization and analysis of esterification reaction of cashew nut shell liquid (CNSL)-derived epoxy resin using response surface methodology. *J. Hazard. Mater.** **2011**, *185*, 1198–1204. [CrossRef]

24. Kumar, D.S.; Shukla, M.J.; Mahato, K.K.; Rathore, D.; Prusty, R.K.; Ray, B.C. Effect of post-curing on thermal and mechanical behavior of GFRP composites. *IOP Conf. Ser. Mater. Sci. Eng.** **2015**, *75*, 012012. [CrossRef]

25. Aruniit, A.; Jaan, K.E.R.S.; Krumme, A.; Poltimäe, T.; Kaspar, T.A.L.L. Preliminary Study of the Influence of Post Curing Parameters to the Particle Reinforced Composite’s Mechanical and Physical Properties. *Mater. Sci.** **2021**, *18*, 256–261. [CrossRef]

26. Khan, L.A. Cure Optimization of 977-2A Carbon/Epoxy Composites for Quickstep Processing. Ph.D. Thesis, The University of Manchester, Manchester, UK, 2010.

27. Alavi, S. Thermal, Rheological, and Mechanical Properties of a Polymer Composite Cured at Staged Cure Cycles. Ph.D. Thesis, Wichita State University, Wichita, KS, USA, 2010.

28. Nele, L.; Caggiano, A.; Teti, R. Autoclave Cycle Optimization for High Performance Composite Parts Manufacturing. *Procedia CIRP** **2016**, *57*, 241–246. [CrossRef]

29. Tang, J.M.; Lee, W.I.; Springer, G.S. Effects of cure pressure on resin flow, voids, and mechanical properties. *J. Compos. Mater.** **1987**, *21*, 421–440. [CrossRef]

30. Campbell, F. *Manufacturing Processes for Advanced Composites*; Elsevier Advanced Technology: London, UK, 2004. [CrossRef]

31. Hamdan, B.; Lafi, S.; Hassan, N.M. Optimizing the Manufacturing Processes of Carbon Fiber Epoxy Resin Composite Panels. *J. Manuf. Sci. Eng.** **2017**, *140*, 011003. [CrossRef]

32. Fukunaga, H.; Vanderplaats, G. Strength optimization of laminated composites with respect to layer thickness and/or layer orientation angle. *Comput. Struct.** **1991**, *40*, 1429–1439. [CrossRef]

33. Singh, S.; Vummadisetti, S.; Chawla, H. Influence of curing on the mechanical performance of FRP laminates. *J. Build. Eng.** **2018**, *16*, 1–19. [CrossRef]

34. Xiao, G.; Zhu, Z. Friction materials development by using DOE/RSM and artificial neural network. *Tribol. Int.** **2010**, *43*, 218–227. [CrossRef]

35. Parida, K.A.; Routara, B.C.; Bhuyan, R.K. Surface roughness model and parametric optimization in machining of GFRP composite Taguchi and Response surface methodology approach. *Mater. Today.** **2015**, *2*, 3065–3074. [CrossRef]

36. Pelletier, J.L.; Vel, S.S. Multi-objective optimization of fiber reinforced composite laminates for strength, stiffness and minimal mass. *Comput. Struct.** **2006**, *84*, 2065–2080. [CrossRef]

37. Ghosal, A.; Manna, A. Response surface method based optimization of ytterbium fiber laser parameter during machining of Al/Al2O3-MMC. *Opt. Laser Technol.** **2013**, *46*, 67–76. [CrossRef]

38. Casalino, G.; Campanelli, S.L.; Contuzzi, N.; Ludovico, A.D. Experimental investigation and statistical optimization of the selective laser melting process of a maraging steel. *Opt. Laser Technol.** **2015**, *65*, 151–158. [CrossRef]

39. Derringer, G.; Suich, R. Simultaneous Optimization of Several Response Variables. *J. Qual. Technol.** **1980**, *12*, 214–219. [CrossRef]

40. Deeying, J. Multi-objective optimization on laser solder jet bonding process. *Opt. Laser Technol.** **2018**, *98*, 158–168. [CrossRef]

41. Harrington, E.C. The desirability function. *Ind. Qual. Control** **1965**, *21*, 494–498.

42. Pasandideh, S.H.R.; Niaki, S.T.A. Multi-response simulation optimization using genetic algorithm within desirability function framework. *Appl. Math. Comput.** **2005**, *175*, 366–382. [CrossRef]

43. Dave, R.S. *Processing of Composites*; Hanser Publishers: Munich, Germany, 2000.

44. Aronhime, M.T.; Gillham, J.K. Time-Temperature-Transformation (TTT) cure diagram a review. *Polymer** **1986**, *78*, 83–113.

45. Hernández, S.; Sekt, F.; González, C.; Lorca, J.L. Optimization of curing cycle in carbon fiber-reinforced laminates: Void distribution and mechanical properties. *Compos. Sci. Technol.** **2013**, *85*, 73–82. [CrossRef]
46. Ogunleye, O.; Salawudeen, T.; Suleyman, M.; Faridah, Y. Optimization of process parameters for enhanced mechanical properties of polypropylene ternary nanocomposites. *Adv. Sci. Technol. Res. J.* 2015, 9, 27–33. [CrossRef]
47. Snee, R.D. Experimental Designs for Quadratic Models in Constrained Mixture Spaces. *Technometrics* 1975, 17, 149. [CrossRef]
48. Sun, L.; Pang, S.S.; Sterling, A.M.; Negulescu, I.I.; Stubblefield, M.A. Thermal analysis of curing process of epoxy prepreg. *J. Appl. Polym. Sci.* 2002, 83, 1074–1083. [CrossRef]
49. Odian, G. *Principles of Polymerization*, 3rd ed.; John Wiley and Sons: New York, NY, USA, 1991.
50. D’Almeida, J.; Monteiro, S. The effect of the resin/hardener ratio on the compressive behavior of an epoxy system. *Polym. Test.* 1996, 15, 329–339. [CrossRef]
51. Koushyar, H. Effects of Variation in Autoclave Pressure Cure Temp and Vacuum Application Time on Porosity and Mechanical Properties of Carbon Epoxy Composite. Master’s Thesis, Wichita State University, Wichita, KS, USA, 2011.
52. Asp, L.; Brandt, F. Effects of pores and voids on the interlaminar delamination toughness of a carbon/epoxy composite. Presented at the Paper presented at 11th International Conference on Composite Materials, Gold Coast, Australia, 14–18 July 1997.
53. Morioka, Y.T.K. Effect of lay-up sequences on mechanical properties and fracture behavior of CFRP laminate composites. *Mater. Charact.* 2000, 45, 125–136. [CrossRef]
54. Myers, R.H.; Montgomery, D.C. *Response Surface Methodology*, 3rd ed.; John Wiley and Sons: Hoboken, NJ, USA, 2009.
55. Kataria, R.; Kumar, J. A comparison of the different multiple response optimization techniques for turning operation of AISI O1 tool steel. *J. Eng. Res.* 2014, 2, 1–24. [CrossRef]
56. del Castillo, E.; Montgomery, D.C.; McCarville, D.R. Modified desirability functions for multiple response optimization. *J. Qual. Technol.* 1996, 28, 337–345. [CrossRef]