A study of delamination characteristics (drilling) on carbon fiber reinforced IPN composites during drilling using design experiments

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Abstract. The aim of this entire research approach is to produce the damage free drilling operation on the IPN composites by selecting the suitable cutting parameters. The standard combinations of polyurethane and vinyl ester resins were used as the matrix material to fabricate the IPN composite laminate with carbon reinforcement. To expedite this, the analysis of variance (ANOVA) and taguchi combination method was used. Based on the technique proposed in taguchi, the plan of experiments had been carried out, by opting the variant process parameters of the drilling; similarly, ANOVA was used to determine the drilling characteristics of the IPN laminate (carbon fiber) of various drill bits like Helical flute, Four-flute, Helical flute – K12 drill bits. The main objective upon doing this experiment was that, to establish the finest correlation between the feed rate and cutting velocity as the output of delamination in IPN laminate, by precisely choosing the multi linear regression analysis. At last, the evaluation tests were carried out to compare the obtained result with correlated analysis, as well it had shown significant agreement with each other.

Keywords: Drilling, IPN composites, Vinyl ester, polyurethane, analysis of variance, delamination.

1. Introduction
Now a day’s composite material have become the replaceable material in our day to day life in all sector of engineering industries which starts from sports to defense utility vehicles. Despite the cost associated to manufacture the composite material is comparatively high as compared with the conventional metallic material, still it is considered as the predominant thriving material in all the sectors since it possess the very good weight to stiffness ratio, corrosion resistance, abrasion resistance and chemical resistance. Especially the usage of the composite material in aerospace industries have become as the irreplaceable one, most of the aerospace sectors have started to employ the composite material instead of the conventional duralumin material. Moreover it explicitly satisfies the need of the
engineers in replacing the metallic material in peculiarly aerospace industries. Even the defence sectors have started to use the composite material in building of army tank manufacturing because of its extended tailor made quality [1-2].

However the manufacturing of the composite material in the view to replace the individual components and assembling the same for getting the unified or assembled component needs sophisticated technology and skilled man power employment. Many of the beginners are frequently tried to find out the different manufacturing technology to overcome the assembling issue which frequently encountered to get the assembled or final component. Since naturally the composite material possess the brittleness nature and anisotropic property, machining of composite material become as become as the hectic task for the production peoples. Usually, drilling of the laminate is universally accepted and proposed towards achieving the assembled component rather than adopting the composite machining. Whereas, while performing the drilling operation delamination issue on the edges of the laminate during insert and exit, has become as the unwanted issue in most of the fiber reinforced composite [3-4].

Furthermore the superior reinforcement materials like carbon fiber and glass fiber as well encountering such a defect during the drilling operation of the laminates. Most of the researchers have pointed out that the tool geometry and tool materials are playing the vital role in getting the final un-delaminated composite plate. The common defects encountered during drilling operations are fiber pullout, thermal damage and cratering, among all, delamination has been treated as the most critical affecting parameter during drilling operation. Many of the researchers have comprehensively approached this above issues in detailed manner in the view to uphold negative issues encountered during drilling operation. It was also observed that, the defect free drilling operations are also possible on the laminate by choosing the exact feed and cutting speed. In spite of all the issues, still fabricators face the issue of delamination in the entry and exit points of the drilling operations, as well still this issue has not been completely sorted out in composite laminates [5-6].

In this work, by taking all the issues encountered in the conventional drilling operations of the fiber reinforced polymer laminates upon usage of common resin material, new approach has been initiated upon choosing the interpenetrating polymer network as the matrix material, along with the carbon fiber reinforcement. The carbon fiber reinforced IPN laminate was subjected with the drilling operation in order to validate the delamination defects which is been commonly encountered in the traditional composite material. The blends of vinyl ester and polyurethane resins have been chosen as the matrix material along with the carbon fiber, by adopting the common fabricating technique called hand lay up technique. Analysis of variance method was executed to do the trail experiments, following which taguchi correlation method was used to evaluate the obtained values during the drilling operation [7-8].

2. Materials and methods

2.1. Materials

The carbon fiber was employed as the reinforcement agent in this work, purchased from sakthi fibers Chennai as shown in figure 1. Similarly the used resins are vinyl ester and polyurethane, which was also procured from vasavi bala resins, Chennai. All the resins were used as such purchased from the dealer without any purification process [9].

2.2. Fabrication methodology

The exact proportionate of vinyl ester and polyurethane was used as the matrix material in this work. Initially the mixture was thoroughly mixed and their corresponding accelerator, promoter and catalyst were added into it. The already cut carbon fabric with density of 350 gsm was placed over the poly vinyl alcohol (PVA) coated surface, and carbon fabric was wet with help of the brush, subsequently six layers of the fabric were positioned one over the another in order to obtain the 4 mm thickness of the IPN laminate [10].
After completion of this procedure, the entire laminate was allowed to be in the ambient temperature for the time of 24 hours, following that, kept the same in the hot air oven in order to insure the complete covalent bond formation in the matrix material (2 hours) by maintaining the temperature of 70 deg to achieve the complete covalent bond in the IPN laminate.

2.3. Experimental procedure

The experiments had been studied over the IPN laminate, which consists of 6 layers with thickness of the 4 mm. The drill bits used in this study were Helical flute, four-flute and helical flute drill – K12 as per the ASTM standards. The drilling machine with 3 kW of spindle power, as well with highest spindle speed of 3000 rpm had been employed to do these experiments, besides that, to do the drilling operation standard drill size of 112° point angle was used. The laminate was very firmly fixed on the fixture to avoid the unnecessary movements during the drilling operation, as well as to make sure the vibration was completely arrested. Three cutting parameters like speed, feed rate, cutting velocity were chosen based on the previous work done by the many researchers. Moreover these parameters are the primary and predominant parameter which determines the output of the operation, like surface finish and timing required to complete the operation. Once the holes had been produced on the IPN laminate, the damages aroused around the laminate were measured with help of the microscope with 5 micro meter resolution [11-13].

2.4. Taguchi technique – plan of experiments

Most of the engineering problems with having the notable investigation, have been easily solved with help of the taguchi technique with controlled way; also it was approved as the easy method, to choose the no of experimental trails and to execute the experimental analysis. Similarly the analysis of variance was used to carry out analysis on the experimentally obtained data’s. While using the taguchi, two factors with three level methodologies were used in the study. The detailed factor level studies and assignment of corresponding levels were given in the table 1. The L9 array was chosen in this study, which normally has 9 rows with 8 degrees of freedom with 3 levels, which shown in the table 2. Actually nine tests of experiment was planned, out of which first column was assigned to cutting velocity (V), second column to feed rate (f) and remaining all were assigned for the interactions. The response was delamination factor (Fd) in IPN laminate [14-15].
3. Results and discussion

3.1. Effect of cutting parameters in the delamination factor

Table 1. Assigning of levels to factors

| Level | Speed (N) (rpm) | Feed rate (f) (mm/rev) | Cutting velocity (V) (m/min) |
|-------|-----------------|------------------------|-----------------------------|
| 1     | 1200            | 0.06                   | 18                          |
| 2     | 1700            | 0.10                   | 26                          |
| 3     | 2200            | 0.16                   | 34                          |

Table 2. Orthogonal array (L9) of taguchi

| L9 (2^4) Test | 1 | 2 | 3 | 4 |
|---------------|---|---|---|---|
| 1             | 1 | 1 | 1 | 1 |
| 2             | 1 | 2 | 2 | 2 |
| 3             | 1 | 3 | 3 | 3 |
| 4             | 2 | 1 | 2 | 3 |
| 5             | 2 | 2 | 3 | 1 |
| 6             | 2 | 3 | 1 | 2 |
| 7             | 3 | 1 | 3 | 2 |
| 8             | 3 | 2 | 1 | 3 |
| 9             | 3 | 3 | 2 | 1 |

After the hole was drilled into the IPN laminate successfully, the damage around the hole was calculated using the microscope, and the same was presented in the figure 2.

![Damage](image)

Figure 3. Scheme of the measurement of maximum diameter (Dmax)

The value of delamination factor (Fd) was calculated ratio on the value measured on the drilled hole (Dmax,) to actual drill size (D), in this study, initially the drilled hole size was measured by the microscope which was noted as the measured value (Dmax,), similar kind of drilling was been done on the entire surface of the IPN laminate with the same drill bit and their corresponding Dmax values were also measured with the microscope, in order to find out the delamination factor (Fd).

Table 3. Delamination factor with respect of velocity and feed rate

| Test | V (m/min) | f (mm/rev) | Helical flute drill | Four-flute drill | Helical flute drill – K12 |
|------|-----------|------------|---------------------|------------------|----------------------------|
| 1    | 0.06      | 1.052      | 1.062               | 1.050            |
| 2    | 0.10      | 1.062      | 1.071               | 1.058            |
| 3    | 0.16      | 1.072      | 1.077               | 1.069            |
| 4    | 0.06      | 1.064      | 1.071               | 1.057            |
| 5    | 0.10      | 1.074      | 1.077               | 1.064            |
| 6    | 0.16      | 1.082      | 1.088               | 1.079            |
| 7    | 0.06      | 1.063      | 1.077               | 1.055            |
| 8    | 0.10      | 1.079      | 1.082               | 1.068            |
With the intention to find out the accuracy towards these results, the average values on each of five drilled was tabulated with respective to the drill bit chosen in this study. The table 3 illustrates the delamination factor which was averaged upon doing the tests on all the studies.

![Delamination Factor Vs Feed Rate](image)

**Figure 4.** Delamination factor (Fd) versus feed rate for different tool materials

The figure 4 illustrates the delamination factor of the IPN laminate, subjected with the drilling of various drill bits. From the graph it was noticed, the Fd kept increases with the feed rate and with the consecutive cutting speed. The delamination factor value was nearly 1.052 while using the helical flute drill with the feed rate of 0.06 (mm/rev), similarly as feed rate increases, the value of the delamination factor also kept increases. This phenomenal growth continuously observed in all set of drill bits. The four flute drill bit also evidences with the hike in the delamination factor, the obtained value was 1.067 for their corresponding 0.06 feed rate. Surprisingly the helical flute drill has given the delamination factor value as quite high as compared with remaining set of all drill bits. In the same way the velocity also played the important or significant role in delamination factor, as much a velocity increases, it kept increase the delamination factor in higher level. Apart from that, analysis of variance tool was been used in order to find out the relationship between the feed rate and velocity upon obtaining the progressive approach in delamination factor. In this work, two phases of analysis of variances were used, out of which one was used to find out the relationship between the effect of factors and their interactions, the another one was that, correlation between velocity and feed rate. The table 4, table 5, and table 6 showed the results obtained from the analysis of variance with their corresponding output as delamination factor in IPN laminate [16].

From the data analytics in table 4, 5 & 6, the cutting velocity and feed rate, both the factors have statistical and physical significance towards obtaining the delamination, particularly the velocity factor. The error associated with respect to helical flute, four flute and helical flute drill K - 12 was nearly 7.01%, 13.81% & 20.01% respectively.

**Table 4.** ANOVA – Delamination factor (Fd) – helical flute drill

| Sources of variance | Sum of squares | Degree of freedom | Variance | Test F | $F_{α} = 5\%$ | Percentage of contribution |
|---------------------|----------------|------------------|----------|--------|---------------|----------------------------|
| V (m/min)           | 8.67E-04       | 2                | 4.30E-04 | 43.34  | 7.01          | 73.52                      |
| F (mm/rev)          | 2.52E-04       | 2                | 1.30E-04 | 13.31  | 7.01          | 21.12                      |
| Error               | 4.00E-05       | 4                | 1.00E-05 | -      | -             | 7.01                       |
| Total               | 1.18E-03       | 8                | -        | -      | -             | 100                        |
Table 5. ANOVA – Delamination factor (Fd) – four flute drill

| Sources of variance | Sum of squares | Degree of freedom | Variance | Test F | Fα = 5% | Percentage of contribution |
|---------------------|---------------|------------------|----------|--------|---------|---------------------------|
| V (m/min)           | 1.67E-04      | 2                | 9.30E-04 | 18.61  | 7.01    | 66.52                     |
| F (mm/rev)          | 6.20E-04      | 2                | 3.30E-04 | 6.31   | 7.01    | 20.12                     |
| Error               | 2.40E-05      | 4                | 5.10E-05 | -      | -       | 13.81                     |
| Total               | 2.45E-04      | 8                | -        | -      | -       | 100.00                    |

Table 6. ANOVA – Delamination factor (Fd) – helical flute drill – K12

| Sources of variance | Sum of squares | Degree of freedom | Variance | Test F | Fα = 5% | Percentage of contribution |
|---------------------|---------------|------------------|----------|--------|---------|---------------------------|
| V (m/min)           | 4.67E-4       | 2                | 2.4E-4   | 14.34  | 7.01    | 63.52                     |
| F (mm/rev)          | 2.52E-4       | 2                | 1.3E-4   | 13.31  | 7.01    | 16.91                     |
| Error               | 1.1E-4        | 4                | 2.1E-5   | -      | -       | 20.01                     |
| Total               | 6.18E-3       | 8                | -        | -      | -       | 100.00                    |

The factors velocity and feed rate shown a statistical significance of F > Fα 5%. Similarly the error associated in the ANOVA table to their respective output Fd was nearly 7%.

3.2 Correlation (cutting parameters with delamination factor)

The correlation between the cutting velocity and feed rate towards obtaining the delamination factor was achieved through the multiple linear regression analysis. The obtained equations were mentioned as follows.

\[
\text{Helical flute drill (Fd)} = 1.032 + 1.41 \times 10^{-3} V + 0.128 f - (1) \\
\text{Four flute drill (Fd)} = 1.038 + 1.10 \times 10^{-3} V + 0.168 f - (2) \\
\text{Helical flute K12 drill (Fd)} = 1.020 + 1.21 \times 10^{-3} V + 0.096 f - (3)
\]

Where v and f are the cutting velocity and feed rate.

Table 7. Experimental investigation on drilling tests and their comparison with the ANOVA models.

| Test | Experimental values | Predicted model | Error |
|------|---------------------|-----------------|-------|
| 1    | 1.057               | 1.061           | 0.37843 |
| 2    | 1.065               | 1.072           | 0.65728 |
| 3    | 1.071               | 1.081           | 0.93371 |
| 4    | 1.045               | 1.062           | 1.62679 |
| 5    | 1.052               | 1.072           | 1.90114 |
| 6    | 1.075               | 1.091           | 1.48837 |

The Table 7. Illustrates the analysis of experimental values and predicted model and their corresponding errors. Both the experimental value and predicted model has shown in good agreement with each other [17-19].

4. Conclusions

From the study of doing experimental procedure, upon using of various drill bit on IPN laminate, the following points were drafted.
• The helical flute K 12 drill proves to be the less damage effect on the calculation of the delamination factor assessment, compared with other two drill bits.
• Simultaneously another finding was that, IPN laminate evidences with the higher delamination effect as cutting speed and feed rate increases.
• As well, the cutting velocity had shown the good numerical and substantial influence on the delamination factor on the IPN laminate.
• The confirmation tests had shown the better agreement with the predicted models.

5. References
[1] Caggiano, A. Machining of fibre reinforced plastic composite materials. Materials 2018, 11, 442.
[2] Kumar, D.; Singh, K.K.; Zitoune, R. Experimental investigation of delamination and surface roughness in the drilling of GFRP composite material with different drills. Adv. Manuf. Polym. Compos. Sci. 2016, 2, 47–56.
[3] Saoudi, J.; Zitoune, R.; Gururaja, S.; Salem, M.; Mezleni, S. Analytical and experimental investigation of the delamination during drilling of composite structures with core drill made of diamond grits: X-ray tomography analysis. J. Compos. Mater. 2018, 52.
[4] Zitoune, R.; Cadorin, N.; Collombet, F.; Síma, M. Temperature and wear analysis in function of the cutting tool coating when drilling of composite structure: In situ measurement by optical fiber. Wear 2017, 376–377, 1849–1858.
[5] Durão, L.; Tavares, J.; de Albuquerque, V.; Marques, J.; Andrade, O. Drilling damage in composite material. Materials 2014, 7, 3802–3819.
[6] Eneyew, E.D.; Ramulu, M. Experimental study of surface quality and damage when drilling unidirectional CFRP composites. J. Mater. Res. Technol. 2014, 3, 354–362.
[7] P. Sethu Ramalingam, K. Mayandi, T. Srinivasan et al., A study on E-Glass fiber reinforced interpenetrating polymer network (vinylester/polyurethane) laminate’s flexural analysis, Materials Today: Proceedings, https://doi.org/10.1016/j.matpr.2020.06.330
[8] G. Suresh, T. Srinivasan, C. T. Chidambaram et al., A study on sliding wear behaviour of carbon fiber reinforced IPN composites, Materials Today: Proceedings, https://doi.org/10.1016/j.matpr.2020.05.124
[9] T. Srinivasan, G. Suresh, P. Ramu et al., Effect of hygrothermal ageing on the compressive behavior of glass fiber reinforced IPN composite pipes, Materials Today: Proceedings, https://doi.org/10.1016/j.matpr.2020.06.102
[10] G. Suresh, T. Srinivasan, C. T. Chidambaram et al., A study on sliding wear behaviour of carbon fiber reinforced IPN composites, Materials Today: Proceedings, https://doi.org/10.1016/j.matpr.2020.05.124
[11] Alessandra Caggiano, Ilaria Improta and Luigi Nele, Characterization of a New Dry Drill-Milling Process of Carbon Fibre Reinforced Polymer Laminates. Materials 2018, 11, 1470; doi:10.3390/ma11081470.
[12] C.C. Tsao, H. Hocheng, The effect of chisel length and associated pilot hole on delamination when drilling composite materials, International Journal of Machine Tools & Manufacture 2003, 43 (11), 1087–1092.
[13] S. Bharani kumar,S, Arul S, Murugan C, Sethuramalingam P, K.Mayandi, International Journal of Innovative Technology and Exploring Engineering 2019, 9, 1-4.
[14] J.Jeevamalar, B.Vinoth, International Journal of Advanced Science and Technology 2020, 29, 7718-7727.
[15] J. Jeevamalar, S. Bharani Kumar, P. Ramu et al., Investigating the effects of copper cadmium electrode on Inconel 718 during EDM drilling, Materials Today: Proceedings, https://doi.org/10.1016/j.matpr.2020.07.416
[16] J Jeevamalar, S Ramabalan, C Senthilkumar, Experimental Study with Rotating Tool Electrode of EDM on Inconel 718 Alloy, International Journal of Printing, Packaging & Allied Sciences 2016, 4(3): 1490-1503.
[17] J. Jeevamalar, Improving the performances of electro-discharge drilling process parameters, Journal of Advances in Chemistry 2015, 12(1): 5047-5059.

[18] Piquet R, Ferret B, Lachaud F, Swider P. Experimental analysis of drilling damage in thin carbon/epoxy laminate using special drills. Int J Mac Tools Manufact 2000:1107–15.

[19] Ugo Enemuoh E, Sherif El-Gizawy A, Chukwujekwu Okafor A. An approach for development of damage-free drilling of carbon fiber reinforced thermosets. Int J Mac Tools Manufact 2001:1795–814.