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# A Review on Drilling Process of Carbon Fiber Reinforced Plastic Laminates

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***Abstract:*** **Carbon Fibre Reinforced Plastics have found wide range of application in aerospace, automobiles, sports and in energy sector due to their high strength to weight ratio. Drilling CFRP composites is a challenge as they are anisotropic materials. Over the years though lot of work has been done to address this issue there is still huge scope for improvement in drilling CFRP composites. This paper gives a literary review of drilling of CFRP composites over the years. This paper also identifies the various factors causing delamination and affecting the quality of the drill and thus provides general recommendations for the selection of process parameters of the drill for better quality of finish.**

***Index Terms*****—Carbon Fiber Reinforced Plastics, Artificial Neural Networks, ANNOVA.**

## I. INTRODUCTION

Carbon Fibre Reinforced Plastics are manufactured by various process like moulding, compression moulding, filament winding, vacuum bagging, pultrusion, etc. The manufactured CFRP often has to undergo secondary manufacturing process like turning, milling, drilling, etc. so that required shape can be obtained to facilitate assembly. Machining of Carbon Fibre Reinforced Plastics has been a challenge due to their anisotropic and nonhomogeneous material property. The major problems faced during drilling CFRP are fibre breakage, micro cracking, thermal defects and delamination. Out of these delamination is considered to be the major defects occurring while drilling CFRP composites.

CFRP is made up of carbon fibres bound by mostly thermoset resins like epoxy. Carbon fibres form the reinforcement and epoxy resin is the matrix of the composite. The carbon fibre give the directional strength property which is unlike isotropic materials like steel, copper, etc. Masoud Motavalli and Peter Flueler [1] carried out experiments on characterization of unidirectional CFRP laminates and their results indicate that CFRP has more strength in the direction of the fibre than in transverse direction. Santhana Krishnan et al. [2] conducted experiments to study the machinability characteristics of fibre reinforced plastics and found that the carbon fibres in CFRP fracture sharply giving better finish than other fibre reinforced plastics. Keizo Sakuma et al. [3] observed a new type of combined wear occurring while drilling in Reinforced Plastic Composites. The wear is high while drilling initially and wear is higher in high speed steel than carbide drills. Martin's study [4] of various geometric shapes carried out shows that approach of damage estimation is qualitative. Sheikh Ahmad et al. found the abrasiveness of fibres affects the tool sharpness. The flank wear increases with increase in cutting speed or with decrease in feed rate, thus increasing the tool force. This in turn increases the temperature resulting in degradation of the machine part as well as the finish of the drill. Chen [6] correlated the delamination factor with the average thrust force only for CFRP laminates and found it to behave linearly.

To overcome the various difficulties it is necessary to identify the proper machining parameters that could provide proper finish of the hole with minimum work and machine degradation. Frederic Lachaud et al. [7] correlated the thrust force by taking into account the nature of geometry of contact between different tool shapes and composite laminates. Tsao [8] carried out experiments and found that drill type and feed rate are most influential factors affecting the induced thrust while drilling the laminates.

 

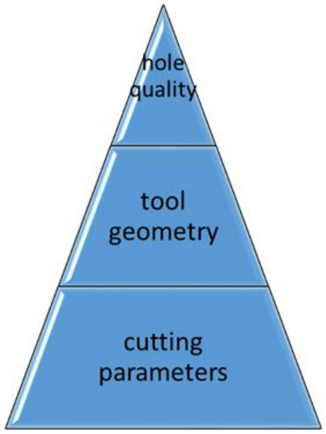


*Fig 1: factors to be considered while drilling CFRPs*

Tagliaferri et al. [9] conducted various experiments to analyse the effect of drilling parameters on finish and mechanical properties of Glass Fibre Reinforced Plastics (GFRP) and found that that the width of the damage zone is correlated to the ratio between drilling speed and feed rate and the tensile strength of specimens with holes does not depend on the quality of the material at the edge of the hole. H. HOCHENG and H. Y. Puw [10] revealed some aspects of drilling characteristics for both carbon fiber-reinforced.

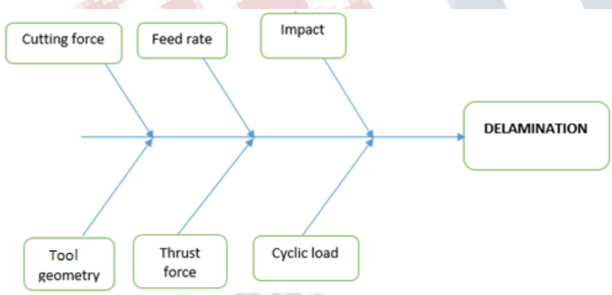


*Fig 3: Factors causing delamination.*

The moplastics and thermoset and found that cutting chips that the former presents, a large amount of deformation in chip formation is observed, while the latter tends to fracture. The various factors that are to be considered while drilling CFRP to get best performance are shown in Fig1.

Hence this review is comprehensive and focuses primarily on the drilling operation which is the most commonly used secondary process in manufacturing CFRP components. Although CFRP components are usually manufactured by moulding, weaving process, etc. they still need some secondary operations such as drilling, milling, and turning. This review focuses on the drilling of CFRPs and considers the important factors that cause delamination and affect the drill hole quality. Based on the recommendations of several researchers, the review also provides general recommendations on selection of process parameters when drilling CFRPs as well as discusses challenges in drilling of CFRPs.

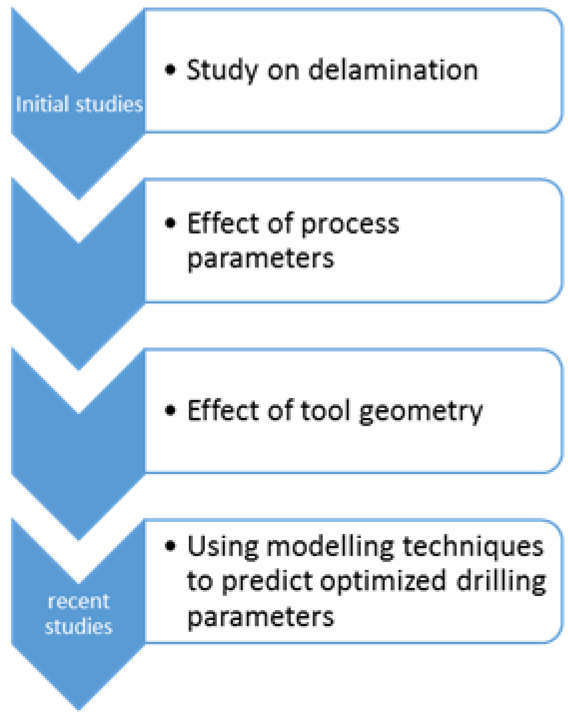


*Fig 2: Orientation of concepts concentrated in this paper.*

1. Delamination
2. Delamination
3. Delamination

## II. DELAMINATION

Delamination is a type of failure that occurs in composite materials. Delamination is primarily caused by factors like impact, cyclic loads, high shear, etc. Delamination causes the layers to separate. It also results in formation of a layer of mica like structures. This results in significant decrease in mechanical toughness of the composite.

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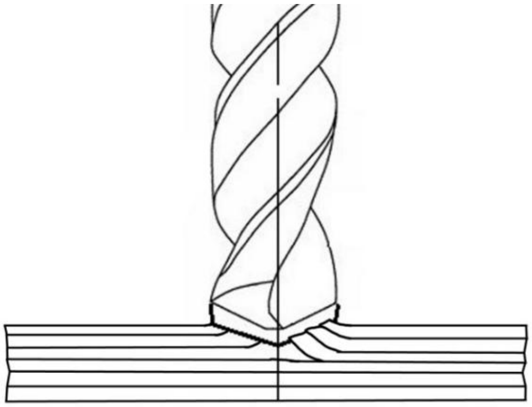

***Fig 4: Delamination at entry***

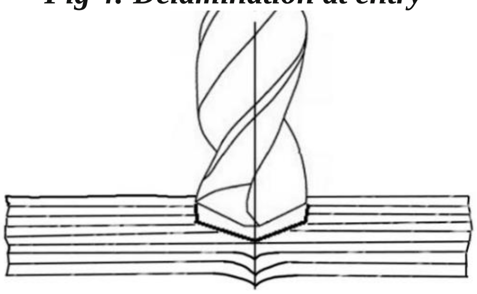

***Fig 5: delamination at exit.***

Ho-Cheng and Dharan [11] found the mechanism of delamination at entry of the drill and exit of the drill. At exit the thickness of the laminate is less and high thrust forces causes the defect. At entry the cutting edge peels up the laminate. S Jain and Yang [12] conducted experiments and proposed critical feed rate and critical thrust force models for delamination free drilling.

Ho-Cheng and Tsao [13] performed analysis of delamination of composite materials using core drill. Their experimental results revealed clear correlation among feed rate, thrust force and delamination area. Their results showed that within the tested range of drilling conditions the delamination is varying with the thrust force linearly. Their models can be used as a guide for drill design and the approach can be extended to examine the effects of other special drill designs.

Tsao and Chen [14] conducted experiments to predict the location of delamination and proposed an equation,

$$h^* = .0000254 h_{ply} \left( h^*_{anisotropic} \right)$$

$$\left[\frac{E_{22}}{E11}\right]^{0.62208} G_{IC} E_C \qquad (1)$$

Where,

$$Ec = 2E_{11} + {}^{2}/_{3} \left(\frac{E_{11}}{E_{22}}\right)^{1/2} \{E_{22}V_{12} + \quad 2G_{12}(1 - V12V21 \qquad (2)$$

$E_{11}$ is Young's modulus parallel to fibre direction. $E_{22}$ is Young's modulus transverse to fibre direction. $h_{ply}$ is thickness of the ply.$G_{IC}$ is critical crack propagation energy $h^*_{anisotropic}$ is value of h for critical thrust force.

Design experiments were used to study the delamination in CFRP composites by Davim and Pedro Reis [15] and they found a correlation between cutting velocity and feed rate with delamination in CFRP. The equations were obtained by multiple linear regression and are as follows

For helical flute HSS drill,

$$F_d = 1.021 + 1.31 \times 10^{-3} v + 0.158 f \quad (3)$$

For four flute K10 drill,

$$F_d = 1.037 + 1.0 \times 10^{-3} v + 0.158 f \quad (4)$$

For helical flute K10 drill,

$$F_d = 1.010 - 1.16 \times 10^{-4} v + 0.097 f \quad (5)$$

Where

$F_d$ is the delamination factor

$f$ is the feed rate.

$v$ is the cutting velocity.

Tool geometry is also an important factor that affects delamination in composites while drilling operation. Hocheng and Tsao [16-18] presented a review of various methods of drilling composites for a path towards no delamination. They also presented a review of special drill bits. Before presenting a review of delamination free drilling. They also presented a comprehensive analysis of delamination induced by different drill bits and presented method for reduction of thrust force of various drill bits.

The experimental results of drilling induced delamination showed that critical feed rate of core drill was the highest followed by candle stick drill, saw drill, step drill and conventional twist drill. The advantage of special drill bits is that the thrust force is equally spread towards the drill periphery instead of the centre of the drill. The critical feed rate for core drill, candle stick drill, saw drill, step drill and twist drill were observed to be 7.5, 6.9, 5.1, 4.9 and 8 respectively in their experimentation.

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Haijin Wang et al. [19] performed experiments on drilling composites at different depths to investigate the developing process of delamination. They also analysed the regularity pattern of delamination with different drilling depths. They observed that actual area of delamination consists of observed area of delamination and a hidden delamination zone that cannot be detected. This hidden delamination zone is created when the edge of the delamination zone is highly compressed.

Therefore the delamination area detected by popular means is actually smaller than the actual delamination.Luis Miguel et al. [20] suggested that in conventional drilling the feed rate should be kept as low as possible as higher feed rate resulted in higher delamination extension. In delamination onset test they found that as uncut thickness increased the delamination onset load also increased.

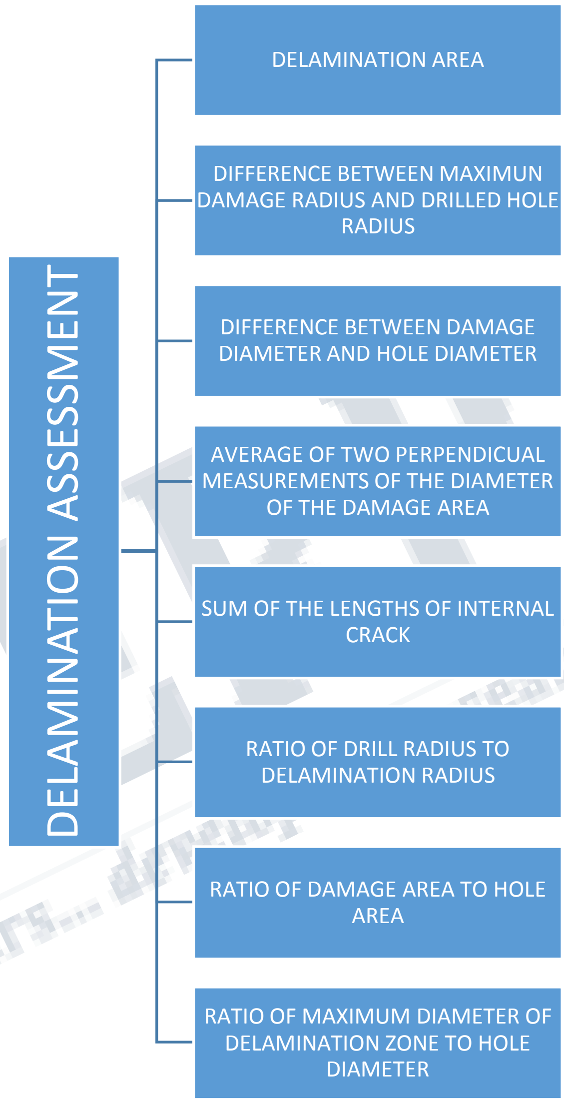


***Fig.6: Factors used in evaluating delamination.***

A flute in a drill is the helical or straight grooves cut or formed in the body of the drill to provide cutting lips, to permit removal of chips, and to allow cutting fluid to reach the cutting lips. Birhan Işık & Ergün Ekici [21] performed damage analysis in woven glass fibre reinforced plastic and found that increasing the flute number of the drill subsequently increased the damage factor at hole exit but decreased the damage factor at entry. Similarly increasing the feed rate decreased damage factor at entrance but increased the same at exit. Decreasing the point angle decreased the damage at both entry and exit.

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They observed the shear stress was high at bottom and thus damage factor was higher at bottom.

Eshetu D. Eneyew and Mamidala Ramulu [22] experimentally studied the surface quality and damage while drilling unidirectional CFRP and found that the best quality of hole was obtained by increasing the cutting speed and decreasing the feed rate.Hybrid effect is a phenomenon where there is deviation in mechanical property in composite materials. Wisnom et al. [23] separated hybrid effect into: an effect on initiation of failure, because of constraint at the fibre level, and another effect caused by delay in establishing stable fragmentation resulting from constraint at the ply level.

I. Singh and N. Bhatnagar [24, 25] carried out experiments on drilling unidirectional GFRP laminates and stated that drilling induced damage depends on speed/feed ratio. The damage zone observed was elliptical in shape with its major axis parallel to the fibre direction. It was also observed that the drill geometry played a major role in thrust force and torque response. They also studied the influence of drilling induced damage on the residual tensile strength of laminates. The damage was minimum at low speed low feed ratio and the resulting residual tensile strength was also increased. As the cutting speed-feed speed ratio increases the drilling induced damage around the hole increased and the residual tensile strength initially increased and later decreased. From finite element model they observed that the drilling induced damage was not dependent on thrust force alone. Torque was also a contributing factor to the drilling induced damage. Therefore analytical models based on thrust force alone should also take into account the effect of thrust for precise damage prediction.

Tsao and Huang [26] analysed the thrust induced drilling of hemispherical drill of composite materials. The critical thrust force developed in hemispherical drill was found to be less than critical thrust force induced in twist drill and these critical thrust force results were verified in industrial practice.

## III. DRILLING PARAMETERS

The role of machining parameters in drilling quality or finish of the drill is the subject matter that most of the investigations are about. These parameters like cutting speed, torque, thrust force, feed rate, etc. affect the drill quality directly. Hocheng and Puw [10] studied on drilling characteristics of thermoset and thermoplastic FRPs. Thermoset materials required more cutting force as they have higher strength. Depth of cut was proportional to thrust force and regardless of chip formation mechanism, larger depth of required larger thrust force. The fig.7 represents the relationship between thrust force and depth of they observed. Jose Mathew et al. [27] investigated the effect of trepanning tool on thrust force and torque of drilling GFRP and found that trepanning tool is superior to twist drill as they required less thrust force and torque. This trepanning tool produced 50% less thrust and 10% less torque than the twist drill.

Bhatnagar et al. [28] carried out experiments on drilling CFRPs and found from their experiments that the ratio of thickness of composite layer to the diameter of the hole influenced the thrust force of the drill. Generally high cutting speeds are recommended for drilling FRP, but they obtained the best clean cut hole at 500 rpm and at the feed rate of 100 rum/min for 8mm and 10 mm dia drills of all the drill geometries.

Talgiaferi et al. [9] found that damage is dependent on ratio of cutting speed to the feed rate that was adopted for drilling. The lower the ratio is, the poorer the quality of hole is but after a certain limiting value of the above mentioned ratio, it didn’t influence the extent of damage. This ratio is basically dependent on the resin type, fibre format, thickness of composite laminate and manufacturing method.

Zhang et al. [29] developed a mechanical model for predicting the thrust force and torque in vibration drilling fibre reinforced plastics. The analytical model gives an expression for thrust force in terms of drill geometry, drilling conditions, vibration and shear flow stress. They observed that for the same given drilling conditions the thrust force and torque was nearly 20-30% less in vibrational drilling than conventional drilling. Similarly Ramkumar et al. [30] attempted a new technique of oscillatory assisted drilling of GFRP laminates to minimize the damages involved in drilling. They analysed the performance of cutting through measurement of power, force and tool wear. They observed that the critical number of holes drilled using the conventional drilling method to attain the critical limits was 30 while in super imposed drilling it is around 60.

E. Ugo. Enemuoh et al. [31] developed an approach for multi objective optimization which included

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factors drilling parameters like delamination, damage width, surface roughness and drilling thrust force. Their approach involved design of experiments for developing the optimization technique in order to account for various contributing factors. They recommended that high speed and low feed rate for production of delamination free drilling with good surface finish of holes.

Aper Uysal et al. [32] studied the effects of cutting parameters on tool wear in drilling polymer composites. Their results showed that wear in tools with 80° drill point angle was less than the others with 100° and 120° drill point angles and cutting speed was the least effective factor while feed was the most significant followed by the drill point angle for minimum tool wear. Similarly Montoya et al. [33] established the wear mechanisms of coated and uncoated tungsten carbide drills when drilling carbon fibre reinforced plastics. In both coated and uncoated tools abrasion wear was the predominant wear observed, thus affecting the entire cutting edges. The abrasion wear was high in the case of uncoated tools which lead to significant increase in thrust force.

Vijayan Krishnaraj et al. [34] reported an experimentation on a full factorial design performed on thin CFRP laminates using K20 carbide drill by varying the drilling parameters like spindle speed and feed rate to determine optimum cutting conditions. It was observed that Spindle speed is one of the major factor affecting the circularity of the drilled hole and best results were obtained at 20,000 rpm. The optimized spindle speed and feed rate was found to be 12,000 rpm and .137 mm/rev respectively for high speed drilling. At this condition no significant tool wear was observed until 150 holes.

Hamzeh Shahrajabian and Masoud Farahnakian [35] presented a methodology for the determination of the optimized cutting parameters such as spindle speed, feed rate and tool point angle during the drilling process of CFRP to maximize the material removal rate by considering surface roughness, delamination and thrust force. They achieved minimum thrust force and delamination at spindle speed of 4000 rpm, feed rate of 50 mm/min, tool angle point of 100 degrees, while the maximum delamination at spindle speed of 1250 rpm, feed rate of 800 mm/min, tool angle point of 140 degrees. They achieved minimum surface roughness was achieved at spindle speed of 4000 rpm, feed rate of 50 mm/min, tool angle point of 140 degrees, while the maximum surface roughness was achieved at spindle speed of 1250 rpm, feed rate of 800 mm/min, tool angle point of 100 degrees.

Rahamathullah & Shunmugam [36] developed a mechanistic approach for predicting forces involved in micro drilling of glass reinforced epoxy sheets and found that the rubbibg of micro drill with the side walls of the hole affected the torque and thrust force. Considering this factor they observed that the variation was up to 12.75%. Khoran et al. [37] used a factorial experimental design to assess the importance of drilling parameters. The drilling parameters were assessed based on two factors including delamination factor DF and uncut fibre factor UCFF and it was observed that the feed rate had the greatest influence. Following feed rate, cutting speed and hole diameter have the highest influence. DF and UCFF increased when the feed rate was increased. DF UCFF decreases with the increase of drill diameter. There is a maximum point for cutting speed (1600 rpm) in evaluation of UCFF.

Chongyang Gao et al. [38] developed a 3D micro mechanical finite element model of machining FRP composites considering the three phases of a composite in which the interphase between the fibre and matrix can realize interfacial de-bonding to represent the failure and allow heat transfer. Observation of machined surface and surface roughness measurements of CFRP composites at different fibre orientations were done and then, the model predictions of the machining responses, like cutting force, temperature, and surface roughness, at different fibre orientations were compared with various experimental data for model validation. It is indicated that the three-phase micromechanical model is capable of precisely predicting machining responses and describing the failure modes of fibre shearing or bending related with fibre orientations in the process of chip formation. It was seen that cutting force increased with increase in cutting speed. Although the increase in cutting speed can lead to high cutting temperatures, the cutting speed did not drop because the magnitude of cutting temperature was very small.

Shubham. S. Dabhade [39] studied the surface roughness characteristics of drilled hole in GFRP and found that feed rate showed a non-linear effect on the roughness of the drilled hole. It was also seen that when the feed rate was high there was sudden increase in temperature between tool and chip interface due to high friction. Lower feed rate gave good quality of the drilled hole in GFRP material. The effect of spindle speed was also observed to be non-linear. Though the roughness

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value increased for increase in spindle speed from 600 rpm to 800 rpm it suddenly dropped later when it was further increased.

Bin Luo [40] et al. developed a prediction model for thrust force and torque in drilling CFRP. Their model was able to predict the thrust force and torque of entry stage of drilling process for CFRP well. They observed both feed rate and spindle speed have significant effect on beginning values, and only feed rate has apparent effect on the ending value of thrust force, while spindle speed has little influence on the ending value of torque. Chang-Ying Wang et al. [41] studied the drilling temperature and hole quality during drilling of CFRP and found thrust force to be almost proportional to the feed rate. They measured the temperature using a rotational motion temperature measuring system and the results showed that the temperature increases with spindle speed and decreases with increase in feed rate. They also indicated that a higher spindle speed can achieve a smaller diameter difference between the CFRP and Al.

## IV. OPTIMIZING TECHNIQUES

Optimizing techniques are used to predict the drilling parameters that affect the delamination during drilling and quality of the drilled hole and select appropriate values for delamination free drilling and better quality of the drilled hole. There are various optimization techniques used such as Taguchi's method, mathematical modelling, Genetic Algorithm, Artificial Neural Networks, ANOVA and multi constrain modelling.

Analytical models are mathematical models that use an equation to describe the behaviour of a system. The results obtained from the equation are used to represent the data in a table or a graph which gives more aesthetic appeal than numerical method. Pierre Rahme et al. [42] used an analytical model for studying the delamination involved during drilling of composite materials. Their approach was based on number of assumptions such as initiation of crack was assumed to be caused by pressure of the cutter and propagation of crack was assumed to be caused by normal stress perpendicular to the plane of the layers.

Taguchi method is a statistical approach developed by Genichi Taguchi to improve the quality of product manufactured. This method is also called as robust design method. It offers a simple systematic approach to optimize the design for performance, quality and cost. Taguchi method combines the design of experiments and quality loss function to solve much complex problems in manufacturing. It uses orthogonal arrays to study the parameter space in lesser number of experiments. Then the results from experiments are converted into signal to noise ratio to measure the deviation of characteristics. Greater the signal to noise ratio the better the quality. Tsao [43] analysed the drilling quality associated with the core drill in drilling of composite material using Taguchi analysis. In this study, thrust force and surface roughness were selected as a quality character factor to optimize the drilling parameters. The confirmation test carried out showed a feasible and effective method of evaluation of thrust force and surface roughness with errors within the range of 10%. Alper Uysal et al. [44] evaluated the effect of cutting parameters on tool wear in drilling composites by Taguchi method. Taguchi method was used to find the optimized drilling parameters for minimum tool wear. They used drill point angle, feed and cutting speed as key factors in orthogonal arrays. They obtained a model giving an approximation with 5.547% error.

Analysis of Variance is a statistical technique for determining the degree of deviation or similarity between two or more groups of data. This technique is based on the average value of common component. Vinod Kumar and Venkateswarlu Ganta [45] worked on optimizing the process parameters in drilling of GFRP composites. They used ANOVA tests to determine the significance of each parameter on drilling. Their results indicate that feed rate is the most significant factor influencing the thrust force. They suggest that this work will be useful for industries while selecting the process parameters in drilling GFRP composite materials, to improve the quality of the drilled holes by reducing the delamination. Ergün Ekici and Ali Riza Motorcu [46] evaluated drilling Al/SiC composites with cryogenically treated HSS drills.

ANOVA was applied to determine the effects of control factors on dimensional accuracy and surface roughness. Their results showed that cryogenically treated drills performed better than untreated drills. According to the results of ANOVA which was carried out at 95% confidence level, cutting tool and cutting speed were the most effective parameters on dimensional accuracy and cutting speed. Genetic algorithm is based on Darwin's theory of evolution. It is a search algorithm used to find the best input parameters for best results. It combines evaluation of solution with randomized structured exchange of information between solutions. It works on a

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population of solutions and is a robust method as no restrictions are imposed on search space. Genetic Algorithm does not require any prior knowledge and have no limitation on search solution space.

Artificial Neural Networks are highly structured data processing units that operate parallel to minimize the huge computational ability of human brain and nervous system. Neural networks learn from experience, generalize from previous example, abstract essential data from input and deal with fuzzy situations. It consists of three types of layers including input layer, hidden layers and output layer. The input layer is used to input the data. Hidden layers contain number of neurons interconnected to each other and process the input data. There are number of neurons in the output layer based on the number of variables to be predicted. Krishnamoorthy et al. [47] recommended that ANN model is highly suitable for the prediction of delamination as it was observed from their work that ANN model predicts delamination for any machining parameters with maximum error of .081% and minimum error of .03%.

Multi-objective optimization is area of optimization concerned with mathematical optimization involving two or multiple objective function that is to be optimized simultaneously. Kumar Abhishek et al [48] worked on optimization of thrust, torque, entry and exit delamination during Drilling of CFRP composites and developed a PCA-fuzzy-Taguchi based integrated optimization module of multi response optimization. Their introduced the concept of MPCI and NCQL in their optimization module and found it to be quite efficient as it could overcome the limitations that exist in Taguchi based optimization approaches. Noorul Haq et al. [49] found that the use of grey relational analysis in the Taguchi method for the optimization of multi response problems is very useful for predicting surface roughness, cutting force and torque in drilling Al/Si composites as it did not involve complicated mathematical theory. Their determined optimum conditions of drilling satisfied the real requirements for the drilling operation. Hamzeh Shahrajabian and Masoud Farahnakian [35] presented a methodology for determination of optimal cutting parameters for drilling process. They considered surface roughness, thrust and delamination as the constraints for Genetic algorithm and Response Surface Methodology and ANOVA was performed. Their results indicated that that the response surface method coupled with the GA can be utilized effectively to find the constrained optimum cutting conditions in drilling of CFRP.

## V. CONCLUSION

The following conclusions can be drawn from this work: The mechanism of delamination and various factors causing delamination were mentioned. The effect of various drill bits was comprehended. Considerable agreement among the authors exist in developing new cutting tools for improved drilling quality. The effect of various drilling parameters on the composite laminates during the drilling process was mentioned. It was observed that feed rate and thrust force were the most influential factors causing delamination in most of the work carried out by various authors. General recommendations have been made on optimized drilling parameters for better quality of the drilled hole.

Taguchi method of optimization was found to be the most widely used technique for optimization various optimization techniques and modelling techniques used by a number of authors in their investigation have been discussed. Artificial Neural Networks were found to be the most accurate modelling technique as their results reveal that errors were found to be in the range of 0.08% and lower. Generally multi objective modelling is recommended for more accurate prediction of process parameters.

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