CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

Considerable amount of research has been carried out on the effects of drilling on composite materials. Most of them have been concerned with study on defects such as delamination and their significance. Yet no definite solution has been proposed to reduce it. The present study focuses on an alternative to chip removal associated drills by way of fine blanking of Glass Fiber Reinforced Plastics (GFRP) which minimizes delamination factor compared to the other methods. To understand the response of composite material to machining environments, detailed literature survey is carried out on processing and machining of GFRP composites.

2.2 PROCESSING OF GFRP COMPOSITES

Khondker et al (2004) have investigated on the mechanical properties of aramid/nylon and aramid/epoxy composites and their relationship to the fiber/matrix interfacial adhesion and interaction. Weft-knitting technique was used to produce textile reinforcements for aramid/nylon composite processing. Aramid/epoxy knitted composites were also fabricated to compare them with aramid/nylon thermoplastic composites. With the increase in processing time, tensile modulus and strength of aramid/nylon composites increased and decreased, respectively. Pressure-hold has the greatest influence on strength and moduli. Aramid/nylon knitted
composites exhibited relatively better interfacial bonding properties than aramid/epoxy composites, which suffered fiber/matrix debonding. This is attributable to the flexibility in the matrix nylon compared to epoxy. Results also suggest that there is an optimum molding condition by which maximum tensile properties can be obtained.

Sakaguchi et al (2000) have investigated on the mechanical properties of unidirectional thermoplastics composites manufactured by micro-braiding technique. Micro-braided yarn is a processing material system that may be used for complex-shaped composites such as textile structural composites. The dimensions of the braided fabric depend on the fiber-bundle volume fraction, the number of fiber bundles used to fabricate the braided fabric, and the fiber-orientation angle. Braided fabrics with various dimensions can be fabricated by selection of these parameters. In their study, unidirectional glass-fiber/P A6-Nylon composites manufactured from micro-braided yarns were molded in order to investigate the effect of the micro-braiding structure and processing conditions on impregnation and mechanical properties. The void content was determined in order to examine the quality of impregnation and was found to decrease with increasing holding time when the pressure was applied to the perform. Axial and transverse bending tests were carried out. The axial-bending strength was well correlated with the void content. However, the transverse bending strength was affected by both the void content and the dispersion of the glass-fiber bundles (probably due to void coalescence in transverse loading).

Lin Ye et al (1995) have investigated on the relationship between impregnation mechanisms, consolidation quality and resulting mechanical properties of CF/PEEK thermoplastic composites manufactured from a commingled yarn system. A small compression mould was used to apply the different processing conditions (i.e. pressure, holding time and processing
temperature). A model for qualitatively describing the impregnation and consolidation processes for commingled-yarn-based thermoplastic composites was developed, which predict the variations of void content during consolidation as well as the time, temperature and pressure required to reach full consolidation. Good correlations between predictions and the experimental data indicate the success of the approach.

Manwar Hussain et al (1996) have investigated on the mechanical properties of carbon fiber reinforced composites and Al₂O₃ particles dispersed carbon fiber hybrid reinforced composites. Hybridization of the fiber reinforced epoxy composites by nano- and micro-sized Al₂O₃ dispersions showed improvement in mechanical properties. The presence of micro/nano-sized filler particles resulted in formation of roughness on the fiber surface without damaging the fiber, and strong interfacial bonding at the fiber matrix interface due to roughening of the surface texture and thermal residual stresses on the fiber surface. The roughness and strong interfacial adhesion act as mechanical interlocking and improved frictional coefficient which contribute to the higher flexural and interlaminar shear strength. Normally in the case of composites, mechanical interlocking and strong interfacial bonding will lower the flexural resistance. Incorporation of Al₂O₃ filler results in higher fracture toughness by improving significantly the toughness of the matrix and crack deflection/annihilation by the presence of filler particles. This could be the main contributing factor for the reported high flexural and interlaminar shear strength. Usually the design of reinforced composites will look for weaker interfaces.

Gao et al (1995) have observed on the damage development in composite laminates reinforced with two, four and six layer carbon fiber reinforced polyimide eight harness satin weave fabrics as a function of applied strain. The major damage developed in eight-harness satin-weave
carbon-fiber-reinforced polyimide laminates under quasi-static loading is transverse matrix cracking and delamination at crimp regions (illustration of weakness of laminates in transverse direction / easy failure across fiber).

Chazeau et al (1999) have investigated on the mechanical behaviour of a plasticized PVC matrix reinforced with cellulose whiskers above the glass transition temperature to evaluate the mechanical properties of such composites in the rubbery state. A simple modeling of the mechanical behaviour, using the classical elasticity theory is proposed. Damage is explained mainly as debonding of the matrix at the whisker interface. Small-angle neutron scattering experiments performed on stretched composites provide information on the matrix microstructure with and without whiskers. Results confirm the heterogeneous characteristic of the matrix.

2.3 COMPARISON OF GLASS/CARBON REINFORCED POLYMERIC COMPOSITES

Christopher Wonderly et al (2005) have compared the mechanical properties of glass/vinyl ester and carbon fiber/vinyl ester composites. The carbon fiber laminates outperformed glass fiber laminates in all aspects except transverse tensile strength. This is mostly due to response of the carbon fiber to transverse loading.

In the ballistic impact study, it was found that the absolute energy absorption is roughly the same for glass and carbon fiber composites. The energy to break the carbon fibers in tension is approximately equal to that for glass fibers due to high strength of the carbon fibers, however with larger strain to failure for the glass fibers. This means that the matrix polymer is largely the deciding factor. For hybrid composites, for a given glass and carbon volume fraction, the mean glass and carbon fiber lengths increase with increase in glass fiber volume fraction, whilst they decrease with increase of
the carbon volume fraction. As a result, the notched charpy impact energy of composites increases with increase of glass fiber volume fraction and reduces with carbon fiber volume fraction (Fu et al 2005). This can be attributed to the higher brittleness of the carbon fibers.

The glass and carbon fiber reinforced composites were studied at varying strain rates (Ochola et al 2004). Kinking and shear failure experienced by both CFRP and GFRP at low strain rates appear to be a low energy event as compared to debonding and delamination at higher strain rates. The mechanisms of failure at increasing strain rates have been examined using microscopic techniques. The results have shown that the variations in strain rate result in changes in failure modes experienced by CFRP and GFRP. In compression, epoxy was seen to be strain rate sensitive as well as having considerable recovery indicative of viscoelastic materials. The most pronounced effect of increasing the strain rate for both composite systems results in changes in the modes of failure. The modes of failure appear to have certain energies associated with them. As the strain rate increases, the CFRP undergoes complete disintegration, this is deemed a higher energy event than shear fracture which is the dominant failure mode at low strain rates. GFRP fails by fiber kinking at low strain rates, with delamination and interfacial separation dominating the high strain rate failure regime. It is suggested that this transition in failures is again associated with an increase in energy, from low strain rates to high strain rates. The relatively stiffer interface in the case of CFRP composite can’t absorb much energy, hence results in disintegration.

Polypropylene is one of the most used polymers for fiber reinforced composites, especially due to economic reasons, ease of processing, environmental friendliness and working security and recyclability (Lopez-Manchado and Arroyo 2000). There are currently many types of
reinforcing fibers used in composite materials. Glass fibers are the most common reinforcing fibers for polymeric composites due to their low cost and high strength and are used in many high volume applications particularly the automotive industry. Of late, carbon fibers are the most widely used advanced fibers and are generally manufactured by the pyrolysis of a polyacrylonitrile (PAN) or a pitch precursor. They have the highest specific strength and modulus among all reinforcing fiber materials (Kuriger et al 2002). Fu et al (1999) have demonstrated that the fracture surface morphology of such composites is dependent on both fiber-matrix interfacial adhesion and matrix shear yield strength.

Optimum damage strength of composite is favoured by longer fibers and good adhesion between fibers and matrix at low levels of loading (Benzeggagh and Benmedhakene 1995). However, at high loading levels a weak interface results in high energy dissipation and corresponding improved damage resistance. The consolidation time dominated the flexural modulus and void content while increased press-force and mold temperature decide proportional mould fill (Wakeman et al 2000).

2.4 DYNAMIC MECHANICAL ANALYSIS

Apart from focusing on the role of processing on structure and interface characteristics, research has been focused on viscoelastic behaviour of matrix for assessing the relationship between status of structure and its role on stiffness related features.

Dynamic mechanical analysis (DMA) method has been widely employed for investigating the structures and viscoelastic behavior of polymeric materials for determining the relevant stiffness and damping characteristics for various applications. Many researchers have carried out DMA studies of short fiber and natural fiber reinforced polymeric composites.
Knowledge of dynamic mechanical properties of fiber reinforced composites is of importance when considering energy dissipation in cyclic loading applications. The dynamic properties of polymeric materials are of considerable significance if they are determined over a wide range of frequency and temperature. They can yield an insight into various aspects of material structure, provide a convenient measure of polymer transition temperatures which may influence other important properties such as fatigue and impact resistance. The dynamic properties are also of direct relevance to a range of unique polymer applications, concerned with the isolation of vibrations or dissipation of vibration energy in components. The dynamic properties are generally expressed in terms of storage modulus, loss modulus and damping factor which are dependent on time and temperature.

Varadharajan et al (2006) have studied Mechanical and machining characteristics of GF/PP and GF/Polyester composites. From this study, the following conclusions are drawn: (i) Compared to thermoset composites, thermoplastics composites exhibit higher order impact resistance, (ii) unlike the brittle mode of fracture associated with thermoset composites, thermoplastics composites experiences ductile mode of failure, (iii) DMA studies show that reinforcing thermoplastics enhances the glass transition temperature and the damping properties, (iv) Unlike the case of rupture associated machining in the thermoset composites, the thermoplastics composites undergoes plastic deformation by thermal induced matrix sliding and removal of material, (v) Higher order thrust force was experienced by thermoset composites; this will facilitate machining induced defects such as debonding and delamination, (vi) Thermoplastics composites experience lower order thrust forces, and also temperature prevailing over the cutting zone favors the formation of lubricating, ablative layer thereby minimizing the tool wear.
Joseph et al (2003) have studied on dynamic mechanical properties of short sisal fiber reinforced polypropylene composites with reference to the effect of fiber loading, fiber length, chemical treatments, frequency and temperature. The dynamic mechanical properties are of considerable significance for several reasons, particularly if they are determined over wide range of frequency and temperature. The storage modulus and loss modulus of chemically treated fiber composites were higher than those of the untreated fiber composites due to the improved fiber-matrix interfacial adhesion. The coupling agents increase the fiber-matrix interfacial adhesion causing reduced molecular mobility in the interfacial region. Both storage and loss modulus decreased with increase in temperature. Reduction in modulus with increase in temperature is associated with softening of the matrix at higher temperature. Dynamic moduli increase with increasing frequency. Unidirectional glass fiber/polyamide 66 composites with different additives in the matrix (like nucleating agent, thermal protectors, lubricants) and different glass fiber surface treatment (like various amount of coupling agent or sticking agent) were characterized by static and dynamic flexural tests including fatigue and viscoelasticimetry. The presence of a coating agent aminosilane, on the surface of the glass fiber improves the mechanical properties of the composite. During viscoelastic measurement, the coating does not modify the material glassy state component, but increases the rubbery state modulus. This behaviour could be attributed to the chemical bonding apparition, increasing the interface stiffness. This stiffness increase, produced by the presence of coating, is confirmed by reduction in tan δ value at the glass transition. These viscoelasticimetric results are confirmed by the results obtained with the dynamic shear test. The dynamic shear modulus (G') increases with the aminosilane quantity in the coating (Cinquin et al 1990).
Zhang et al (2002b) have investigated on the dynamic mechanical properties of polytetrafluoroethylene (PTFE) based composites blended with different contents of polyetheretherketone (PEEK) and reinforced with various amounts of short carbon fibers. Dynamic mechanical thermo-analysis was employed using a three point bending configuration. The influence of different characteristics of PTFE and PEEK at various temperatures were considered. They explain that in addition to low-strain and high-strain damping, the fiber matrix interface strongly affects the mechanical properties of the composite and has also an influence on its damping level. In short fiber reinforced thermoplastics, both the storage modulus and damping are governed by polymer matrices, but influenced by other fillers as well. Based on measured results an artificial neural network approach has been introduced.

Melo and Radford (2005) have studied the time and temperature dependence of the viscoelastic properties of CFRP by dynamic mechanical analysis. Understanding the viscoelastic properties of composite materials is essential for the design and analysis of many advanced structures. Viscoelastic material characterization is critical in designs that incorporate specified levels of damping, and to the understanding of processing problems. However, experimental viscoelastic characterization of anisotropic materials can be complicated because of the number of independent parameters to be evaluated. An approach leading to the 3-D viscoelastic characterization of transversely isotropic materials using a reduced number of measured parameters has been used to evaluate the time and temperature effects on the viscoelastic properties of unidirectional carbon fiber reinforced laminae and cross-ply laminates. The experimental investigation is conducted on sub scale specimens loaded in flexure, using dynamic mechanical analysis (DMA) equipment. The results presented demonstrate that DMA equipment offers good potential to study changes in viscoelastic properties of transversely isotropic laminae and laminates, related to temperature and frequency. This
work provides a means for the study of viscoelastic properties of fiber-reinforced composites. Hence, constitutes a valuable contribution to the understanding of time and temperature dependent of these mechanical properties.

Smita Mohanty et al (2006) have studied the suitability of Maleic Anhydride grafted polyethylene (MAPE) modified jute, as reinforcement in HDPE matrix and consequent viscoelastic behavior of the composites. The storage modulus showed an increase in the magnitude of the peaks with fiber reinforcement and addition of MAPE. The damping properties of the treated and untreated composites, however, decreased in comparison to the virgin matrix. This again confirms the significant role of matrix on fiber-matrix interface related properties.

Bosze et al (2006) have studied the mechanical properties of pultruded rods of unidirectional hybrid glass/carbon-epoxy composites and evaluated the retention of high-temperature properties up to 250°C. Matrix softening and loss of fiber-matrix adhesion were major factors influencing/effecting the strength reduction observed at high temperatures. The storage modulus, measured by dynamic mechanical analysis (DMA), showed temperature dependence nearly identical to the tensile strength of the composite A correlation was observed between the temperature dependences of the storage modulus and tensile strength in unidirectional composite rods produced by pultrusion. The similarity stems from the dependence of both the properties on matrix shear strength, which was strongly affected by the test temperature. DMA measurements of the storage modulus of the prototype composites revealed that matrix properties diminish at higher temperatures in a manner nearly identical to the tensile strength. Normalizing the storage modulus curves provided an accurate prediction of the temperature dependence of the tensile strength.
Wielage et al (2003) have investigated on processing of natural-fiber reinforced polymers and the resulting dynamic-mechanical properties. By means of dynamic mechanical analysis (DMA), selected application specific properties of flax-and hemp-fiber reinforced polypropylenes (PPs) have been determined for material characterisation. The compound samples were manufactured both by consolidation of hybrid nonwovens and compounding and injection moulding with the addition of natural fibers. The conditioning (long and short fibers), the manufacturing process and the processing parameters are the most important influencing factors on the mechanical properties of the final product. The results also reveal that the elastic properties (stiffness, storage modulus) of the composite material are dependent on the type of coupling agent. Other influencing parameters are the specific surface and the content of added fiber. The parameters mentioned can be varied by fiber separation or post treatment procedures. The recycling behaviour of natural-fiber reinforced PP shows that multiple processing has only insignificant influence on the fiber lengths and the mechanical properties. In addition, it is possible to draw conclusions very quickly about the quality of the composite material, such as fiber-matrix adhesion and damping behaviour. Fractographic evaluations through scanning electron microscope (SEM) confirm the quantitative characterization obtained from DMA. The DMA studies have also indicated the significance of fiber- matrix interface on the strength and damping characteristics of composites. The significance of coating of fiber on properties has also been highlighted.

2.5 ENERGY ABSORPTION

Apart from strength requirements, specifically high-energy absorbency/ unit mass is also possible with composite materials by initiating and maintaining proper failure mechanisms during the crack event. Metals absorb energy through plastic deformation, whereas, composite materials
absorb energy through interfaces and combination of failure mechanisms. It is known that stiffness and related properties of composite are load and loading-duration sensitive unlike metals. Kevlar reinforced composites absorb energy through an accordion buckling failure mechanism similar to the mechanism of metal structures. Graphite and glass-reinforced composites absorb energy through interfaces and failure mechanisms involving delamination, interply cracking, and fiber fracture. Because energy absorbency of a structure is directly dependent on the failure mode that occurs, and the failure mode is a function of the loading history and environment (Dubey and Vizzini 1998).

The overall energy absorbing ability of composite materials depends on properties of the composite components which include fibers, matrix, fiber matrix interface and interface between plies (Espinosa et al 1998). Beaumont (1979) concluded that with post debond fibers sliding appears to be the primary energy absorbing mechanism in glass fiber reinforced composites, whereas, fiber pull-out is responsible for much of the toughness in carbon fiber composites.

2.6 FATIGUE OF POLYMERIC COMPOSITES

During service of a component, if precise nature of the degradation can be determined or represented (Siow 1998), there is a hope of generating a rational philosophy, which can predict the behavior. The residual strength, residual life, and stiffness can be determined only through testing (through off line measurements only).

For the analysis of damage development in composite materials under quasi-static and dynamic (cyclic) loading, it is necessary to consider the following points (Siow et al 1998).
- The chronology and duration of damage-events, nature of damage development and damage mechanisms.
- The specification of ‘damage state’ which is to be used for stiffness and life determination (stress and strength state), in the same way that fracture mechanics in homogenous material is based.
- The development of a model based on experimental data, which can be used to predict the behavior.

Damage development in metallic materials under cyclic loading is concerned with yielding, threshold cross-over and crack initiation propagated as failure. However with composite materials, one has to consider initiation of damage and damage state which influences stiffness / life of the composites. The above discussion illustrates the important aspects of failure/damage in polymeric composites and also the need for damage tolerancing for composites materials. Based on this, a study is made on hole making of polymeric composites using emphasis on the defect generated during loading and their influence on structure of polymeric composites in containing the same. From this data, it might be possible to identify damage-property relationship.

The concept of fatigue was introduced by Wohler (1871) to classify material degradation or failure, which was proportional to the number of cycles of applied load. The term has been associated with single crack growth in homogenous material and crack growth rates has become the single most common design approach for dealing with such behavior. The fatigue behavior of composite materials is complex, owing to the microstructure that introduces a wide range of fatigue damage modes that normally act on one another to produce a collective result (Reifsnider 1980).
The matrix material frequently exhibits non-linear response such as yielding, plastic flow, creep and viscoelastic deformation. This non-linear response contributes different amounts to the response depending on the fiber orientation to the load direction. This effect is not just the anisotropy effect, but an interesting situation, which depends on the comparative anisotropy of stiffness and strength; a coupled effect. It is to be noted that strength and stiffness are not simply related.

The matrix related properties such as creep, plastic flow, strain hardening, cracking, crazing and other non-linear behavior affect fatigue in proportion to the degree of matrix control, which in turn is controlled by orientation of fibers and material properties. For graphite epoxy materials, the shear dominated matrix strength response may reach a maximum degree of influence at angles as small as 10° or 12°. This shows that orientation of reinforcing fibers has only marginal influence on fatigue behaviour.

An important laminate characteristic that influences fatigue response is the constraint effects exerted by each ply on other plies having different orientations, including the coupling of response characteristics that result from such constraints. The coupling effects are subtle and difficult to isolate, but their importance is appreciable for bending, shear and compressive, including stability behavior.

Lamination constraint stresses also introduce new damage modes during cyclic loading. If edges are present and not clamped, edge delamination may occur. The constraint effects can be classified as in plane effects and through the thickness effects (Kenneth Reifsnider 1980).

Fatigue behavior of composites differs considerably from that of metals in that they exhibit several modes of failure. One major difference between the behavior of composites and metals in fatigue is the change in
stiffness, which can occur continuously over a large portion of fatigue life to fracture. This phenomenon has been observed in fatigue testing of glass, graphite, and boron reinforced epoxy, glass reinforced polyester, and boron reinforced aluminum. Change in secant modulus can be used as a measure of damage. When fracture occurs, secant modulus in fatigue decreases to within the scatter of the secant modulus at static failure. In both static and fatigue, cracks appear early in 90° plies and then in the E 45° plies. These cracks eventually coalesce into partial delimitation (Hahn and Kim 1976).

Thus, an understanding is needed for designing composite materials, where we have the freedom to design the material to enhance or suppress observed or anticipated behavior. No other class of material has such great fatigue strength even when compared to their high static strength, and their extremely low fatigue notch sensitivity.

2.7 THE CHARACTERISTIC DAMAGE

The damage on continued cycling occurs by local debonding of interply bonds at the fronts or ahead of the interply cracks. This causes delamination, which grows in the interlaminar planes, leading to coalescence of adjacent delamination zones and stress enhancement in the separated plies. This enhances fiber breakage and induces instability of the damage developments leading to failure. The complexity of the damage development process has not yet allowed a quantitative description of the rates of the process (Talreja 1993). Woven Fabric Composites are useful class of composites in particular for structures with large thickness.

The change in Young's Modulus E/E₀ with fatigue life for fabric composite and straight fiber cross ply laminates has been compared. The difference in the two systems appears beyond 50% fatigue life suggesting that delamination at the undulating regions in the woven fabric is responsible for
the extra reduction in stiffness. The fatigue limit of woven fabric was found at 0.62% strain as compared to 0.85% for straight fiber cross ply laminate. This is attributable to interplaner weakness in the case of woven fabrics.

For long and continuous fiber composites the fiber orientation with respect to the loading direction has been seen as the major factor governing initiation and growth of cracking. The role of fibers is that of the primary load-bearing constituent and constraining element in the growth of matrix cracks.

2.8 DAMAGE MECHANISMS

2.8.1 Stiffness Reduction Mechanism in Composite Laminates

The three important mechanical properties of structural material are strength, stiffness and life. Measurement of strength or life during a test is not feasible as only one such measurement can be made on a specimen, and it is difficult to compare the damage states between two specimens. However, Stiffness measurements can be made frequently during a test without further degrading the specimen. Therefore, stiffness is a potential nondestructive parameter, which could be used to monitor the damage, which develops in a component during service, and to establish residual strength and life. The three principal damage modes - transverse cracking, delamination and fiber breakage may all contribute to the degradation of the mechanical response of the laminate, no single stiffness measurement will suffice to classify the damage (Highsmith and Reifsnider 1980).

2.9 MACHINING OF COMPOSITE MATERIALS

The literatures on processing of composite, dynamic mechanical analysis and fatigue performance of composite highlight the role of both matrix and reinforcements on physical properties and related fatigue
performance. Mostly the constraining element is the matrix causing crazing and delamination/debonding. Such damages and associated mechanisms act during machining as well.

2.9.1 Drilling of FRP

Composites are mostly used for structures and panels in automobiles and aircrafts. Hence drilling is the widely practiced machining operation in composites.

Hocheng and Tsao (2005) predicted the effects on delamination using a back-up plate in drilling composite materials with a saw drill and a core drill. Delamination can be effectively reduced or eliminated by decreasing the feed rate during exit and by using back-up plates to support and counteract the deflection. The approach used was to perform the experimental work and hold the machinability data to account for delamination of different materials for various tools and machining parameters. A mathematical analysis was carried out for drilling with a saw drill with and without back-up and with a core drill with and without back-up. Composite laminates from WFC200 fabric carbon fiber of coupon specimens 60 mm by 60 mm and 4 mm thickness were used as specimens. Drilling was carried out on a LEAD WELL MCV-610AP vertical machine with a Kistler 9273 piezoelectric dynamometer. Theoretical results were obtained based on classical elasticity, linear elastic fracture mechanics, and energy conservation law. The experiment showed that both drills with back-up offer a higher critical thrust force than those without backup. No delamination was observed at higher feed rate / higher thrust force.
Miller (1987) has studied the complexities of tough fibers embedded in a soft matrix and concluded that the machining of two phase materials calls not only for new concepts of tooling but also for different realms of cutting conditions. The thrust and torque during drilling of composites depend on cutting parameters and their behavior is similar to metal machining. However, the absolute value of the forces is of a magnitude depending on the nature of composite. A relatively high tool stress is observed for FRP (Konig and Graß 1989).

In drilling of FRP, the phenomena observed by Konig et al (1984), which resulted in the deterioration of quality of the cut work-piece are clogging deposition of the resolidified molten resin, curling of fibers, rounding of the cutting edge and flank wear of the tools. The brittle fracture of glass and carbon fibers is clearly identified as compared to the ductile fracture of the aramid fibers. They have suggested that the aramid fibers should be preloaded in tensile stress and then cut with a shearing action. This will minimize the tendency of fuzzy and clogging of chips curls over the cutting wedge. Konig et al (1985 and 1989) has shown that conventional machining is more preferred than non traditional machining of composites.

Sakuma et al (1983a and 1983b) carried out drilling of GFRP and CFRP using High Speed Steel (HSS) and carbide tipped drills. The wear of HSS drills was remarkably higher than that of carbide drills. Slender belt like grooves referred to as "combing wear" were observed during drilling of CFRP. They presumed that chipping in the early stage of drilling produced grooves. Concentration of fibers into hollows (bundling) accelerates the groove like wear. The sharp fracture of the fiber and consequent transients on the cutting edge, results in segmental chipping/cracking over the cutting wedge.
Drilling tests were carried out on GFRP composites in order to verify the effect of machining parameters on the cut quality (Tagliaferri et al 1989). Experimental results showed that the quality index was strongly affected by the cutting speed (V) to feed (s) ratio.

Jain and Yang (1993) have proposed a model to predict critical thrust and feed rates at different ply levels for unidirectional laminates. Chisel edge has been identified as the major contributor to the thrust force, the point angle being only of secondary importance. According to them, an increase or decrease of point angle will not affect the forces during drilling. The composite materials being poor conductors of heat, the heat developed during machining has to be carried by the tool itself. Increasing the point angle will reduce the area of heat transfer causing additional (tool) stability problems. Moreover, as per their studies, small chisel edge and low point angle are beneficial, but the stability of the tool to provide sufficient strength and hardness at those small dimensions may be a limiting factor. Recent developments in modified point drills are in the direction for thrust force reduction in drilling. This includes zherov point drills and tripod drills.

Twist drills with a positive rake angle at the outermost periphery, obtained by means of a ‘C’ shaped cutting edge have been suggested by Doerr et al (1985). To obtain good quality holes in FRP's, it is required to reduce the thrust and torque. Johanson and Mattila (1977) found that holes of only one-meter length in total could be drilled before HSS drills were worn out when drilling 0.6 mm holes at a speed of 1.5m/s. Runikutgumjorn (1978) found that by drilling hybrid composites, the drills last for only a few holes before they are broken down. Force fluctuation and severe abrasion account for this.

An important aspect of study on composite drilling is to find the cutting energy and cutting temperature in the drilling zone. Konig and Graß (1989) reported that only a small portion of heat generated flows through the
chip and work material unlike in metal cutting where majority of heat generated is carried by the chip and workpiece. Thus in GFRP drilling, a relatively higher stress (both mechanical and thermal) on the tool occurs. This stress increases with increase in feed rate, as the time available for transfer of heat to workpiece is further reduced. Sakuma and Seto (1981) used various tool materials to study the relation between cutting temperature and tool wear in turning of GFRP composites. They found that the temperature at the cutting edge is lower with higher thermal conductivity of tool material.

During drilling of graphite composite materials, high surface finish is attributed to the characteristics of composites, such as sharp fracture of fibers and absence of any matrix material being pulled out. Precision tooling like diamond is suggested, while HSS tools suffer extreme wear and these should not be used for composite processing. Carbide tipped insert is suggested as a good alternative to HSS tools (Friend et al 1972).

Jain and Yang (1994) have developed expressions for critical thrust and critical feed rates by modeling the delamination zone as an elliptical plate in unidirectional laminates. The model though developed for unidirectional laminates, they claim it can be used for multi-directional laminates. Small chisel edge length is preferred, but the ability of the tool to provide sufficient strength and hardness at those small dimensions was tested. For smaller diameters, the model seems to be better, but for larger diameters these drills give rise to thrust force larger than the critical thrust. A diamond impregnated tubular drill was suggested such that the mechanism of material removal was changed to that of grinding. It is almost like trepanning without any thrust force. Moreover, in conventional drilling, the entire volume under the tool diameter is cut down into small chips and for the tubular drill, depending on the wall thickness only a fraction of the entire volume is ground away. Finally, a conventional drill due to its point angle needs to travel an extra
distance in order to completely clear the laminate, whereas, due to its flat end, the tubular drill can stop right after it reaches the bottom of the laminate resulting in time saving and also reduction in exit damages.

Di Paolo et al (1996) studied on the length of the damage as the drill emerged from the workpiece and was correlated to the measured cutting forces at the drill exit. The thrust and the torque forces arising in the various cutting regions on the drill in terms of the tool geometry parameters and machining conditions were modeled. Three significant damage mechanisms have been identified as being responsible for delamination growth. They are plate bulge, spall opening and spall tearing/twisting. The thrust force is due to both the squeezing action of the chisel edge and cutting action of the cutting lips. The damage outside the radius of the drill is produced for high-speed condition. But for low feed, the damage is within the radius. But the paper does not give any information about the variation of torque/force as a function of angular rotation.

Finite element analysis was used to predict the load causing delamination in graphite/epoxy laminate during drilling operations. The results indicated that, the thrust force for delamination decreases as the uncut portion of the laminate decreases. With an aluminum plate backing the laminate, the drilling force for induced delamination can be significantly increased. However, either with or without a support, the laminate will delaminate at a very small drilling load if the uncut portion is small. It is suggested that the drilling operation should be controlled to prevent delamination as the drill approaches the exit plane. This can be accomplished by reducing the drill feed rate as the tool approaches the exit plane (Sadat et al 1992).

Radhakrishnan and Wu (1981) have evaluated the on-line hole quality of FRP composites by using dynamic data system techniques. They
analyzed the dynamic characteristics of the drilling thrust, the corresponding hole surface and obtained a good correlation. Lamination frequency, unique in FRP was considered to constitute the waviness aspect of the hole surface and its standard deviation was found to correlate with drill damage.

Most of the problems associated with drilling of composites in general, are quality related. It is generally regarded as a resin or matrix dominated failure behavior, which usually occurs in the inter-ply region. The direction of maximum damage propagation is when the drill cutting lips are in the region of about the 0/180-degree cutting orientation line. The damage appears to be unaffected during the rest of the drill rotation (Petrof 1986). Cutting along fiber direction will result in buckling/deformation and consequent damage intensity.

The mechanistic approach adopted to develop models to predict thrust and torque at the different regions of cutting drill exploits the geometry of the process, which is independent of the workpiece material. Models were calibrated for a particular material using relationship between chip load and cutting forces, which are modified to take advantage of the characteristics of drill point geometry. For FRP composites, only orthogonal cutting was assumed for the chisel edge. But here, the model predications do not seem to match the experimental data suggesting that the assumptions are incorrect and there is an additional thrust/push mechanism that occurs at the chisel edge while drilling FRP composites (Chandrasekharan et al 1995). With normal point geometry chisel edge mostly extrudes the material; hence to reduce the consequent thrust chisel edge is modified to present two more cutting edges (Zherov point).

Stone and Krishnamurthy (1996) implemented a neural network based thrust force control scheme for graphite/epoxy composites with the aim of minimizing delamination. Equations were developed using fracture
mechanics approach. Testing of the model was carried out only with carbon/epoxy composites. Water-soluble oil was used as a coolant. No absorption of the coolant fluid was observed during the short time of drilling.

The cracking of the top surface of the workpiece is usually insignificant (peeling off effect), but at the exit surface, the drill causes significant cracking which can affect the integrity of the surface. Exit delamination was found to influence only the compressive strength and not the tensile or fatigue strength of the laminate. Further tests were required to verify these trends. Proposed delamination requirements were relaxed to a growth to three hole diameters in length for non-compression applications. But for the other environment applications delamination growth should be minimized if not eliminated (Pengra and Wood 1980).

Drilling of unidirectional CFRP laminates were conducted using HSS and carbide tipped drills (Wen-Chou Chen 1997). The variation of thrust force and torque at the entrance and exit were different with and without the onset of delamination. In drilling mostly exit-delamination occurs; like any other defect, delamination can influence the fatigue life. A linear relationship between average thrust force and delamination factor was found for unidirectional and multidirectional CFRP composites. The relationships between the above forces vary with different composite laminates using the same tool material and cutting conditions. It was observed that flank surface temperature of the drill increases with increasing cutting speed but decreasing feed rate. Normally reduction in feed rate increases the effective clearance angle and reduces the temperature.

Velayudham et al (2005) have evaluated the drilling characteristics of glass reinforced polymeric composite. The glass reinforced composite used in their experiments had high volume fraction of fiber glass reinforcement, which means that the volumetric fraction of the reinforcement to that of the
matrix material was high. The authors tried to study the drilling characteristics of a composite material that is used mainly for structural purposes. For most engineering applications of GFRP composite, the glass fiber reinforcement is restricted to within 20% lest the composite should become brittle. However higher volume fraction composite is generally used in places that need higher load bearing capacity. A higher fraction would mean that the energy absorption of the composite will be higher. The drilling experiments were performed on a universal milling machine. A two-component piezoelectric dynamometer was used to measure thrust force and torque. Machining induced Vibration was monitored using an accelerometer. Data from the dynamometer and the accelerometer were fed to the computer for further analysis. The author also measured flank wear using a Universal measuring microscope. Flank wear was measured after a specific number of holes were drilled. From this study, the following conclusions are drawn:

- With higher cutting speed and feed (80.4 m/min and 315 mm/min) lower order peak thrust and torque were monitored. Only a marginal variation in thrust and wear occurs with 80.4 m/min of cutting speed and 400 mm/min.

- Thrust constrained drilling results in controlled variation in hole size. Wavelet packet decomposition of monitored vibration signal provides comprehensive and distinguishable time–frequency information about tool cutting conditions.

- A good correlation between vibration power spectrum and wavelet packet transform can be seen. A critical wear of around 60μm can be seen above which there is a rapid increase in vibration power and corresponding wavelet coefficient.
Ramkumar et al (2004) have attempted a newer technique of superimposing oscillatory vibration to minimize the damages during drilling of GFRP composites. Compared to conventional drilling, this method has resulted in reduced cutting forces, reduced tool wear and consequent damages.

Arul et al (2006a) have observed during study on drilling of GFRP composites using HSS drill that monitored parametric influence on flank wear, showed minimum wear with best cutting parameters. Also, relatively closer variation in flank wear was seen with minimum feed rate. Arul et al (2006b) have reported that the defects in drilling of composites are due to thrust force experienced by the work piece. The parametric influence on cutting force was also experimentally evaluated. The experimental results show that the defect’s tolerated drilling can be attained by proper selection of cutting parameters and tool material/geometry.

Velayudham and Krishnamurthy (2007) have shown that point geometry of twist drills could be modified to minimize thrust and consequent defects.

From the investigative analysis of parametric influence on delamination factor in high-speed drilling of carbon fiber reinforced plastic (CFRP) composites, it has been observed that high-speed cutting plays a major role in reducing damage at the entrance of hole. On the other hand, the combination of low feed rate and point angle is also essential in minimizing delamination (Gaitonde et al 2008). The direct effect analysis reveals that the delamination is sensitive to all three parameters, namely, spindle speed, feed rate and point angle. A combination of high speed and low values of feed rate and point angle seems to be an appropriate selection for minimizing the delamination (Karnik et al 2008). The delamination factor increases with both cutting parameters, which means that the composite damage is bigger for
higher cutting speed and for higher feed. The cutting velocity is the cutting parameter that has the highest physical as well as statistical influence on the delamination factor in CFRP laminate (Davim et al 2003).

Apart from drilling, composites were also machined by turning process. Santhanakrishnan et al (1989a, b) have carried out face turning trials on glass fiber reinforced plastics (GFRP), carbon fiber reinforced plastics (CFRP) and Kevlar fiber reinforced plastics (KFRP) cylindrical tubes to study their machined surfaces for possible application as friction surfaces. The surface roughness obtained and the observed morphology of the machined surface of fiber reinforced plastics (FRP) composites were compared and is reported in the work. Among the machined composite surfaces, CFRP exhibited the best finish value. The best surface structure of CFRP is due to the least fiber pull out with insignificant loose fibers / fiber protrusions on the surface.

The machinability of GFRP influenced by tool materials and geometries was investigated experimentally by Sang-Ook An et al (1997). By proper selection of cutting tool material and geometry, excellent machining of the work piece can be achieved. The surface quality relates closely to the feed rate and the cutting tools. They have concluded that single crystal diamond tool was more effective in terms of good surface quality and lower cutting force, since the single crystal diamond tool possesses the characteristics of excellent sharp edge and good thermal conductivity. Cutting tool with straight edge geometry performs better than the round edge cutting tool, for the improvement of surface texture in GFRP machining. They have also reported that the surface roughness was not related to depth of cut and cutting speed, with respect to various tools. This is usually the trend; however round cutting edge with relatively larger nose radius can yield better surface texture, at the cost of higher force.
Paulo Davim and Francisco Mata (2005, 2007 and 2008) have studied the machinability in turning processes of fiber reinforced plastics (FRP) using polycrystalline diamond cutting tools. Controlled machining experiments were performed with cutting parameters prefixed with the work piece. A statistical technique, using orthogonal arrays and analysis of variance, was employed to investigate the influence of cutting parameters on specific cutting pressure and surface roughness. The objective is to evaluate the machinability of these materials as a function of manufacturing process (filament winding and hand lay-up). A new machinability index was also proposed. The new machinability index was calculated by using the following equation (2.1).

\[
\text{MI} = \frac{1}{K_S \times \alpha} \left( \frac{1}{R_a \times \beta} \right) \times 10^3
\]  

(2.1)

where, \(K_S\) is the Specific cutting pressure and can be calculated by using the following equation (2.2).

\[
K_S = \frac{F_c}{S} = \frac{F_c}{(f \times d)}
\]  

(2.2)

where

- \(\text{MI}\) - Machinability Index
- \(F_c\) - Cutting force
- \(S\) - Chip section
- \(R_a\) - Surface roughness
- \(f\) - Feed rate
- \(d\) - Depth of cut
- \(\alpha, \beta\) - Co-efficients

It is seen that machinability index is inversely proportional to specific cutting pressure and surface roughness parameter. Mostly cutting pressure and surface roughness are influenced by the stability of the cutting
nose. Normally, machining with fine feed and depth of cut results in triangulation wear of the nose region which affects its geometry.

Paulo Davim et al (2004) have investigated on the machinability of glass fiber reinforced plastics (GFRP’s) manufactured by hand lay-up method. The objective of the work is to evaluate the machinability of these materials as a function of cutting tool (polycrystalline diamond and cemented carbide tools). The study concludes that feed rate is the cutting parameter that has the highest physical and statistical influence on surface roughness and specific cutting pressure.

Arola and Ramulu (1994) have investigated on the chip formation mechanism in orthogonal trimming of a graphite epoxy composite using polycrystalline diamond cutting tools. They have found the characteristic chip formation to be primarily dependent on the fiber orientation. With 0° fiber orientation, the chip formation mechanism included failure along with fiber-matrix interface through cantilever bending and fracture perpendicular to the fiber direction. In positive fiber orientations up to 75°, chip formation involved compressive loading-induced shear at the tool nose. In the 90° and negative fiber orientations, the chip formation mechanism was composed of out-of-plane shear with severe compressive loading-induced interlaminar deformation (upsetting ahead of the tool).

Koplev et al (1983) have conducted experiments on the orthogonal cutting of unidirectional-carbon fiber reinforced plastic (UD-CFRP) laminates at 0° and 90° fiber directions in order to understand the chip formation process. They have found that the chip creation process includes crack propagation parallel to the cutting direction, bending of the fibers in front of the cutting tool and a fracture perpendicular to the fiber direction, which releases the chip from the specimen. Unlike metals, the chip formation is accompanied by a series of brittle fractures and there is negligible plastic
deformation. They have also discussed observations on the machined surface as a function of machining orientation relative to the fiber direction (upset lumps, with minimum deformation).

Wang et al (1995a) have conducted an experimental study of orthogonal cutting mechanisms in the edge trimming of unidirectional graphite/epoxy composite laminate with polycrystalline diamond tools. The effects of tool geometry and operating conditions were evaluated from an analysis of chip formation, cutting force and machined surface topography. All aspects of material removal were found to be primarily dependent on the fiber orientation. Discontinuous chip formation was noted throughout this study, regardless of trimming parameters. Chip dimensions and force measurements depicted a change in chip formation with fiber orientation, and the presence of three distinct mechanisms in edge trimming of fiber reinforced composite material. With 0° fiber orientation, chip formation mechanisms included fracture along the fiber/matrix interface attributed to cantilever bending, followed by fracture perpendicular to the fiber direction. In positive fiber orientations up to 75°, chip formation comprised compression induced shear perpendicular to the fiber axis. Chip release occurred through fracture along the fiber/matrix interface. In the case of 90° and negative fiber orientations, chip formation and material removal in trimming of unidirectional material was construed of both in and out of plane shear fracture along the fiber/matrix interface with a severe macro deformation induced by compressive tool load. A combination of cutting, shearing and fracture along fiber/matrix interface was observed. This is mostly due to possible buckling of the fiber and consequent failure over the interface.

Wang et al (1995b) have further studied the graphite /epoxy multidirectional composite laminate. Cutting mechanisms for 0° and 45° plies
were identical to those for trimming the unidirectional material. However, chip formation mechanisms in trimming 90° and -45° plies of the multidirectional laminate changed due to the support provided by adjacent plies. Empirical cutting force models for principal and thrust force components were constructed by factorial design and regression methods. Empirical modeling suggests that the optimum tool geometry for minimizing the resultant cutting force is constituted by 6-7° rake with a 17° clearance angle.

Puw and Hocheng (1998) have explained that fiber angle plays the most important role in the mechanism of chip formation and affects the quality of cut in the case of fiber-reinforced composite material. Cutting conditions show relatively insignificant influence. They have studied analytically and experimentally the chip formation in the case of cutting perpendicular to the unidirectional fiber reinforcement as a fundamental reference for adequate machining of FRP. Bending failure is found to produce chips in cutting perpendicular to fibers. Elementary beam theory and laminate mechanics are used to construct a model of the chip formation. Correlation between the cutting force, chip thickness and chip length is established. The proposed model explains the experimental results as well. Separation of chip instead of a single complete chip often occurs due to the intrinsic bonding defects. The experiment also shows post matured overbent chips due to inhomogeneous local material strength. The average of their chip dimensions agrees with the predicted value. Based on the acquired knowledge, one can better understand the problem of cut integrity in machining FRP and further development methods to cut this material properly. It is surprising to note that machining condition exert insignificant influence on performance. Cutting condition influences the status of tool-work interface and consequently the cutting dynamics and quality of the machined surface.
Caprino et al (1996) have investigated on the effect of tool wear on cutting forces in the orthogonal cutting of unidirectional glass fiber reinforced plastics. Orthogonal cutting tests were carried on unidirectional GFRP composites, holding cutting direction parallel to the fiber direction with HSS tools. The microscopic examination of the worn tools showed that both the face and flank wear essentially consisted of more and more marked rounding or plastic deformation of the tool at increasing cutting lengths. No crater formation on the tool was observed, probably because of the absence of notable thermal effects due to the low cutting speeds adopted or notable chip contact (due to short segmental chip). The tool wear was found to be very rapid and progressed on both the face and flank approximately at the same rate. Higher relief angle seems to result in lower flank wear. However, it is to be limited considering the strength of tool-nose. Both the horizontal and vertical forces undergo large variations with increasing tool wear.

Eitoku Nakanishi et al (2003) have observed the deformation and dynamic fracture phenomena of aramid fiber microscopically during machining aramid fiber reinforced plastics (AFRP). Machining of AFRP causes rough machined surfaces. The surface condition is much affected by orientation of fibers. For the fiber angle of 45°, peeling at fiber matrix interface and large deformation of aramid fiber within the matrix could be clearly observed. This induces inferior surface. A simulation based on Timoshenko’s theory of beams on elastic foundation was made. In the analysis, the beams were regarded as aramid fibers and the elastic foundation as matrix material.

Mathew et al (1999) have studied the trepanning of E-glass/epoxy unidirectional laminates. Trepanning tools, which were used in this study, were found to give reduced thrust while making holes on thin laminates. In the case of trepanning tools, cutting action starts from the periphery of the
cutting edge of the tool which puts the fibers in tension during the entire cutting operation. The fact that the fibers are in tension (without buckling) when they are being cut makes the cutting easier. The models for prediction of critical thrust and critical feed rate at the onset of delamination during trepanning of unidirectional composites based on fracture mechanics and plate theory also have been presented. The process is however affected by constraints on feed rate.

2.9.2 Unconventional Machining

Apart from traditional machining, composites were also subjected to select unconventional machining processes. Composite materials are being increasingly used in high performance applications owing to their superior specific strength and stiffness. However, the macroscopically distinct multiphase material structure makes such materials difficult to machine with conventional tools. Ordinary cutting tools wear drastically. To overcome the rapid tool wear experienced in conventional machining of some composites containing hard, abrasive or refractive constituents, alternative material removal operations have been adopted. Laser machining, water jet cutting and abrasive jet cutting, electrical discharge machining are basically non-contact machining operations.

Among the non-traditional machining technologies, laser and water jet techniques produce satisfactory cut-quality for aramid fiber composites due to their extremely localized action. The former produces a narrow heat affected zone and is characterized by the absence of forces on the laminate. With water jet cutting, absorption of water by the composite will weaken the composite. Both these techniques are suitable for contouring operations and performing large and fast cuts, but are not suitable for the production of small holes for rivets and bolts (Hurlburt and Cheung 1985).
2.9.2.1 Laser machining

Laser machining is based on the interaction of the work material with an intense, highly directional coherent monochromatic beam of photon light, by which material is removed predominantly by melting and/or vaporization. In the case of resin matrix material, it is removed by chemical degradation. The type of laser to be used for the machining of a given composite depends upon the following characteristics of the beam and the work material properties like power density, wavelength of emission, interaction time, polarization of the beam, absorption coefficient at the given wavelength, melting and vaporization temperature, thermal conductivity, heat capacity diffusivity, and heat of vaporization.

Laser machining, a non-contact process does not involve any mechanical cutting forces and tool wear. However, as laser cutting is based on the interaction of the laser beam with the composites, defects that are thermal in origin will arise if proper care is not taken regarding the selection of the cutting parameters. Mathew et al (1999) have conducted parametric studies on pulsed Nd: YaG laser cutting of carbon fiber reinforced plastic composites. Predictive models have been developed based on important process parameters, viz. cutting speed, pulse energy, pulse duration, pulse repetition rate and gas pressure. The responses considered are the heat affected zone and the taper of the cut surface (kerf). The optimization of process parameters was done using response surface methodology (RSM). They have concluded that the thermal properties of the constituent materials and the volume fraction of the fibers are the principal factors that control the cutting performance. The differential thermal properties of the matrix and reinforcement of the composite can result in dimensional defects and excessive fiber projection.

Laser Machining is characterized by a small heat affected zone in a narrow kerf and a very narrow zone of transformed material along the edge.
But the thermoplastics with their relatively low melting temperature will generally have a transformed zone more than the temperature resistant thermosetting plastics. Kerf is found to be increasing linearly with the thickness. Edge roughness increases with increasing feed rate. Because of the absence of tool contact, laminates can be machined at high speeds without cracking, crazing or mechanical degradation of the edge (Vanderwert 1983).

Hand laid GFRP, CFRP and AFRP were cut by a CO₂ laser (Caprino and Tagliaferri 1988). From the observations, it was seen that high power laser systems with high feed rates gave the best performance. This would permit high quality together with high productivity. A thermal model correlating maximum cutting speed, power and material thickness has been developed. With lower power densities and feed rates, bulk conduction losses will take place and the model developed will probably fail, since the model was expected to work for high power density and feed rates where the heat conduction losses can be neglected and the process is considered quasi adiabatic. It is to be noted that flux density / power intensity of CO₂ laser is lower than that of solid state Nd:YaG laser (owing to different wavelengths). This is significantly influences the material response.

Yung et al (2002) have discussed the characteristics of the heat affected zone (HAZ) of a UV YAG laser-drilled hole in GFRP printed circuit boards. The structures of these HAZ produced by different laser parameters were analyzed. The structure of the HAZ is strongly influenced by the average laser power and pulse repetition rate. However, the differential thermal properties of matrix and reinforcement can pose quality related problems. Since laser machining is a thermal process, polymeric composites with widely varying thermal properties of the constituents will pose serious problems to productivity-error control.
2.9.2.2 Water jet machining

Apart from application of intense transient heating by laser, application of mechanical transients can also facilitate machining of composite materials. As early as 1974, Mohapat and Burns (1974) have provided an equation for energy balance and predicted the depth of cut for machining of polymers by water jet cutting as a function of nozzle diameter, nozzle pressure and feed rate. Since the cutting theory includes material property of energy absorbed per unit volume during cutting, which is unknown, it requires preliminary experiments to determine several coefficients within the equation.

High pressure water jet cutting, with or without abrasives is a possible process for machining non-homogeneous materials, such as polymer matrix composite materials. Water cools the workpiece and hence minimizes the thermal deformation problems commonly experienced in conventional machining of composites. A narrow kerf, minimum amount of dust and toxic fumes, and practically no delamination effects are the salient features of this system (Komanduri 1993). The rapid tool wear commonly experienced in conventional machining of composites is not an issue in water jet cutting or abrasive water jet cutting. However, absorption of water may pose a serious problem.

Hocheng and Chang (1994) presented an analytical approach to study the delamination-defect during drilling by water jet piercing. The analysis uses fracture mechanics with plate theory to describe the mechanism of delamination as a function of hole depth and material parameters. The absorption of water/moisture and also impregnation (hydraulic wedge) can pose integrity related problems.
Kerf geometry, kerf wall features and cutting front characteristics of abrasive water jet machined graphite/epoxy composites were studied by Arola and Ramulu (1996). A macroscopic analysis suggests that, the geometrical features associated with water jet machining of graphite/epoxy laminates were influenced by their macro regions along with the cutting depths. The presence of these regions including initial damages at jet entry, smooth cutting over the middle region and rough cutting where the jet exits depends on operating conditions. Cutting front analysis revealed that, the mechanism of material removal does not change over the jet penetration. In general, high quality uniform cuts may be obtained by minimizing initial damage at the jet entry and by extending the smooth cutting region beyond the laminate thickness through the appropriate choice of cutting parameters (effective defocusing).

2.9.2.3 Ultrasonic assisted machining

Ultrasonic assisted drilling involves the use of tools where an axial vibratory motion at high frequency is superimposed. Ultrasonic vibration can reduce friction, break chips and reduce tool wear. It is particularly a useful technique when the matrix or the reinforcing fibers are hard, brittle materials; though slow, the operation can result in high finish and accuracy of intricate parts. It is advantageous to cut prepregs with an ultrasonic knife which separates the individual fibers in the rovings. When applied to brittle fibers this oscillation supported by feed force, initiates separation at low degree of deviation by inducing locally limited fracture systems. In contrast to machining of glass and ceramics, this process specifically exploits the brittleness and low fracture toughness of the material to achieve the machining on a low force level. Fiber reinforced thermoplastics have higher impact toughness, fracture strain and in particular non-deformability at temperatures up to 250°C due to the development of high temperature
resistant thermoplastics, such as polyetherimid (PEI), polyetheretherketone (PEEK), polyethersulfone (PES) and polyamidimide. It is the extreme ductility of the thermoplastics matrix which is a problem specific to this process. The routing of unidirectional glass-fiber reinforced polyetherimid shows that high process temperatures combined with poor thermal conductivity of material soften the polymer in the area of engagement. The molten material adheres to the relief face of the tool, thus intensifying friction. Unlike the cutting of fiber reinforced thermosets, there is no dust generation in the routing of thermoplastics. Chip formation occurs especially at 90° fiber orientation. Due to the brittle fibers, there are no continuous chips but shapes that can be compared to lamellar chips. According to the state of the art, the formation of chips is caused by the considerably high impact toughness and fracture strain of thermoplastic matrices. These properties manifest themselves in a plastic deformation of the matrix before this is cut (upsetting ahead of the tool wedge). Carbon fiber and glass fiber reinforcements differ only marginally. This kind of material removal is best regarding the protection of the operator and machine tool. Since the chips are about 15 times larger than those of thermosets, there is no hazard of pulmonary affection, and the enclosure of both working area and machine parts is less problematic.

2.9.2.4 Ultrasonic machining

Ultrasonic machining is suitable for composite materials owing to nature of material removal by impingement of small individual abrasives. Ho-Cheng and Hsu (1995) have conducted experiments on the ultrasonic drilling of carbon/epoxy and carbon/PEEK. The examination of surfaces and abrasives after machining illustrates machining by hammering and impact of the abrasive particles on the workpiece.Brittle fracture of fibers and plastic deformation of matrix are seen. The research highlighted the influence of the
concentration of abrasives, the size of abrasive grains, the energy of ultrasonic oscillation and the feed rate of tool on the machinability in terms of material removal rate, surface roughness and hole accuracy. Dimensional analysis synthesizes the significant parameters in machining. Ultrasonic machining can produce better surface finish and hole quality than conventional drilling. However, absorption of slurry used for machining can be a problem. Even with ultrasonic machining, delamination can occur to a limited extent.

2.9.2.5 Electrical discharge machining

Electrical discharge machining (EDM) can make complex shapes with high precision. It is a slow process, but automation can bring down the cost of manufacturing. The pre-requisite for EDM is that the work material be electrically conducting. Organic matrix materials are therefore not materials for this method of machining. They can be made conductive by being impregnated with metallic fillers, but that can defeat the purpose of composites for high strength and lightweight applications (Komanduri 1993).

Guu and Hocheng (2001) have investigated on EDM of carbon fiber reinforced carbon composites. Empirical model of the composite was also proposed based on the experimental data. Experimental results indicate that the extent of delamination, thickness of the recast layer and surface roughness are proportional to the power input. EDM process can effectively produce excellent surface characteristics and high quality hole in composites under low discharge energy conditions. The occurrence recast, resolidified layer with polymeric composites can be highly stochastic. Especially in the case of polymeric composites with widely different melting point of ingredients, quality of machined surface cannot be sustained.
2.10 VIBRATORY DRILLING

Arul et al (2006b) have tried to study the effect of vibratory drilling on the quality of the holes drilled. The primary difference between conventional drilling and vibratory drilling is that conventional drilling is a continuous process, whereas, vibratory drilling is a pulsed process. Conventional drilling and vibratory drilling were performed on glass fabric reinforced plastic (GFRP) composite of 4 mm thickness. The reinforcing material used for the experiments was woven glass fabric, and the matrix material was commercially available epoxy resin L Y-556. Experiments were performed with cutting speeds of 9.43 to 30.16 m/min, feed rates of 0.02 to 0.06 mm/rev, vibration frequency of 50 to 300 Hz, and vibration amplitude of 5 to 20 µm. The authors utilized an improvised technique of low-frequency, high-amplitude vibratory drilling, and inducing vibration in the direction of the feed. They found that, by following this new technique, the thrust force can be reduced which in turn leads to an improvement in the quality of the hole drilled.

Zhang et al (2001) have theoretically predicted the mean values of thrust and torque in vibratory drilling of composite. Model is based on mechanics of vibration assisted cutting and the continuous distributions of thrust and torque along the chisel edge and the lip of a twist drill. The result of a simulation study has shown good agreement between the theoretical predictions and the experimental evidences. For the same cutting conditions, the thrust and torque by the vibration assisted drilling method are reduced by 20-30% when compared with conventional drilling.

Chhabra et al (2002) have developed a new machine tool based on linear drive technology for low frequency modulated assisted drilling. Results pertaining to torque, thrust and controlled chip breakage when drilling ductile aluminum alloys were presented. Applying superimposed modulation of
appropriate frequency and amplitude produces consistent chip breakage, thereby, facilitating easy drilling process. These conditions lead to reduction in mean torque and thrust values when compared with conventional drilling. A simple model for chip formation and forces in modulation-assisted drilling which predicts the optimal frequency and amplitude was also developed and verified.

Liu et al (2002) have characterized the cutting force in the vibration cutting of a particle reinforced metal matrix composites SiCp / Al. The influences of three cutting parameters, namely cutting velocity, amount of feed and cutting depth on the cutting force were analyzed for both with and without vibration. The ultrasonic vibration turning produces a much lower main cutting force than that in normal turning when adopting smaller cutting parameters, but when using larger cutting parameters, the difference will become inconspicuous. There are remarkable differences in cutting force-cutting velocity characteristics in ultrasonic vibration turning, which is mainly because a built-up edge does not emerge in ultrasonic turning. The main objective of inducing vibration during cutting is to minimize the thickness of the chip periodically so that segmental chip only results; this will influence the cutting performance.

Xiao et al (2002) have showed experimentally that chatter is effectively suppressed without relying on the tool geometry and the work displacement amplitudes are reduced from a wide range of $10-10^2$ microns to the range of 3-5 microns by applying vibratory cutting. A new cutting model, which contains a vibratory cutting process, was also proposed. Simulations of the chatter model exhibit the main feature of charter suppression in vibratory cutting. The simulation results are in good agreement with the measured values and accurately predict the work displacement amplitudes of vibratory cutting.
Zhang et al (2002a) have investigated the fracture mechanisms during the vibration assisted drilling of holes in ceramics. The reasons for material removal are believed to be ploughing and hammering of the effective abrasive grain on the end face of the drill. The results show that, in the terminal period of vibration drilling, the stress on the periphery of the hole exit are at its maximum. The condition for no fracture at the exit is achieved by applying a uniformly distributed reaction force (opposite to feed direction) to the back surface of the workpiece. This shows that even with vibratory drilling one has to anticipate fracture (delamination at exit).

Ramkumar et al (2004) have investigated the effect of workpiece vibration on drilling of GFRP laminates. It was observed that by vibrating the work piece during drilling tool wear, temperature, power and surface roughness can be very much reduced.

2.11 FINE BLANKING - CHARACTERISTICS

Thiruvarudchelvan and Ong (1990) have conducted experiment on fine blanking and shown that by applying radial compressive stress, some improvement in piercing holes is possible. The urethane pad exerts radial compressive stress on the sheet metal being pierced. Though, there is no way of measuring the magnitude of the stress to compare with the theoretical prediction, results are found to be encouraging. With the tests reported in this paper, the following are improved with the present method: (i) the penetration before fracture; (ii) the edge radius. The force needed is about 2 to 3 times that needed in conventional piercing, but this is on account of having to compress the polyurethane, most of the energy involved being recovered on the return stroke. Also the taper/relief given on punch/die face for scissoring the blank in conventional die set up is absent; this contributes the observed higher force. The essence of fine blanking (piercing) is inducing perfect shear during blanking, by the application of suitable hydrostatic compression on the
blank and apt for tool design. Further tests, perhaps with increased radial compressive stress, may give better results.

Morreale et al (1992) have developed software to study the fine-blanking process. Once the boundaries are given through a set of data files concerning the geometry, the slip lines are determined automatically. Friction and simulation of work hardening are considered in building the slip line field. Although, the slip line method allows for an approximate calculation of stresses and strain rates during forming, the comparisons with experiments are very satisfying. It was found possible to evaluate the influence of the tool configuration on the quality of the fine blanking. This code is thus a powerful means of simulating quickly numerous forming processes.

Solkowski et al (1992) have analyzed the cold fine-blanking of the hole at bottom of drop-forged parts is possible, and reported that is economically advantageous since boring of the ports is then eliminated. Nevertheless, to increase the dimensional accuracy of the blanked ports, the forged holes that are pre-designed for the ports should have a geometry that is different from the traditional geometry. The holes should be made on one side - the upper - only or if they are to be made on both sides, they should be unsymmetrical, the lower hole being of smaller diameter than the upper hole.

The hot- and warm-blanking of hole bottoms of this shape, employing a very small clearance, assure a smooth and satisfactory sheared surface. In cold-blanking, by choosing the optimum clearance and by heat-treating the forged steel parts by normalizing, a non-severe and uniform fracture can be obtained, where-by, use of a simple subsequent plastic equalizing operation, the ports surfaces can be finished to specification.

Chan et al (1998) have compared the fine blanking process with that of bar cropping. They reported that in fine-blanking, the cutting surface quality is good due to the blank-holding force exerted by the vee-ring
projection of the stripping plate in the entire cutting process. However, in the bar cropping process, the cutting surface quality is poorer than that of fine blanking for the same die and blade clearances, due to the lack of an additional force (hydrostatic stress) that is present in the fine-blanking process.

Klocke et al (2001) have investigated the blanking and fine blanking processes through finite element simulations. This holds true for the investigation into the tool load and coating-related topics, which helps in solving problems concerning tool life. Workpiece geometry can be calculated. The formation of cracks, which is to be avoided in fine blanking, can be forecasted. Different combination of tool element forces, clearance, friction properties and blanking material can be modeled and allowed for an optimization of blanking parameters with the computer. This can hardly be done in practical tests due to the high effort that would be involved because of numerous variations.

Chen et al (1999) have conducted the study of fine blanking process using large deformation FEM. In order to avoid the accumulation of errors due to rigid body rotations, an incrementally objective mid-interval integration algorithm has been proposed. To deal with large rotations and unloading, a consistent tangent operator and full Newton–Raphson iterative solution schemes together with the projection integration algorithm and line search algorithm have been used to preserve the computation convergence. From the numerical results, it may be concluded that the shear band will occur in the regions around the cutting edges and the clearance zone. Under the high hydrostatic stress, the growth of shear band will eventually cause the shear fracture of the workpiece. Hence, a smooth cutting surface of fine-blanked parts can be achieved. In normal blanking process, the pushing of the material into the die opening will result in radial tension and lateral compression. This
will result in gliding of metal above the neutral axis in reverse direction. This induces the corrugated fracture on top and bottom of the blank.

Kwak et al (2002) have performed a finite element analysis and experiment to investigate the effect of clearance between the punch and die on shear planes in the fine blanking part of an automobile safety belt. As a result of this study, the following conclusions can be drawn:

i) When the clearance was increased, the shear band of the material was widely spread leading to earlier fracture.

ii) When the clearance was increased, the width and depth of the die-roll was increased.

iii) When the clearance was decreased, the depth of the fracture zone was decreased and the depth of the shear zone was increased.

iv) FE analysis shows that reduced clearance between the punch and die improves the quality of sheared parts.

Sutasn Thipprakmas et al (2008) have created the FEM model of the fine blanking process enabling surface flaws to be predicted. The FEM simulation results compared well with experiment outcomes, thus validating the method for predicting the blanked surface quality. Therefore, it is indicated that FEM simulation could be a useful tool for predicting a fine blanked surface and determining design and working parameters for fine blanking process.

Li and Fan (2008) have developed a method which determines if the material of deformation field enters the plasticity regime. The results indicate that the work piece of fine plastic shearing could be obtained by use of a common blanking machine. The quality and accuracy of the blanked
work piece could be improved greatly. The length of the smooth shearing fracture could reach more than 90% thickness of the metallic sheet. This means that controlled rectilinear motion of the punch through the die opening is one of the prerequisite for fine blanking. By introducing axial compressive force, the blank will experience hydrostatic compression and subsequent perfect shearing.

Emad Al-Momani and Ibrahim Rawabdeh (2008) have developed a model to predict the shape of the cut side. The model investigates the effect of potential parameters influencing the blanking process and their interactions. This helped in choosing the process leading parameters for two identical products manufactured from two different materials blanked with a reasonable quality on the same mold. Finite Element Method (FEM) and Design of Experiments (DoE) approach are used. The combination of both techniques is proposed to result in a reduction of the necessary experimental cost and effort in addition to getting a higher level of verification. It can be stated that the Finite Element Method coupled with Design of Experiments techniques can be used in order to contribute towards the optimization of sheet metal blanking processes. However in the case of heterogeneous material, one has to optimize the blank holder pressure and counter punch pressure to minimize/avoid buckling of fiber and consequent matrix crazing and delamination/debonding.

2.12 NON-DESTRUCTIVE TESTING OF COMPOSITES

From various stages of material processing to in-service inspection, it is desirable to have a rapid, non-contact, non-destructive testing (NDT) method that would allow for the simultaneous two-dimensional (surface) characterization of material properties and defects as well. NDT techniques for fiber reinforced composite components are being investigated intensively due to the increasing use of these materials in critical areas. Many parts
cannot be dismantled and shifted for inspection; in-field service testing techniques are developed for such cases. Among these techniques, IR thermography is very effective and efficient. IR thermography has proven to be a reliable and cost effective inspection technique for many materials including composite laminates.

IR thermography has a wide range of applications in military, industrial, civil engineering and medical fields. It can be used to investigate a broad range of situations where variation in surface temperature may indicate a change in a particular property of the materials below the surface. The recent availability of highly sophisticated thermal imaging systems, in particular, digitized scanners with storage and computational capabilities, has enabled NDE and condition monitoring for critical situations.

Hansen (1999) has used a relatively new non-destructive inspection technique using infrared thermography which was found to be very useful in detecting damage initiation and growth during NDE of impacted woven fabric composites tested in tension-tension fatigue. He has also stated that the technique supplies valuable information for characterization of the operating fatigue damage mechanism. With fatigue occurrence, the associated damage in the composite material will exhibit different thermal responses depending on the type of defect and its intensity.

Brady et al (1999) explains that thermal image analysis is an emerging non-destructive evaluation (NDE) technique that shows promise as a potential on-line monitoring and inspection method for composites. He has also analyzed and applied thermal imaging techniques to detect delamination in carbon-carbon composite plates. Two-dimensional distributions of thermal diffusivity were obtained and verified with values obtained by the ASTM-standard, laser flash diffusivity method.
Kulkarni and Brady (1996) have introduced the pulse video thermography (PVT) as an emerging thermal wave imaging technique. Preliminary results show that the PVT thermal diffusivity values for a carbon-carbon composite plate compare favorably with those obtained by the widely used laser flash diffusivity method.

Hobbs and Temple (1993) described the technique in relation to the inspection of aircraft for information on structural integrity, specifically for the detection of the defects such as delamination and debonding. For pulse heating, experimental and numerical modeling results for carbon-reinforced plastics are used to show how the resolution of subsurface features is related to the size and depth of the anisotropy in thermal properties common in such composites. For periodic heating, thermal wave characteristics are introduced to show how the resolution of subsurface features influences modulation frequency and local focal spot radius. This was dealt by Almond and Peng (2000).

2.12.1 Ultrasonic Testing

Scarponi and Briotti (2000) have evaluated the delamination using ultrasonic NDI technique on several CFRP, GFRP and KFRP composite laminates subjected to low-velocity impact test. The results have shown that good capabilities of the NDI ultrasonic methodology in terms of delaminations detection, location and evaluation.

Hasiotis et al (2007) have investigated the efficiency of the ultrasonic inspection method for detecting defects in laminated composite fibrous materials. The parameters of the study involved two different materials and two different manufacturing methods. The artificial defects
were of various shapes and sizes and were placed at various positions in the thickness direction. The main conclusions drawn from this study are the following:

1. The equipment used and the procedures applied proved much more efficient in the case of the CFRP specimens than when inspecting the GFRP ones. This happened due to the intense echoes that were deflected by the glass fibers, which were frequently overlapping the echoes coming from the actual defects. This phenomenon did not happen in the case of the carbon fibers.

2. The method proved capable of accurately defining the position of the artificial embedded defects in the CFRP specimens. In the case of the GFRP specimens, position detection of these defects was less accurate, however satisfactory.

3. The shape of the embedded defects was also accurately monitored in the case of the CFRP specimens. On the contrary, the shape of the defects in the GFRP specimens was not very well defined.

4. Regarding the size of the defects, the method significantly overestimated their values in the case of the CFRP specimens, whereas, it was not possible to estimate any size at all in the case of the GFRP ones.

5. The wrinkle defect was accurately detected in the case of the CFRP specimens, whereas, it was not detected at all in the case of the GFRP ones.

6. The orientation of the fibers was clearly detected in both types of specimens.
7. The ultrasonic inspection of the GFRP specimens could probably result in a much better representation of the actual situation if alternative sensor, having lower frequency (i.e. 3.5 MHz) was used. In this way, the scattering of echoes coming from the glass fibers would considerably decrease.

Siva Shashidhara Reddy et al (2005) have measured the elastic modulus using two different immersion techniques namely, back-reflection and through-transmission techniques. Experiments were conducted on (i) aluminium samples of three thicknesses 25.3, 12.6 and 6.6 mm, (ii) unidirectional glass-epoxy composite of thickness 2.16 mm and (iii) unidirectional glass-epoxy composite plates of thickness 10.88 and 4.02 mm, using both back-reflection and through-transmission modes. Based on the results obtained, the following conclusions were made:

1. Using back-reflection immersion inversion procedure, the elastic constants of isotropic and transversely isotropic medium can be measured with an average accuracy of 1.9% when compared with standard ultrasonic contact testing method. It was determined that results from graphite-epoxy samples compared very well with manufacturer supplied data.
2. Back-reflection technique is better than through transmission technique, particularly for thicker samples, due to the limited width of receiving transducer.

Wrobel et al (2007) have conducted ultrasonic experiments and the results have shown that the longitudinal wave velocity increases almost linearly with an increased fiber content in the investigated glass/polyester composite specimens. The second considered parameter of an ultrasonic
wave, namely attenuation coefficient did not correlate with the glass content. It is obvious due to scattered reflection by the glass fibers.

Seung-Joon Lee et al (2007) have evaluated the delamination in CFRP, using generation technique of laser-based ultrasound and reception technique using air-coupled transducer. Technique with air-coupled transducer can make non-contact ultrasonic technique available in evaluation of CFRP. The pitch-catch arrangement using laser-based ultrasound and air-coupled transducer is very attractive for non-destructive testing and evaluation of materials, because it allows one-sided access to the object and is alternative for the immersion testing technique. Wave propagating through delamination region was received with air-coupled transducer and the received signal was evaluated using frequency spectrum analysis and wavelet transform technique.

### 2.13 SCOPE OF THE PRESENT WORK

The main objective of the present study is to develop technique for producing defects constrained hole in polymeric composite. Literatures on polymeric composites have presented conflicting results on the role of matrix and reinforcements on defects induced due to application of service load/environment. Matrix material is reported to play a significant role, while major load carrying member is the reinforcement. Regarding machining of polymeric composites, selection of tool materials and machining conditions are mostly material specific. Definite conclusion could not be arrived out, giving thereby scope for detailed study on drilling of polymeric composites with emphasis on defects constrained drilling.
Accordingly the objectives of the present study are:

- Parametric influence on static mechanical properties of GFRP composites.
- Dynamic Mechanical Analysis of GFRP composites.
- Stiffening of the polymeric composite by cyclic stressing and evaluating its significance on drill performance.
- Generation of data and creating a basis for understanding the process of fine blanking of FRP laminates with varying fiber orientations.
- Parametric influence of volume fraction of fibers on delamination factor in fine blanking of GFRP composites.
- Evaluating the optimum cutting conditions for fine blanking of composites.
- Response of GFRP composites exposed to flexural fatigue loading with a single hole by both drilling and fine blanking.
- Evaluation of tensile properties of polymeric composites with inserted pair of holes.
- Analysis of data using multiple regression analysis.
- Optimization of fine blanking through numerical analysis method.

2.14 METHODLOGY

Block diagram of the methodology adopted for the study is schematically illustrated in Figure 2.1.
Figure 2.1 (Continued)
Delamination factor

Evaluation of delamination factor
Instrument: Ultrasonic C-Scan Immersion Test set up

Optimum Condition

Evaluation of optimum process parameters by experimental and numerical analysis based on delamination factor

Functional Characteristics

Evaluation of tensile & flexural characterization
Instrument: Fatigue Test Rig, Flexural Loading Rig, Instron Universal Testing Machine, Drilling Machine Specimen: Plain, strain-stiffened

Data modeling

Comparing the experimental and predicted values Tool: SPSS statistical

Results and Discussion

Conclusion

Figure 2.1 Methodology