Chapter 7
Challenges in Machining of Natural Fibre Composites

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Abstract The attention in natural fibre-reinforced polymer composites is growing rapidly for many engineering systems. However, their assorted nature, engineer's lack of experience, a little knowledge of machinability databases, parameter setting and difficulty in manufacturing are barriers to large-scale use of composites. Various conventional and unconventional techniques are used for machining composites to obtain the final shape. Machining of these composites creates challenges that do not usually come across in machining of conventional metallic/monolithic material as the composite materials are heterogeneous and anisotropic. Several manufacturing and machining defects include matrix imperfection, resin-starved area, resin-rich area, voids, cracks, blisters, debond, delamination, fibre pull-out and burning. Different methodologies and tools are aimed to prevail over the above-mentioned issues. This chapter focuses on the prospective use of natural fibres in composite materials and challenges in machining of natural fibre composites.

Keywords Natural fibre composites • Mechanical and physical properties • Damages • Machining

7.1 Composite Material

A mixture of more than two materials, i.e. reinforcement and resin (Schwartz 1992), which differs in structure or composition on a macroscale, is known as composite material. This structure results in a material that increases specific performance properties. The components do not disband completely and as a result normally show an interface between one another. Both reinforcing and resin keep their

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physical and chemical identities; however, constituents make a combination of properties that cannot be attained with either of the constituent acting alone.

Composite materials are widely used in several engineering areas due to their better properties like:

- Composite materials are lighter than woods and metals which are vital for good mileage in aircrafts and automobiles.
- Nowadays, in structural applications, composite materials are having greatest strength to weight ratio. One can design the composite strong as well as light (e.g. bamboo-based composites).
- Composites can be used to store chemicals as they resist corrosion from the weather and from harsh chemicals.
- Composites are flexible to the design as they can be moulded into challenging shapes very easily than other materials.
- The whole assembly of the metal parts can be replaced by making a single piece of composite material.
- Many of the composites are nonconductive and nonmagnetic, so they can be used in electrical/electronics applications.

7.2 Importance of Natural Fibre Composites

There are many advantages of natural fibre over synthetic fibres. E-glass fibres have equivalent or lesser specific modulus and specific strength than natural fibres. In the future, many opportunities are there for replacing E-glass fibres by natural fibres (Drzal et al. 2004).

The production of natural fibres requires less energy and CO_2 is used, whereas oxygen is released to the atmosphere. In the case of natural fibres, there is possibility of thermal recycling, while glass fibres cause difficulties in burning. Natural fibres have worthy thermal and acoustic insulating properties. There are many other advantages like no skin irritations, friendly processing and lower cost.

7.3 Challenges in Preparation of Natural Fibre Composite Materials

Natural fibres absorb definite amount of water which degrade the fibres. The water absorption may be high because the hydroxyl is present all the way through the natural fibre. It signs to reduced wettability and fragile interfacial bond amongst fibres and polymers, by way of matrix (Brouwer 2000). To develop composite with good mechanical properties, it is essential to perform appropriate treatments for improving the compatibility of fibres with matrices (Brouwer 2000; Drzal et al. 2004).

The characteristics of constituents of natural fibres are such that they could not be taken equal to temperature beyond 220–230 °C deprived of concerning degradation.

So, composites based on natural fibres could not be operated at temperature beyond 230 °C.

The problem encountered with the natural fibres is the availability in required form. The lower cost of the natural fibres can be annulled out if they should be conveyed to long distances. The nature of the natural fibre is very complex, and it depends not only on the type of fibre but also on how and where the plants are cultivated. Natural fibre composites always contain porosity which decreases density and mechanical performance of composites.

7.4 Machining of Composites

Composites are created to near-net shape which minimizes the need for machining, though machining processes like trimming for giving finished shape and drilling to facilitate joining of parts in intricate assemblies are common operations in industries that deal with these kinds of materials. Amongst these techniques, turning, milling, grinding and drilling are examples that can be used for machining composites to obtain the final shape or achieve required tolerance. Figure 7.1 shows the various machining methods.

7.4.1 Conventional Machining

Machining processes are conventionally transferred to composite machining after appropriate modifications to process parameters like tool geometry, cutting speeds and feed rates. However, kinematics of the machining process for composites and metals remains the same.

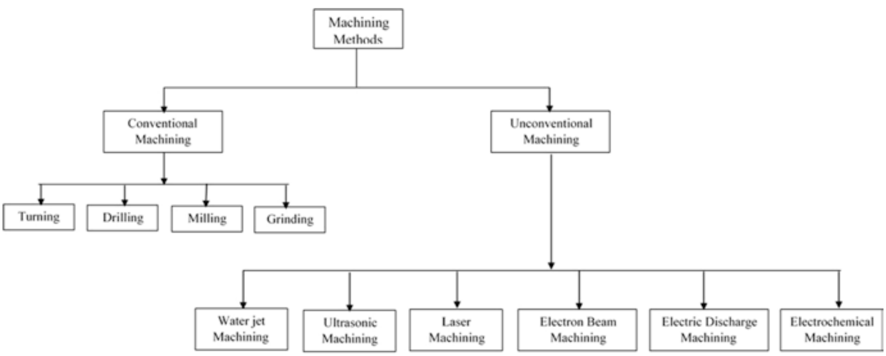


Fig. 7.1 Machining methods

7.4.1.1 Turning

Turning of fibre-reinforced composite materials with HSS or carbide tools has been found to be not cost-effective due to the abrasiveness and inhomogeneity of these materials. Machined parts have poor surface finish and high tool wear (Ramulu 1998; Ramulu et al. 1989). In composites reinforced with carbon fibres, the use of high-speed tools is rare, due to the great abrasiveness of these fibres. Carbide tools are more normally used. Ceramic tooling, due to its low thermal conductivity, is not adequate for this type of materials. Ramulu (1998) investigated machining by turning graphite/epoxy composite material with the purpose of comparing different PCD (synthetic polycrystalline diamond) grain sizes and the identification of dominant parameters in the tool edge geometry. Graphite fibre-reinforced materials are extremely abrasive, leading to the need to use diamond abrasive cutters. The finish of machined surface depends largely on fibre orientation, but roughness values show some variation according to the orientation of the fibres to the cutting edge.

7.4.1.2 Milling

The main characteristic of milling operations on parts made of fibre composite is a low ratio of removed volume to total part volume. Milling is used as a corrective operation in order to produce well-defined and quality surfaces. The fibre has the greater influence in the selection of tools and parameters (Klocke et al. 1998). Optimization of milling process is influenced on one side by the nature of the fibres which must be cut in and near the top layers and on the other side by the thermal stress on the contact surface. The latter is caused by material abrasiveness and the friction between the material and tool, affecting the quality of the cut surface (Klocke and Wurtz 1998a, b). The combination of high cutting speeds with low feeds can lead to matrix melting and stuck to laminate surface or to the chips. Under some conditions, the matrix could even burn. A significant reduction in cutting velocity and an increase in feed can limit this problem. However, these cutting parameters lead to the presence of inadequately cut fibres that remain attached to the surface layers (Klocke and Wurtz 1998a, b). Thermal stress on tools becomes critical when small-diameter tooling is used. Fibre-reinforced composites are characterized by their low thermal conductivity, so the tool has to absorb a considerable amount of generated heat, in opposition to what happens to steels. If the capacity of the tool to absorb the heat is also low, an increase in friction leads to higher thermal stress, more tool wear and poorer operational safety (Klocke and Wurtz 1998a, b).

7.4.1.3 Grinding

Grinding of carbon fibre-reinforced plastics poses considerable problems such as fibre pull-out, delamination, burrs and burning (Hu and Zhang 2001). Surface roughness is a function of fibre orientation, with better results when they are perpendicular to grinding direction. Greater depths of grinding cause more damage to workpiece. When compared with drilling, grinding causes less burrs and edge effect problems.

7.4.1.4 Drilling

In maximum circumstances composite parts need to be assembled with other parts. Composite materials could not be assembled by welding and gluing is somewhat difficult; therefore, mechanical joining by means of fasteners and rivets is the option usually taken on to join composite parts with other parts. The holes required by mechanical joining are generally drilled in the semi-finished composite part. Only bigger-size diameter or intricate contour holes can be created by placing core in the mould while curing. As the composite part must perfectly match with other parts during the joining process, the holes must be located at the exact required position and should have precise diameter. Additionally, because of load transfer when in use, the holes usually undertake concentrated localized stress. Drilling includes the removal of material from a workpiece such that a hole is attained. The holes created are used mainly for joining one component with another, to provide passage for coolants, and for wiring purposes. It is a common process for removing unwanted material. Drilling is generally used to create holes in metals, but because of its availability, it is now used for composites too. Drilling is extensively used as it is the most economical process than other methods and because there are not many other methods that can create deep circular hole. Drilling is repeatedly used for machining composites, because of freely existing machinery. Composites are anisotropic materials, so drilling increases particular problems that will affect the strength of the parts (Hamdoun et al. 2004).

7.4.2 Unconventional Machining

Conventional machining might cause impractical operating conditions because of lower material removal rates (MRRs), tool wear and undesirable responses. Hence, unconventional machining processes may become practical and cost-effective methods for composite machining.

7.4.2.1 Waterjet Machining

To generate thin waterjet by means of high pressure and high velocity is the working principle of waterjet machining. Material removal from workpiece is possible by localized fracture. The performance can be improved by adding abrasive particles. Various methods like kerf cutting, piercing and milling can be used to create holes and slots using waterjet. In piercing, material from the workpiece is removed by means of shock loading (Friend et al. 1973; Adams 1986). The analytical models available for predicting delamination using conventional drilling can be used to determine the required pressure for introducing the delamination (Hocheng 1990). Delamination could be reduced by using lower jet speed, but it affects the piercing capabilities (Hashish 1989). Cutting beside a circle can create better quality holes deprived of delamination. This method can be efficiently used for cutting narrow slits, small holes and non-through holes. The main advantage of using this method is no burning of fibre and no environmental problem, and the main disadvantage is generation of great noise. If the internal pressure generates during cutting, then it will cause layer delamination for composite materials.

7.4.2.2 Ultrasonic Machining

Ultrasonic machining is the method in which a slurry containing abrasives is driven at high velocity beside the workpiece by a vibrating tool. Studies are available on the effect of various process parameters like abrasive concentration, abrasive grain size and feed rate on machining ability with respect to material removal rate (Pentland and Ektermanis 1965; Kremer 1981). The main advantage of ultrasonic machining is that it does not generate thermal or chemical damage on workpiece. With the use of this method, good quality hole can be created in composites, but the disadvantage is that it is a very slow process as it takes time to create a hole with slower speed. Ultrasonic machining can create good quality hole than conventional drilling. This method is appropriate for drilling and slitting some of the composites.

7.4.2.3 Laser Machining

Laser machining uses the light energy from a laser to remove material by vaporization and ablation. Laser beam machining has previously been used in industrial applications for several times; for cutting composites, the general types of lasers used are Nd:YAG laser and CO_2 laser. Nd:YAG laser can be used to cut metal matrix composites which do not contain organic resin because these materials do not absorb laser and decompose easily (Sadat 1991). CO_2 laser can be used for cutting glass fibre-reinforced composites. It is also used for cutting graphite/epoxy composites, but as graphite is a conductive material and temperature is about 3,600 °C, it causes degradation. Laser machining of composites is difficult because the components of composites have varied thermal conductivity (Tagliaferri et al. 1985). Many experiments indicate that good quality of cut surface can be attained, if thermal conductivity of fibres is nearer to that of the matrix. Pan and Hocheng (1998) showed that the heat-affected zone amongst cut could be anticipated by the model of anisotropic heat conduction. Tuersley et al. (1998) studied the effect on the depth of the hole and damage induced in silicon carbide-based composites for various process parameters like gas pressure, focal depth and speed. Rodden et al. (2002) carried out laser drilling on carbon fibre-reinforced composites using long pulse Nd:YAG laser.

7.4.2.4 Electrical Discharge Machining

The process of electric discharge machining is based on the eroding effect of electric spark which is created between electrode (tool) and workpiece in dielectric fluid (Tsao and Hocheng 2004). Electric discharge machining is used for the material which has electrical conductivity, so this method can be used for graphite fibre-based composites (Lau et al. 1990). It is also used for machining metal matrix composites. The main process parameters in this process are current and frequency which affect the surface finish. Better surface finish can be achieved by using higher frequency and lower current. Lau et al. (1990) studied about tool wear in machining of carbon fibre-reinforced composites and showed that copper electrode gives better performance than graphite.

7.4.2.5 Electron Beam Machining

In electron beam machining the electron impinge on the surface of workpiece in vacuumed which generates heat and material vaporizes (Sadat 1991). Vacuum is necessary to eliminate collisions of the electrons with gas molecules. This process is considered to be micromachining. The main advantage of using this method is there is no heat-affected zone and closed tolerance could be achieved. This method is generally used for creating small holes and for slitting some composites.

7.4.2.6 Electrochemical Machining

Electrochemical machining removes material from an electrically conductive workpiece by anodic dissolution. It is the reverse of electroplating. The workpiece is the anode and the tool is the cathode. Material is deplated form the anode (positive pole) and deposited onto the cathode (negative pole) in the presence of an electrolyte bath (Groover 1996). The electrolyte is usually sodium chloride mixed with water, sodium nitrate and other fluids that can chemically react with the workpiece. This process can be used for machining complex cavities and for slitting, drilling and cutting most composites that exhibit continuous and uniform electrical conductivity. One advantage of this process is that it does not cause any thermal damage.

7.5 Research Review on Machining of Natural Fibre Composites

Many researchers worked on machining of polymer matrix composites based on synthetic fibres. Applications of composites based on natural fibres are increasing nowadays. Few of the case studies on machining of natural fibre composites are discussed here.

Jayabal and Natarajan (2010) developed coir–polyester composite and investigated the effect of drill diameter, feed and speed on torque, thrust force and tool wear. Experiments were performed with the help of box–cox method on coir–polyester composites. Various optimization techniques like genetic algorithm and Nelder–Mead technique to optimize parameters and reduce tool wear. Mathematical model for responses was developed to compare significant input parameters. They concluded that if there is an increase in tool wear, then tool life becomes negligible.

Athijayamani et al. (2010) used HSS drill bits to conduct a series of drilling experiments on roselle–sisal hybrid composite. They used artificial neural network and regression model for comparing torque and thrust with speed, feed and tool diameter. They compared experimental values with predicted response values, artificial neural network and regression model. They showed that the artificial neural network model is more valued than the regression model to predict torque and thrust force in the drilling of natural fibre hybrid composites.

Chandramohan and Marimuthu (2011) studied the prediction of torque and thrust force for the drilling of commercially available natural fibre like sisal and roselle–bio epoxy resin composite materials, and the values were compared with the regression model. They used machine vision system to find delamination factor. They found that larger diameter drills and higher feed rates give larger thrust force. They also observed that as volume fraction and feed increase, the thrust force increases, but thrust force was decreased as cutting speed increases at elevated feed values. They also found that with increase in feed and speed, torque increases slightly, but it decreases when increasing the cutting speed.

Jayabal and Natarajan (2011) studied the mechanical and machinability characteristics of coir–polyester composites. They developed regression equations and optimized for studying drilling characteristics using the Taguchi approach. Drill diameter, feed rate and speed were the input parameters to examine the torque, thrust force and tool wear in the drilling process with the greatest hole quality and accuracy. They found the optimum values of machining parameters to reduce tool wear for the drilling of coir–fibre-reinforced composites.

Babu et al. (2012) studied the effect on delamination of hemp fibre-reinforced composite of drilling parameters. They used the Taguchi technique to design the experiments and ANOVA analysis to achieve the conditions for minimum delamination. They examined both the peel-up delamination and push-down delamination. They found that the most critical parameters are the feed rate and cutting speed and should be selected suspiciously to reduce all kinds of damages.

Rakesh et al. (2012) did a survey of the literature published in the last 20 years in this area and found that around 31 % of total papers published are in the last 3 years. Therefore, it can be quantified with sureness that the area of drilling of polymer matrix composites has created wide interest amongst the research group.

Venkateshwaran and ElayaPerumal (2013)studied analysis of delamination at the entrance and exit of the composite plates as a function of the drilling process parameters. By varying the feed and speed, they carried out the drilling on banana fibre epoxy composite. They used machine vision technique to analyse the quality of the hole and also the ultrasonic C-scan imaging method was carried out to find the amount of delamination. They found that with an increase in feed, the delamination increases. They compared experimentally obtained delamination factor with ANOVA technique and observed that the effect of feed rate is more on delamination than speed.

Bajpai and Singh (2013) studied about drilling performance of sisal–polypropylene composite material. They took speed, feed and drill point geometry as input parameters. They used solid and hollow shaped drill geometries for drilling. They used the RSM and ANOVA method to design the experiments for studying the effect of cutting forces and parameters. They found that the cutting forces are considerably affected by the selection of the drill point geometry as the cutting mechanism varies with various drills. They observed that drill point geometry has a significant effect and cutting speed has a minimum effect on the forces during drilling of sisal–polypropylene composites. They concluded that thrust force produced using trepanning tool is significantly small equaled to twist drill through drilling operation and the cutting mechanism of hollow drill is suitable for the drilling of sisal fibre-reinforced PP composites.

7.6 Challenges Observed

Damage in composite materials is caused by several ways during manufacture, assembly and transport or field deployment, besides expected damages during normal use. Composites are used in some critical applications; damages that remain undetected or that are of difficult detection can turn into a serious problem (Strong 1991). One of the possible solutions is to increase the design safety factor, overdesigning the parts, with a penalty in weight and final cost. However, this solution does not prevent damage nor considers its possible extent, which may turn out to be wider than predicted exceeding the safety factor allowance. Unexpected ruptures during service must be avoided. Therefore, the solution most often used is to implement special damage protection methods (Strong 1991). There are a variety of defects that can be caused in composite parts during machining. These operations are normally included in the assembly phase, but one should remind that some damage can be caused prior to assembly, i.e. during parts manufacturing.

Physical properties of composites make them an attractive group of materials; machining poses a certain number of specific issues, when compared with metallic materials. Usually, machined components have poor surface appearance and higher tool wear. The major problem of machining composites is fibre reinforcement which is generally abrasive and causes tool wear and deterioration of machined surfaces (Abrate 1997). Machining could cause some damages like delamination, fibre pullout and thermal damages (Wern et al. 1994). In drilling of composites, better results depend more on fibre than matrix (Boldt and Chanani 1987).

Manufacturing and machining defects include matrix imperfection, resin-starved area, resin-rich area, voids, cracks, blisters, debond and delamination. If too much resin is used in a part, it is called resin-rich area; for nonstructural applications, this

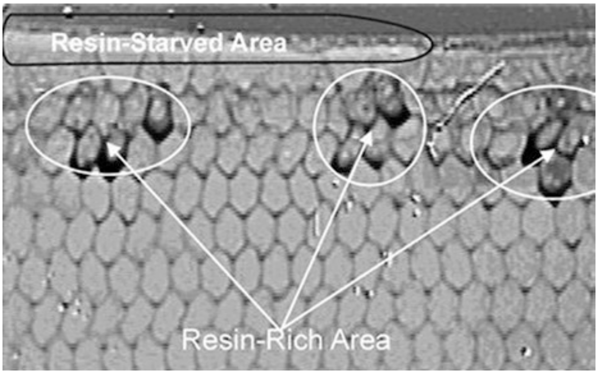


Fig. 7.2 Resin-starved areas and resin-rich areas (Balaskó et al. 2004)

is not necessarily bad, but it adds weight. Apart is called resin starved if too much resin is exploited through the curing or if not enough resin is used during the wet layup process. Resin-starved areas are indicated by fibres that show to the surface. Resin-rich areas and resin-starved areas are shown in Fig. 7.2. The ratio of 60:40 fibre to resin ratio is considered optimum. Matrix imperfections generally arise at the matrix–fibre interface. These imperfections can somewhat decrease certain material properties but are rarely dangerous to the structure, except the matrix degrades extensively.

Damages that are generally initiated by machining composites are burrs, debonding, intralaminar cracks, delamination and thermal damage. The amount of these defects is mainly reliant on selected process parameters. Care should also be paid for circularity of holes after machining. Burrs are small portions of broken material at the corner or at the edge of the surface, but quite attached to a part. Their presence is associated with roundness which does not allow clean cut. Their significance is mostly artistic.

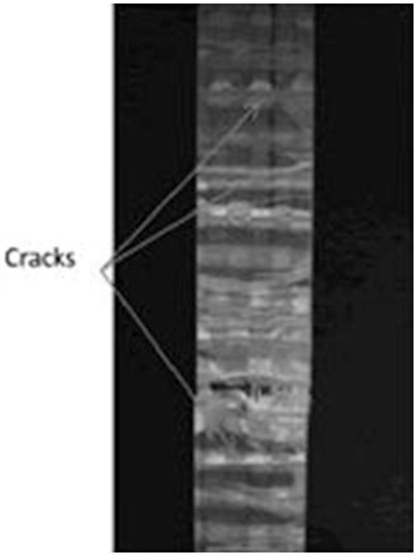
Intralaminar cracking which is shown in Fig. 7.3 begins at the inner plies of the laminate. Generally, it starts at a preference of 60° to the layer plane. The crack spreads along with direction till it extends at the intralaminar plane and turns into delamination (Caprino and Tagliaferri 1995).

Debonds form because there may be no adhesion beside bond line amongst two components and generate delamination in neighbouring laminate layers shown in Fig. 7.4. Under several circumstances debond can raise when it is subjected to frequent loading which causes cataclysmic failure. The acute of debond depends on various parameters like dimension, location in laminate, type of loading and quantity of delamination at specified locality.

Thermal damage occurs because of contact amongst workpiece and tool which generates localized heat, and in machining of composites cooling fluid cannot be used. Higher temperature can cause damage like burning or melting.

Amongst the several defects which are caused by machining, delamination is acknowledged as the most dangerous. Delamination is the separation of layers in

Fig. 7.3 Intralaminar crack (Rios-Soberanis et al. 2012)



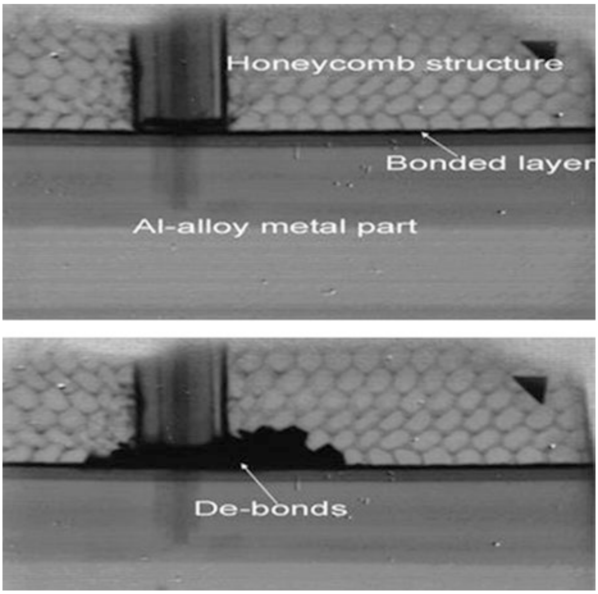


Fig. 7.4 Debonds (Balaskó et al. 2004)

laminate and fibre pull-out which is shown in Fig. 7.5. Delamination factor can be defined by the ratio of damaged area around the hole to actual hole area which is shown in Fig. 7.6. Composite delamination can be divided into two types: peel-up delamination and push-down delamination. If the delamination arises at the

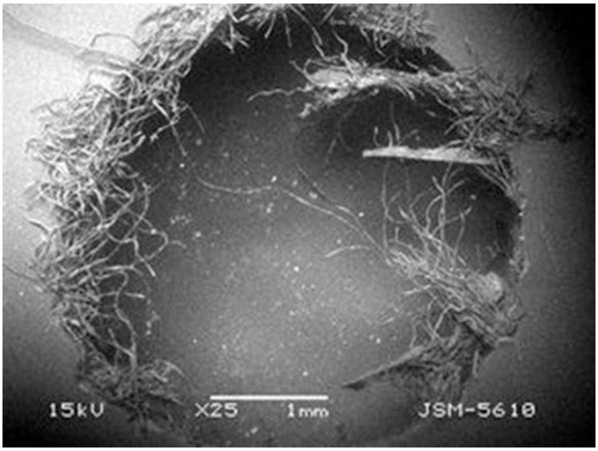


Fig. 7.5 Delamination in drilled hole

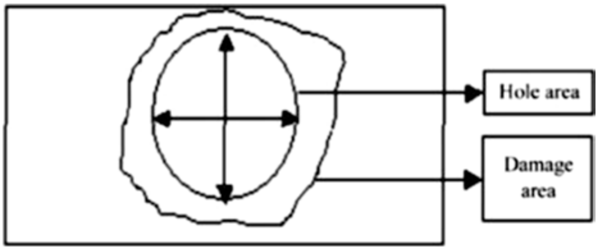


Fig. 7.6 Schematic layout of the damage area and hole area

entrance, then it is called peel-up delamination, and if it occurs at the exit, then it is called push-down delamination which is shown in Fig. 7.7.

Delamination affects the durability of composites and decreases bearing strength which results in performance problems. Other main reasons for delamination are higher thrust force, high feed rate and prompt tool wear. Certain earlier approaches to reduce delamination were to decrease feed rate and thus decrease thrust force with the use of backing plate.

In conventional drilling of composites, circularity shall also be observed, as there is a bouncing-back tendency of the material that causes hole deformation. The return to its initial position causes tightening around the drill, and the drilled diameter is less than the drill diameter. This roundness error is due to the anisotropy of the material (Piquet et al. 2000).These defects are responsible for the rejection of producing parts and contribute to the rise of fabrication costs.

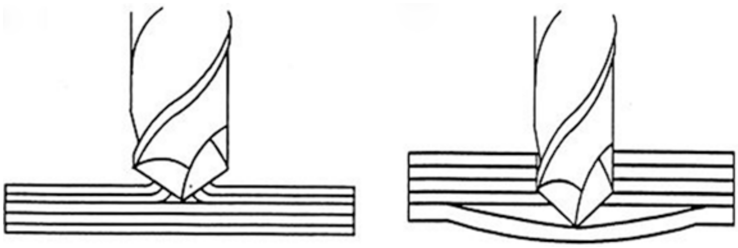


Fig. 7.7 Peel-up delamination at entrance and push-out delamination at exit (Abrate 1997)

7.7 Remarks

The present work was aimed to examine the manufacturing and machining challenges for natural fibre composites. This study also shows the defects observed during manufacturing as well as machining of natural fibre composites. Reduction of defects can be achieved by selecting appropriate cutting parameters, drilling conditions and tool geometry and tool material. It is identified that few of the data are available for machining of natural fibre composites; however, there is a paucity of data for unconventional machining of natural fibre composites. Some important research issues are identified and studies of some critical issues are proposed to meet the challenges in machining of natural fibre composites.

References

Abrate S (1997) Machining of composite materials. In: Mallick PK (ed) Composites engineering handbook. Marcel Dekker, New York, pp 777–809

Adams RB (1986) Water jet machining of composites, composites in manufacturing. SME Paper EM 86-113

Athijayamani A, Natarajan U, Thiruchitrambalam M (2010) Prediction and comparison of thrust force and torque in drilling of natural fibre hybrid composite using regression and artificial neural network modelling. Int J Mach Mach Mater 8:131–145

Babu D, SivajiBabu K, Uma B (2012) Effects of drilling parameters on delamination of hemp fiber reinforced composites. Int J Mech Eng Res Dev 2(1):01–08

Bajpai P, Singh I (2013) Drilling behavior of sisal fiber-reinforced polypropylene composite laminates. J Reinf Plast Compos 32(20):1569–1576

Balaskó M, Veres I, Molnár G, Balaskó Z, Sváb E (2004) Composite structure of helicopter rotor blades studied by neutron- and X-ray radiography. Physica B Condens Matter 350:107–109

Boldt JA, Chanani JP (1987) Solid-tool machining and drilling. Engineered materials handbook, vol 1. ASM International Handbook Committee, Metals Park, pp 667–672

Brouwer W (2000) Natural fibre composites in structural components: alternative application for sisal? Seminar, Commond fund for commodities- alternative applications for sisal and henecuen. Food and Agriculture Organization of the UN (FAO) and the Common Funds for Commodities (CFC), Rome

Caprino G, Tagliaferri V (1995) Damage development in drilling glass fiber reinforced plastics. Int J Mach Tools Manuf 35:817–829

Chandramohan D, Marimuthu K (2011) Drilling of natural fiber particle reinforced polymer composite material. Int J Adv Eng Res Stud 1(1):134–145
Drzal L, Mohanty D, Burgueno R, Misra M (2004) Biobased structural composite materials for housing and infrastructure applications: opportunities and challenges. Proceedings of the NSF housing research agenda workshop, vol 2, pp 129–140
Friend CA, Clyne RW, Valentine GG (1973) Machining graphite composite materials. In: Noton BR (ed) Composite materials in engineering design. ASM, Washington, pp 217–224
Groover MP (1996) Fundamentals of modern manufacturing: materials, processes, and systems. Prentice Hall, New York, pp 543–611
Hamdoun Z, Guillaumat L, Lataillade JL (2004) Influence of the drilling on the fatigue behavior of carbon epoxy laminates. ECCM 11, Rhodes
Hashish M (1989) Machining of advanced composites with abrasive water jets. Manuf Rev 2(2):142–160
Hocheng H (1990) A failure analysis of water jet drilling in composite laminates. Int J Mach Tools Manuf 30(3):423–429
Hu N, Zhang L (2001) Grind ability of unidirectional carbon fiber-reinforced plastics. ICCM-13, Beijing
Jayabal S, Natarajan U (2010) Optimization of thrust force, torque, and tool wear in drilling of coir fiber-reinforced composites using Nelder–Mead and genetic algorithm methods. Int J Adv Manuf Technol 51:371–381
Jayabal S, Natarajan U (2011) Drilling analysis of coir–fibre-reinforced polyester composites, Indian Academy of Sciences. Bull Mater Sci 34(7):1563–1567
Klocke F, Koenig W, Rummenhoeller S, Wuertz C (1998) Milling of advanced composites, machining of ceramics and composites. Ed Marcel Dekker, New York, pp 249–266
Klocke F, Wurtz C (1998a) Comparison of techniques for the machining of thermoplastic fiber reinforced plastics. ECCM-8, Naples, vol 2, pp 729–735
Klocke F, Wurtz C (1998b) The use of PCD tools for machining fiber reinforced Materials. ECCM-8, Naples, vol 2, pp 509–515
Kremer D (1981) The state of the art of ultrasonic machining. Ann CIRP 30(1):107–110
Lau WS, Wang M, Lee WB (1990) Electrical discharge machining of carbon fiber composite materials. Int J Mach Tools Manuf 30(2):297–308
Pan CT, Hocheng H (1998) Prediction of extent of heat affected zone in laser grooving of unidirectionally fiber-reinforced plastics. J Eng Mater Technol 120:321–327
Pentland EW, Ektermanis JA (1965) Improving ultrasonic machining rates—some feasibility studies. J Eng Ind-T ASME 87:39–46
Piquet R, Ferret B, Lachaud F, Swider P (2000) Experimental analysis of drilling damage in thin carbon/epoxy plate using special drills. Compos Part A 31:1107–1115
Rakesh PK, Singh I, Kumar D (2012) Drilling of composite laminates with solid and hollow drill point geometries. J Compos Mater 46(25):3173–3180
Ramulu M (1998) Cutting-edge wear of polycrystalline diamond inserts in machining of fibrous composite material, machining of ceramics and composites. Ed. Marcel Dekker, New York, pp 357–410
Ramulu M, Faridnia M, Garbini JL, Jorgensen JE (1989) Machining of graphite/epoxy materials with polycrystalline diamond tools, machining characteristics of advanced materials. Winter annual meeting of ASME, pp 33–39
Rios-Soberanis CR, Cruz-Estrada RH, Rodriguez-Laviada J, Perez-Pacheco E (2012) Study of mechanical behavior of textile reinforced composite materials. Dyna 176:115–123
Rodden WSO, Kudesia SS, Hand DP, Jones DC (2002) A comprehensive study of the long pulse Nd:YAG laser drilling of multi-layer carbon fibre composites. Opt Commun 210(3–6):319–328
Sadat AB (1991) Machining of composites. Int Encycl Comp 3:95–102
Schwartz MM (1992) Composite materials handbook, 2nd edn. Mc Graw Hill Inc., USA, pp 34–35
Strong AB (1991) Damage control. Int Encycl Compos 2:1–6

Tagliaferri V, DiIlio A, Crivelli Visconti I (1985) Laser cutting of fiber reinforced polyesters. Compos 16(4):317–325
Tsao CC, Hocheng H (2004) Analysis of delamination in drilling composite materials using core-center drill. 11th ICCE, Hilton Head
Tuersley IP, Hoult TP, Pashby IR (1998) Nd-YAG laser machining of SiC fibre/borosilicate glass composites. Part II—the effect of process variables. Compos Part A 29(8):955–964
Venkateshwaran N, ElayaPerumal A (2013) Hole quality evaluation of natural fiber composite using image analysis technique. J Reinf Plast Compos 32(16):1188–1197
Wern CW, Ramulu M, Shukla A (1994) Investigation of stresses in the orthogonal cutting of fibre-reinforced plastics. Exp Mech 36:33–41