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Ultrasonically-Assisted Drilling of Carbon Fibre-Reinforced Plastics

by

FARRUKH MAKHDUM

A Doctoral Thesis

Submitted in partial fulfilment of the requirements for the award of Doctor
of Philosophy of Loughborough University

May 2014

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~ III ~

ABSTRACT

Carbon fibre-reinforced plastics (CFRP) are widely used in aerospace, automobile and other structural applications due to their superior mechanical and physical properties. CFRP outperform conventional metals in high strength-to-weight ratio. Usually, CFRP parts are manufactured near to net-shape; however, machining is unavoidable when it comes to assembly. Drilling the holes are essential to facilitate riveting and bolting of the components. However, conventional drilling (CD) induces different types of damages such as cracking, fibre pull-out, splintering and delamination due to the abrasive nature, inhomogeneity and anisotropy of CFRP. A novel technique, ultrasonically-assisted drilling (UAD) is hybrid machining technique in which high-frequency (typically above 20 kHz) vibration are superimposed on a standard twist drill bit in axial direction using ultrasonic transducer. UAD has shown several advantages such as thrust force reduction, improving surface quality and lower bur-formation in drilling of conventional metals. UAD has also effectively been used for drilling brittle materials.

In this work, three transducer systems were designed, manufactured and their performance was analysed for drilling process. Firstly, a finite element model for Eigenfrequency analysis (using Abaqus 6.11) was developed and validated with experimental data. Then three new transducer systems were designed using this model. New designs helped in achieving significant drilling force reduction (UAD vs. CD) which was impossible before. One of the new designs achieved the force reduction using $\varnothing 12$ mm drill bit which has never been reported formally. Different machining conditions in terms of feed and spindle speed were analysed. The newly designed transducer systems improved the dry drilling of CFRP with significant reduction in average drilling forces. Comparative analysis with CD process at spindle speed of 40 rpm and feed rate of 16 mm/min showed that UAD reduces the average drilling forces in excess of 90%. Temperature profiles were obtained for CD and UAD for CFRP and thermal evolution of drilling process was analysed to achieve the knowledge of temperature in cutting zone. A comparative study of surface analysis was carried out for

CD and UAD holes and three-to-four fold reduction in surface roughness was observed. The chip was analysed for both UAD and CD using optical microscopy and scanning electron microscopy. It was observed that the chip formation changed completely from powder form (in CD) to ductile chip (UAD). This change in chip formation behaviour for CFRP was observed for first time and is a result of ultrasonic vibration. Micro-computed tomography, for the structural analysis of drilled holes, was conducted for both CD and UAD for the comparative study of structural damage. It was observed that UAD considerably reduces delamination.

Keywords: Ultrasonic, drilling, hybrid drilling, carbon fibre-reinforced plastics, drilling forces, surface roughness, circularity, delamination, ultrasonically-assisted drilling.

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PUBLICATIONS

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- **Makhdum F**, Nurdiyana NP, Roy A and Silberschmidt VV (2012c). Ultrasonically Assisted Drilling of Carbon Fibre Reinforced Plastics, Solid State Phenomena, **188**, 170-175.
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- Phadnis VA, **Makhdum F**, Roy A and Silberschmidt VV (2012). Drilling-Induced Damage in CFRP Laminates: Experimental and Numerical Analysis, Solid State Phenomena,**188**, 150-157.
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CHAPTER1

INTRODUCTION

Carbon fibre-reinforced plastics (CFRP) have found their applications in aerospace, automobile and other structural applications. For example, in B2 stealth bomber aircraft and Airbus XWB more than 80% and 50% by weight (Gwad, 2011; Airbus, 2012) was composed of CFRP, respectively. CFRP offer high strength-to-weight ratio, high stiffness, high corrosion resistance compared to conventional metals such as aluminium and steel. Due to these attractive properties of CFRP, their consumption is increasing every year. According to one estimate, CFRP would occupy the global market of \$36 billion by the end of 2020 (Jacques, 2012).

Despite the increasing market and attractive properties of CFRP, they offer poor machinability due to anisotropy, poor thermal conductivity, high abrasive nature of the fibres. Usually, parts are manufactured near to net-shape, machining cannot be avoided in order to facilitate assembly. Holes are necessary for bolting and riveting. It was reported that about 55.000 holes are drilled in Airbus A350 body (Müller-Hummel et al., 2008). To produce holes, conventional drilling (CD) operation is carried out;

however, CD introduces several drilling defects such as delamination, dimensional inaccuracies and poor surface finish. It was reported by many researchers (Davim, 2003; Hocheng and Tsao, 2006) that the cause of these defects are drilling forces. In order to keep the drilling forces less than a threshold value and, to avoid these drilling associated defects, additional machining operations are carried out, e.g. pilot holes are drilled before drilling with the required size of a drill bit, this increases the process cost and production time. However, additional machining operations can be avoided with the application of newly developed hybrid machining technique. One of these techniques is ultrasonically assisted machining (UAM).

UAM is a hybrid machining technique in which high frequency (~20 kHz) vibrations are superimposed on a standard machining tool. Ultrasonic vibration has been used to improve machining of advanced alloys such as Titanium (Maurotto, 2012; , 2013) in case of turning. Similarly, vibrations were superimposed on twist drill-bit in ultrasonically-assisted drilling (UAD) (Shoh, 1970). Several advantages (such as machining forces reduction, improved surface quality and improved dimensional accuracy) of UAD have been reported (Devine, 1985; Bone 2005; Baghlani et al., 2013). However, UAD is highly nonlinear process and reproducibility is one of the main challenges of this technique (Gerthsen et al., 1980; Takahashi et al, 1994; Beige, 1983; Mukherjee et al, 2001). Moreover, a complete study of UAD on CFRP in terms of drilling forces reduction, surface finish, delamination and temperature effects has not been conducted.

Two main objectives were considered in this project: (i) reproducibility of the results and; (ii) experimental study of UAD on CFRP. The former one was achieved by improving the design of a drilling transducer using numerical analysis and, in the latter one, drilling forces, surface quality, hole size, thermal analysis, delamination and tool wear was studied for UAD and compared with CD to compare and contrast the effectiveness of UAD as viable machining process. Moreover, the effect of tool wear on drilling forces, surface finish, hole size and delamination was also studied.

1.1 Aim and objectives

The aim of this project is to achieve reduction in drilling forces in CFRP using UAD and, to compare the effects of UAD with CD on damage in drilled laminates. To achieve the aim of this research, the following objectives should be implemented:

- To suggest designs for drilling ultrasonic transducers to drill bits of various diameters;
- To study the effects of feed rate on drilling forces in UAD and compare them to those in CD;
- To investigate the response of CFRP to UAD by measuring surface roughness, circularity and delamination: and compare these parameters to those for CD;
- To perform a comparative study of tool wear in UAD and CD and analyse their effect on drilling quality.

1.2 Motivation and novelty

As mentioned CFRP are used in different applications due to their attractive properties. Due to high strength-to-weight ratio, fluid resistivity, corrosion resistivity and low thermal conductivity compared to metals, the use of CFRP is growing rapidly, for example, only in aerospace industry compound annual growth rate for CFRP is estimated as 11.8% (Plastemart, 2013). This increased use of CFRP in the global market is also unavoidable. However, since the development of CFRP, drilling is a challenging and unavoidable machining operation and efforts were made to improve the hole quality in drilling. Drilling defects e.g. surface finish, hole circularity and delamination were minimised by reducing the drilling forces with application of coolants/cutting-fluids or by drilling the pilot holes. As, CFRP is hydroscopic material therefore the special coolants are used which are expensive and despite the extensive care dimensional problems occur with the application of these coolants/cutting-fluids. When the pilot drills are used, the production time increases. Both of these increase the cost of production. Although, different researchers used UAD to reduce the drilling associated

problems in metals (Shoh, 1970; Devine, 1985; Bone 2005; Baghlani et al., 2013), limited knowledge is available on UAD of CFRP.

In the first part of this research, a finite-element model is proposed for the design and improvement of the drilling transducer in order to achieve the maximum vibration affect on the drill-bit-tip. An approach, to estimate the vibration frequency of a transducer for a particular material, was also suggested.

In the second part of this research, the drilling parameters were suggested to achieve high level of drilling-forces reduction in UAD compared to CD. The recommendations were also provided to achieve the same level of forces reduction at high spindle speed and feed rate.

It is the first study of its type on UAD of CFRP in which the effects of UAD on CFRP were reported. Drilling forces, circularity, hole roundness, surface roughness, hole surface hardness and delamination were studied and compared with CD.

Tool wear in case of UAD was reported for the first time. The tool wear was documented as a material loss after drilling a certain number of holes. Indirect tool wear parameters such as drilling forces, surface roughness, circularity and delamination was also studied with the increase in drilling-holes using the same drill bit.

1.3 Research methodology

A schematic of research methodology is shown in Figure 1.1. This can be divided into two main areas (i) finite-element modelling of transducers; (ii) experimentation;

Due to the scope of this project a comprehensive literature review was carried out in three main fields: (i) composites; in which the importance of composites especially CFRP was discussed and different properties of CFRP that could affect drilling process were addressed; (ii) drilling process is explained, and effect of different parameters on hole quality were discussed. It was found that UAD was used to improve the hole quality in different materials, at similar process parameters.

Ultrasonically-assisted drilling of carbon fibre-reinforced plastics

Figure 1.1. Schematic of thesis outline

However, UAD is a nonlinear process due to the inherited nonlinear properties of piezoelectric-transducer; (iii) transducer's design; in which the challenges and implications in designs of ultrasonic transducers was discussed.

It was found that CFRP machining especially drilling is practiced very often and; it encounters different challenges in CFRP. Unlike metal machining, in CFRP machining the tool experiences alternatively matrix and reinforcement materials, of which response to machining can be completely different. These challenges could be minimised using UAD but for the implementation of UAD in CFRP, an improvement in drilling transducer design was necessary. Conventional drilling (CD) implies large distribution of stress concentration in the materials and also delamination and surface quality degradation (Keonig, et al.,1985; Davim and Reis, 2003; Zitoune et al., 2005). This reduces the fatigue strength of components, hence, the long-term performance decreases (Torres et al., 2009; Persson et al., 1997). Stress generated during drilling process can be reduced with the help of UAD because UAD lower level of drilling forces is encountered by workpiece and drill bit. Moreover, the effects of UAD on CFRP are necessary to study for the qualification of this drilling process for CFRPs.

In this project, preliminary experiments were conducted on CFRP with existing transducer. However, no significant reduction in drilling forces was observed. It was decided that the design of a transducer should be improved. This was achieved into two steps: (i) Numerical modelling was conducted for an existing transducer and the model was validated with experimental data; (ii) three new transducer-systems were designed and manufactured to accommodate Ø3 mm, Ø6 mm and Ø12 mm drill bits.

Drilling experiments were conducted using each size of mentioned drill bit. Drilling forces were analysed for each of the drill bit whereas, a study on drilling forces, thermal effects during drilling process, surface finish, hole size, circularity, delamination and tool wear was carried out using Ø3 mm drill bit.

CHAPTER2

COMPOSITE MATERIALS

A composite material is combination of two or more substances that exhibits the overall mechanical properties superior to those of the original constituents (Chawla, 2009). Another definition states that a composite material is a structural material consisting of two or more combined constituents at a macroscopic level that are insoluble in each other and exhibiting superior properties than each of the constituents (Gau, 2006). Composites have been practiced since ancient times. As in those days, composites of the modern age are also a combination of different materials. These materials form a new material, which usually exhibits excellent mechanical and physical properties as compared to conventional metals such as aluminium alloys and steel alloys (Matthew and Rawlings, 2003). The use of composites varied through history, but it is definitely increasing nowadays.

2.1 History of composites

The history of composites is dated back to ancient times (10,000 BC); for instance the Book of Exodus states that Maya used straws to strengthen the mud in brick-making. Egyptians used a composite material made of sheets of papyrus to make the mummy cases. Later in history, swords were made up of alternative layers of Toledo and Damascus during the middle ages (Jones, 1975). Then bronze was invented during 1500 BC. After Bronze Age, consumption of steel alloys gained popularity, much later in 1850s. This led to the maximum consumption of metals and alloys, which was recorded from 1940 to 1960. Consumption of different materials during different ages is shown in Figure 2.1.

From 1960s the consumption of metals and alloys, as a percentage of total material consumed, declined whereas the consumption of composites increased. It started in 1930s when the first modern synthetic resin was developed by Aero Research Limited UK (U.S. Congress, 1988). The manufacturing of high-strength, high-stiffness carbon-fibre composites took place in 1964 when Watts, Phillips and Johnson conducted successful experiments at Royal Aircraft Establishment (Watts et al., 1966).

During the same decade, epoxy gained its superiority over other matrix materials for structural applications. Since that time the production of advanced composites has been increasing, with a global market of \$10 billions in 1990s. In 2012, the global market of CFRPs was recorded as \$ 14.6 billion and is expected to grow at a compound annual growth rate (CAGR) of 13% leading to the global market as high as \$36 billion by the end of 2020 (Jacques, 2012)

With all the developments in carbon fibres and epoxies, the use of composites in commercial aircrafts increased from 10% of total weight of aircrafts in 1970 to 50% in 2013 for Airbus™ A350 XWB (Airbus, 2012). In Boeing™ 787 the structure of overall aircrafts is composed of composites making more than 50% of its total weight. Moreover, in military applications, the body of B2 stealth bomber is composed of more than 80% of CFRP (Gwad, 2011). This is mostly thanks to the fact that composite

Figure 2.1. Materials consumption for different ages (Ashby, 1987)

materials outperform the conventional metals such as aluminium, steel and other alloys due to their high strength-to-weight ratio, high modulus-to-weight ratio, high corrosion resistance and low density. Fibre-reinforced composites are preferred in aerospace and structural applications due to the perfect balance of their properties to suit the loading conditions and resistance to the environment (Matthew and Rawlings, 2003). Due to these attractive properties of CFRP, the use of composite materials in aircrafts increases; this is shown in Figure 2.2 (Cookson, 2009). The composite materials cannot be used in these applications without successive machining operations, e.g. drilling. The machining dynamics of the composites, is completely different from that for conventional metals due to composites anisotropy and non-homogeneity. In order to study their machining behaviour, it is important to understand the structure of composite materials.

Figure 2.2. Aircraft composite content over time (Cookson, 2009)

Fibre-reinforced composites are composed of three main constituents, the fibres, the resin (matrix) and the interphase. The applied load is effectively distributed to the resin and fibres because the matrix adheres the fibres together. The resin protects the fibres from external scratching, moisture, chemical corrosion and oxidation. In composites, their properties such as failure mechanisms, shear, transverse tensile and compression are dominated by fibres over resin. As resins have lower heat resistance compared to fibres, the matrix dominates the thermo-mechanical behaviour of fibre-reinforced composites. Several types of thermoset and thermoplastic resins are used in manufacturing of fibre-reinforced composite (Fu et al., 2002). Thermoset resins are a type of resin that cannot reach its liquid state after completion of a curing process. This is due to the fact that when thermosets are cured the irreversible crosslinking chemical reaction takes place. In contrast, the thermoplastics can be re-melted again due to the reversible chain-extension chemical reaction; hence, melting of thermoplastics can be

achieved repeatedly. The common types of thermoset resin are epoxies, polyimides and phenolics. Most commonly used thermoplastics resins are polyphenylene sulphide (PPS), polyvinylchloride (PVC), polyetheretherketone (PEEK) and methylvinylsiloxane (Fu et al., 2002).

In the aerospace industry, epoxy-based resins are used as they exhibit several beneficial features compared to other types of resins. One of their attractive features is their extensive compatibility with fibres reducing interfacial challenges. Resistance to aircraft fluids such as different types of hydraulics and fuels is another important feature of the epoxy resins. Both in commercial and military aircraft the epoxy-based resin fibre-reinforced composites are preferred (Evan and Masters, 1987). Epoxies are reinforced with different types of reinforcements. Four main types of reinforcements are used in structural applications such as whiskers, particulates, flaks and fibres. A common example of whisker composites is alumina matrix reinforced with silicon carbide, used to make cutting-tool materials (Jun and Smith, 1994). The whisker composites are strong, however cannot be used in aerospace applications because of the short length of whiskers, and due to shorter length they break under heavy loading. Particulate composites contains one, or more than one, material in a matrix of another materials such as concrete, which consists of rock and sand in a matrix of wet cement. Particulate composites offer high compressive strength but a poor response to tensile loading, whereas, in aerospace applications both tensile and compressive resistance are equally important. The reinforcements made up of flakes have, predominantly, two-dimensional geometry, which provides several advantages. Although, this kind of composites offer better hindrance to solvent penetration, it is challenging to align composite constituents.

Among fibres, continuous and long fibres are acknowledged in aerospace applications because they offer superior strength, creep and damping properties. Mechanical properties, i.e. tensile strength and stiffness, are dominated by fibres in the composite stack. The stacking sequence, type and orientation of the fibres in a particular layup affect the mechanical behaviour of the layup. Commercially available fibres can be classified into four maintypes: (i) Kevlar; (ii) Glass; (iii) Boron and (iv) Carbon fibres.

Kevlar fibres provide high impact resistance together with high toughness. Their applications are limited because they present poor bonding with matrix and poor compressive strength. Their response to compression deviate from linearity as the load exceeds 20% of ultimate load, resulting in buckling of fibres. Glass-fibre composites are easy to manufacture and are also inexpensive. The application of glass fibres is limited to general-purpose applications such as motor bodies, sinks, sheds and other domestic applications because they have lower stiffness compared to other kinds of fibres.

Boron fibres are much stiffer and were used in the aircraft industry but their high specific gravity, handling problems and high cost of manufacturing prevent their use on larger scales.

Carbon fibres are most suitable for aerospace applications because they offer a balanced combination of properties, i.e. both high stiffness and specific strength (Stephen et al., 1980). The advantages and application of fibre-reinforced composites are given in Table. 2.1. The properties of each type of fibre, i.e. carbon, glass and Kevlar are given in Table 2.2.

Table 2.1. Merits of fibre-reinforced composites and corresponding applications after Hota and Rao (2010)

Parameter	Fibre-reinforced composite application	
	Fibre-reinforced composite	Applications
Stiffness	Very high High	Aerospace Marine, construction, pipes, bridges, reinforcing bars, automotive
Weight	Low	Aerospace, marine, construction, pipes, bridges, reinforcing bars, automotive
Environmental resistance	Very high	Marine, boat industry, construction industry, aerospace
	High	Automotive, leisurely applications
Ease of field construction	High	Buildings, bridges, pavements, kiln linings, wind-mill blades
Ease of repair	High	Bridges, tunnels, underwater piles
Fire resistance	Very high	Aerospace, marine, automotive, blast-resistant FRP construction.
	Medium	bridge decks, leisure products, marine boats
Ease of handling	Very high	Shapes, bridge decks, components and assembled FRP systems
Toughness and impact resistance	High	Bullet-proof vests, vandalism-and_graffiti proof walls

Table 2.2. Properties of fibres (Sheikh-Ahmad, 2009)

Characteristics	Carbon fibres	Kevlar 49	Glass fibre
Diameter (μm)	5-10	8-14	10-20
Density (g/cm^3)	1.7-1.8	1.4	2.46-2.49
Young's modulus (GPa)			
Parallel to fibre axis	250-400	131	80-90
Perpendicular to fibre axis	12-24	70	-
Specific heat (kJ/kgK)	0.7-0.9	0.77	0.41

Carbon fibres are classified into four main classes, i.e. high tensile (HT, type-I) strength fibres, intermediate modulus (IM, type-II) fibres, high-modulus (HM, type-III) fibres and ultra-high-modulus (UHM, type-IV) fibres. Type I fibres are strong with low modulus. Type II fibres have intermediate strength and intermediate modulus. Type III have a higher modulus than both of the previous types with lower strength, whereas, type IV offers a higher modulus than all of the other types presenting minimum strength (Grégr, 2010). These properties for each type of carbon fibre are given in Table 2.3.

Table 2.3. Properties of different types of carbon fibres (Grégr, 2010)

Type of fibre	Tensile strength (GPa)	Young's modulus (GPa)
TypeI (HT)	3.3 – 6.9	200 – 250
TypeII (IM)	4.0 – 5.8	280 – 300
Type III (HM)	3.8 – 4.5	350 – 600
Type IV (UHM)	2.4 – 3.8	600 – 960

Different types of fibres are manufactured in a different manner. The type of manufacturing of fibres influence their properties. A short introduction about the carbon fibres is given below;

Carbon fibres can be manufactured from two constituents such as polyacrylonitrile (PAN-based) and pitch precursors. PAN-based fibres provide high strength to the composite and also better interface between fibre and matrix. Whereas pitch-based fibres are not as strong as PAN-based; however, they have a high modulus, they are easy to manufacture and cost effective (Huang and Young, 1995).

Irrespective of manufacturing process of carbon fibres, they are highly anisotropic; therefore, their mechanical properties vary as the graphite layer orientation changes with respect to the longitudinal axis of the fibre. The fibres are in a size of microns;

hence, they can be clustered into a group to tows and yarn that contains 2 – 48,000 fibres in each group to achieve the desired dimensions (Sheikh-Ahmad, 2009). To summarize information about carbon fibres, they are anisotropic, highly conductive, often clustered in different groups to achieve desired dimensions and are suitable for high-strength applications, e.g. aerospace.

It should also be noted that as the carbon fibres are highly conductive, a great care is needed during machining of these composites. When machining processes are carried out, the dust formed during the process may cause the short circuit in the machine controls. The dust removed could also cause the short circuit problems (Sheikh-Ahmad, 2009).

2.1.1 Epoxy resins

Epoxy resins belong to the family of thermosets. They offer high adhesive forces for different types of fibres such as glass and carbon fibres. Other attractive features of the epoxy resins include high temperature resistance, stability of dimensions, toughness, rigidity, resistance to other chemicals and better mechanical properties as compared to other matrix materials. All of these properties of epoxy resins suit them for hostile environment as required in the aircraft industry (Plotkin, 2006).

Another advantage of the epoxy resin is that they do not produce reaction products when they are cured, which minimises the cure shrinkage. Epoxy materials are produced when epichlorohydrin reacts with biphenol. The proportion of each affect the type of the resin; for example, molecular weight of the resin is decreased by increasing the proportion of epichlorohydrin.

While curing, a curing agent such as a hardener or an activator is used; therefore, curing agents can be referred to as a catalyst. Curing is normally performed at room temperature (Singla and Vikas, 2010). The epoxy-based properties of fibre-reinforced materials generally depend on formation of a three-dimensional network. Such a network is created when a suitable hardening agent reacts with the epoxy resin. This is a two-stage process, referred to as gelation and vitrification. A gelation process takes

place first and is an irreversible process, whereas vitrification can occur at any time during curing and is the transformation of a viscous gel to a glass state (Kubisztal et al., 2009). When the epoxy and fibres are cured to form a composite, an interphase is present between both constituents. This interphase should be treated in a different manner especially, in finite element simulations.

2.1.2 Interphase

Interphase can be considered as a separate constituent because it results from the structural contact between two materials. This provides the strong adhesion between the constituents such as fibres and the matrix (epoxy).

The surface of fibres and quality of the resin affect the adhesion quality. The latter can be defined as a degree of adhesiveness between two materials. When the carbon fibres are introduced to the epoxy materials the surface of the fibres forms a new hydrocarbon group $[(-C - OH), (-C = O), (-CO_2H)]$ that bonds itself, chemically, with the unsaturated matrix. The bonding is a direct result of highly chemically reactive surface of carbon fibres. This helps in absorbing the gases released during the bonding process. Micro roughness of carbon fibres surface increases a specific surface area, which contributes to adhesion of the fibres and the matrix. To achieve increased adhesion, peroxide etch is applied to carbon fibres after the graphitizing stage. As a result, a carbonyl group is formed on the surface of the fibres which interacts with epoxide. At the end, a coating of epoxy such as MY-702 is applied so that damage accumulation can be avoided during handling (Tong et al., 2002).

Mechanical properties, i.e. transverse, shear and flexure, of a composite are strongly dependent on the interface. Weak bonding of interface could lead to fibre pull-out and, hence, cohesive failure may occur. If strong matrix bonding does not exist then fibres can slide, resulting in tensile failure or compressional buckling. The interface that offers high bonding between the matrix and fibres successfully transfers the load to fibres until adhesive failure. Such failure is sudden and disastrous. High-strength fibres are

susceptible to adhesive failure whereas high-modulus fibres are prone to cohesive failure (Ehrburgeral and Donnet, 1980; Donnet and Guilpain, 1991).

CFRP are usually available in the market in the form of prepregs. Prepregs contain all the three constituents (fibres, resin and interphase) in the form of thin sheets with the defined orientation of fibre in the matrix.

2.1.3 Prepregs

The prepregs are manufactured first and can be directly used in the manufacturing of components. A prepreg is a combination of resin and fibres. Unidirectional prepregs are available with fibres aligned in one direction as well as woven ones. Unidirectional composites are anisotropic because their mechanical properties predominate only in one direction. Woven type composites are weaved, and their texture can easily be seen on the stack surface. They consist of two threads, woven together – weft and warp. The weaving style is varied depending on crimp and drapeability. If the mechanical performance is desired then fibres are weaved with low crimp whereas high drapeability of fibres allows adapting complex shapes of layups (Hexcel, 2007).

Carbon-fibre composites are available in different varieties for different applications depending on orientation of the layup of the stack; for instance, quasi-isotropic composites are composed of a combination $[0^\circ, +45^\circ, -45^\circ, 90^\circ]$. Layups can be made in such a way that they offer optimised mechanical properties in various directions. Different lay-ups are shown in Figure 2.3. Quasi-isotropic composites are most suitable for aerospace applications.

Lay ups are processed together to achieve the desired shape, size and properties of a composite. The manufacturing process of carbon epoxy composites is completely different from conventional metals.

2.2 Manufacturing of carbon fibre-reinforced epoxy composites

Carbon fibre-reinforced plastic composites are manufactured in three stages, (Owen et al., 2000 and Campbell, 2004):

(i) **Pre-impregnation** At this stage, carbon fibres are dipped into the viscous epoxy resin and impregnated. Then the impregnated (with epoxy) fibres are wound on the mandrel. At this point the epoxy is almost dry and the material can be handled without losing the resin but the material is still sticky and viscous. This pre-impregnated material is then chopped into different pieces or rolled like a tape. The fibres after this stage are unidirectional and the product after complete process is called prepreg.

(ii) **Laying up process** The prepregs are then cut and laid up at different orientations depending on the application. This process is usually carried out with the help of moulds.

(iii) **Curing process** Layups are then covered with different films and bags to provide an inert atmosphere to support a curing process. The bag is then placed into the oven and the temperature is increased. Different epoxy systems have different heating cycles. Then the composite is cooled down to the room temperature. After this bagging and moulds are removed.

(a)

(b)

(c)

(d)

Figure 2.3. Layups and orientation of CFRPs: (a) plain weave: high crimp/low drapeability; (b) stain weave: low crimp/high drapeability; (c) unidirectional layup; (d) quasi-isotropic layup

Despite the fact that carbon fibres reinforced plastics are suitable for aerospace applications, in most cases they cannot be used without a machining process to facilitate assembly. Hence, the drilling process is often carried out to make the holes for riveting and bolting (Khashaba, 2012). Different properties of CFRP have different effects on drilling quality of the hole. The major properties of CFRP relative to drilling are discussed below in detail.

2.3 Drilling-related properties of carbon fibre-reinforced composites

Materials of fibres and resin must have compatibility with each other and there must be a balance in the mechanical properties of fibres and matrix (resin), especially for successful machining process. Carbon fibres offer high physical and chemical compatibility with epoxy resins due to their high modulus and high specific stiffness. This makes carbon-epoxy system suitable for machining compared to other carbon fibre-based composites.

Depending on the curing schedules and fabrication processes, epoxy resins are formulated for different applications. Low curing shrinkage increases the shelf life of the carbon fibre-epoxy composites compared to other carbon fibre-reinforced composites.

Different standards of carbon-epoxy systems are available for different applications, e.g. M21/T700 is one of those suitable for aerospace applications. In this carbon-epoxy system M21 is a standard epoxy and T700 is a type of carbon fibre with a specific standardized curing process introduced by Hexcel™. Another carbon-epoxy system is 924C/T800 (Hexel™, 2012). Although, this epoxy systems offers relative lower elastic modulus, the allowable compressive loading of this composite is higher.

The properties of the fibre type T700 and T800 are given in Table 2.4. The composites, used in the course of this study, were composed of these two types of fibres and the

epoxy systems, i.e. M21/T700 and M21/T800. Drilling-related properties of fibre, reinforcement and interface are explained in details;

2.3.1 Drilling-related properties of carbon fibre

The properties of carbon fibres with respect to drilling that can affect the manufacturing process are explained below:

(i) **Abrasive nature of carbon fibre** The abrasive nature of carbon fibres increases the tool wear; hence, the drill-bit life decreases. This results in premature failure of drill bit (Sheikh-Ahmad, 2009).

(ii) **Modulus of elasticity** The modulus of elasticity of a carbon fibre depends on the heat-treatment cycle during the manufacturing process. The higher the temperature, the higher the alignment of fibres. The alignment of fibres also affects their strength. As the modulus is related to strength, the modulus of fibre plays an important role on the quality of drilling of fibre-reinforced plastics,

(iii) **Compressive strength** Compressive strength of a typical high-performance carbon fibre-reinforced unidirectional prepreg is in the range of 1600 MPa, which is inherent from carbon fibres (SP Systems, 2000). Carbon fibres could recede in the resin instead of experiencing any shear, when the drilling is initiated. The stress strain curve of IM and HS carbon fibres under compression is shown in Figure 2.4.

Compressive strength of T300 and T800 carbon fibres is 1,300 MPa and 1,57 MPa respectively (Xiao-Su, 2009 and Data sheet Torayc™). Compressive strength of carbon fibres changes with the type of loading and temperature. The decrease in compressive strength of carbon fibres with respect to temperature with time is shown in Figure 2.5. This shows that at higher temperatures the drop in compressive strength is higher. As the temperature increases, the fibre resistance against loading decreases; moreover, the heat-exposure time of the fibre to resist the loading decreases. At higher temperatures, the failure of the fibre during compression is primarily governed by micro-buckling (Soutis and Fleck, 1991); therefore, the fibre alignments are considered important.

During the drilling process, fibres experience compressional, tensile and shear loads at the same time.

It was found that a shear angle with respect to the fibre axis changes at each instant during the drilling process. (Sheikh-Ahmad, 2009). Even a very small misalignment during layups could cause a complete change in the composite behavioural during loading, e.g. 0.25° , misalignment led to a decrease in axial strength from 2,720 MPa to ,850 MPa in XAS/914composite; when the alignment was disturbed by an increase to 3° , the strength decreased to 300 MPa (Hull, 1981; Wisnom, 1990). A slight misalignment of fibres during manufacturing could lead to its earlier failure when it is loaded, and when the fibres are not aligned relative to each other, then they break at different level of stress; this could lead to the different after-drilling defects.

Table 2.4. Properties of different resin systems (Hexcel™, 2007)

Property	M21/35% /134 /T700GC	M21/35% /268 /T700GC	M21/35% /198 /T800S	M21/35% /268/T800S
Fibre type	T700GC	T700GC	T800GS	T800GS
Fibre mass (g/m²)	134	268	198	268
Ply thickness (mm)	0.131	0.262	0.193	0.262
Fibre volume (%)	57.0	56.9	56.9	56.6
Resin density (g/cm³)	1.28	1.28	1.28	1.28
Fibre density (g/m³)	1.80	1.80	1.80	1.80
Laminate density (g/cm³)	1.58	1.58	1.58	1.58
Glass transition temperature (°C)	203	203	203	203
Compressive strength (MPa)	1,461	1,465	1,657	1,669
Compressive modulus (GPa)	118	119	139	136
Tensile strength (MPa)	2,314	2,375	2,981	3,039
Tensile modulus (GPa)	147	148	170	172
In-plane shear strength (MPa)	112	95	94	79
In-plane shear modulus (GPa)	4.7	4.5	4.8	5.0

Figure 2.4. Behaviour of carbon fibre prepreg under compression (SP system, 2000)

Figure 2.5. Decrease in compressive strength with time at different temperatures
(Ramírez-Rico et al., 2012)

(iv) **Brittleness** Carbon fibres are not as ductile as many other structural material; they are highly brittle and experience a brittle failure. Therefore, their breakage happens without any significant bending. Fibres breakage, due to their brittle nature, leads to the material removal in drilling in a powdered form (Sheikh-Ahmad, 2009; Hull, 1981).

(v) **Effect of weave and layup** As a drill bit interacts with a fibre-reinforced composite, the load is distributed. Specially, it was observed that quasi-isotropic and other angular layups were easier to machine than unidirectional ones because the drilling load was distributed uniformly. Similarly, in woven composites the plain weave is easy to drill as compared to the satin weave. Volume fraction of fibres also plays a critical role in drilling, i.e. dense fabrics can be machined with better drilling quality as compared to loose fabrics (König , 1984).

(vi) **Temperature effects** The decomposition temperature of carbon fibres is in excess of **3,500° C** whereas the maximum temperature during high-speed drilling of carbon fibre-reinforced composites was recorded as **75° C** (Ur-Rehman, 2008). The drilling temperature is far lower than the decomposition temperature of the carbon fibres; therefore, the chances of defects in carbon fibres due to drilling temperature are very small. However, the temperature limitations cannot be neglected due to presence of the resin in the stack (König et al., 1985).

2.3.2 Drilling-related properties of epoxy

The following properties of resins are important with respect to the drilling process:

(i) **Heat sensitivity** Epoxy dominates a thermo-mechanical behaviour of carbon fibre-reinforced composites. Epoxy resins demonstrate very low heat resistance compared to that of carbon fibres; for example, the glass transition temperature of **M21** epoxy system is **203 °C** (Hexcel™, 2007).

Although epoxies offer higher heat resistance with respect to the thermoplastics, for machining operations they do not present the desired degree of heat resistance. At the elevated temperatures their shear modulus decreases, and the increase in temperature

also adversely affects bonding between the matrix and fibres, which could lead to delamination between the plies (König et al., 1985).

(ii) Brittleness of epoxy As cross-linking develops in epoxies, their brittleness increases and, as a result, their crack resistance decreases. Rubber-based tougheners are added to the epoxies to decrease their brittleness but this also diminishes the resistance to heat and shear strength (Hertzberg, 1988).

(iii) Hot/wet response A hot/wet response is also known as a hydrothermal response. Some properties such as shear are drastically affected by absorption of moisture or water at increased temperature; these properties are matrix-dominated. The absorption of moisture can cause dimensional-accuracy problems in carbon fibre-reinforced composites. The hot/wet-response tests of the composites are carried out at controlled moisture content and controlled temperature in specialized ovens. The tested specimens are weighted, and their size is measured before and after the tests. The difference in size and weight determines the hot/wet response of the given carbon-epoxy system (Hoskin et al., 1984; Barker et al., 1987).

An experimental study was carried out (Fjeldly, 2011) to investigate the hot/wet response of T700 and T800 fibre composites, in which the single-fibre matrix was created and the composites were cured at room temperature for 24 hrs and then at 80° C for 24 hrs. The obtained specimens were introduced to the boiling water for 3 hrs. The elongation up to 1.8%, 1.9% and 8.5% of original length was observed in T700, T800 fibres and epoxy resin, respectively. A significant difference in the interfacial properties was also observed.

(iv) Curing-induced stress Epoxy resins are cured in two stages; the first stage of curing takes place at room temperature, whereas in the second stage the temperature is raised according to the type of the epoxy system. This increase in temperature induces residual thermal stresses at the interface. Then the composite is cooled and this cooling from higher temperature to room temperature produces the compressive stresses in fibres. This improves the shear strength of matrix-and-fibre bond. When the drilling process is carried out, it produces heat due to friction and shear and thereby

relieves the residual stresses that are exerted by the resin on fibres. The greater the curing temperature, the higher the retention of residual stresses in drilling. Hence, the curing that takes place at elevated temperature is favourable for drilling (König et al., 1985; Sheikh-Ahmad, 2009).

2.4 Summary

A brief overview of composite material is presented in this chapter. Different types of composite materials are discussed, and the application and growth of CFRP is overviewed. Different constituents present in CFRP are reviewed, and mechanical properties of fibre-composite especially CFRP are presented. Mechanical and physical properties of different constituents of CFRP, that can influence drilling process, are discussed. It was debated in the literature that based on mechanical and physical properties of CFRP; they have different machining response compared to conventional metals.

As carbon fibre-reinforced plastics are completely different from conventional metals, the drilling process of these composites is necessary to study for the better understanding. A literature review related to the drilling is given in next chapter which shows how much work has been conducted in this field.

CHAPTER3

DRILLING PROCESSES

Machining is a process, carried out to shape the materials to suit for a particular application. It was reported that machining cost accounts for about 90% of total production costs in ceramic components only (Prabharkat et al., 1995). Machining processes include turning, milling, drilling etc. Drilling is a machining process used to produce or enlarge holes in a workpiece with help of a cutting tool called drill bit. It has been estimated that drilling process accounts for about 25% of all the machining processes (DeGarmo, 2003). It was estimated that only in Airbus aircraft almost 55,000 hole processes are involved (Müller-Hummel et. al., 2008). Another estimate suggested that almost 60% of part rejection, during assembly of an aircraft, are due to drilling process (Wong et al., 1982).

Drilling is a complex three dimensional cutting process which is affected by several parameters such as rotational speed, feed rate and drill geometry. It is observed that, in

any drilling process, rotational speed and feed rate are the basic parameters that influence the drilling process. Other variables include, tool geometry, tool material, workpiece material, workpiece thickness, coolant. The effects of these variables are thrust force, torque, temperature, hole quality and tool wear (Kesavan and Ramnath, 2010). Drilling process is being practiced since ancient civilizations. Drilling operation has been improved through continuous development. The research decreased the process cost, improved the hole quality and reduce the process time. The drill bit, in early times, suffered different problems such as low mechanical strength, low wear resistance, poor hole quality, low production and high cost per hole (Thomas, 2007). The first patent of a drill bit was recorded by Morse (1863). This drill bit was similar to the drill bit (from geometrical point of view) which we use nowadays. It consisted of two discrete spirals to facilitate the chip removal and a point cutting part to improve the cutting action. The development of high speed steel (HSS), in twentieth century, revolutionised the design and development of twist drill bits (Oxford, 1955). The shape and size of a twist drill bit has developed and become universally acceptable both for performance and design for general purpose drilling applications.

3.1 Twist drill bit

A typical twist drill bit is shown in Figure 3.1. The drill bit axis is a vertical straight line that runs across the body of a drill bit. The flutes of a drill bit are helical and run down the drill bit axis. The function of flutes is to remove the chip from workpiece. The drill bits consist of several numbers of flutes ranging from one to four; however, for special applications number of flutes can be increased. The winding of these spiral flutes could be right handed or left handed. The pitch of flutes could also vary depending on the type of drill bit. The pitch of flute is dependent on the leading-edge-angle and drill bit axis referred as a land (Astashov, 2010). On drill bit land, margin is provided for the smooth guidance of the tool into the workpiece. A clearance angle is provided on a drill bit for reducing the friction and it also reduces the chip binding. The drill point is cutting end of a twist drill. A point angle is introduced between the drill bit lips. The section of a

drill bit material, lying between the flutes and joining the land, is called web of a drill bit. Chisel edge is formed by web, in case of two fluted drill bit and the thickness of chisel edge represents the thickness of a web. The chisel angle is the angle formed by chisel edge and cutting lips. The rake angle of a drill bit varies across the drill tip. In the commercially available drill bits, the rake angle could be from negative to positive.

Twist drill bit is considered as a standard drill bit, however different types of drill bit such as stub, jobber and masonry is dependent on the material and geometry of a drill bit. The selection of a drill bit depends on the application. For example stub drill bits are used for high hole accuracy compared to Jobber drill bits. Twist_drill bits are not used for precision cutting operation (Marinescu et al., 2002). On the other hand, the holes can be generated much faster and are economical. For high precision, additional operations such as reaming and boring are carried out. Each part of drill bit plays an important role in facilitating the cutting phenomenon. A normal drill bit process is explained below;

- The chisel edge of a drill bit extrudes the workpiece material. The material is extruded from the centre of a drill bit to the web thickness (diameter of a drill bit)
- The drill bit lips cut the material
- The helical flutes remove the material from a cutting zone by screwing action
- Drill bit's margin and land guide the drill bit into workpiece

The successive cutting of a workpiece, under the action of each drill bit part, is shown in Figure 3.2.

For demonstration, a drilling experiment was conducted on brass workpiece with lead drill bit. The drill bit was stopped instantaneously in the workpiece and then it was retrieved. Two modes of material removal were observed: (i) the hole centre formed by the extrusion of workpiece material that resulted into long stringy chip; (ii) the formation of a uniform large chip that took place by drill bit lips. This is shown in Figure 3.3. The stringy chip could be forced out during the process or they may entwine with the chip formed by drill lips. It may remain separated and ejection takes place after flowing on the flute (Oxford, 1955).

Figure 3.1. Standard twist drill bit geometry (Shatla and Altan, 2000)

Figure 3.2. Cutting mechanisms (DeGarmo et al., 2003)

3.1.1 Considerations for twist drill bit

Material of a drill bit should demonstrate several features such as wear resistance, hardness and toughness at high temperature. The materials, normally, used to manufacture the drill bits are high speed steel (HSS) or sintered tungsten carbide, usually known as carbide. For general purpose drilling, HSS is preferred. However, carbide drills are also used intensively in the industry for drilling. Before the production of HSS and carbide, other alloys were used for manufacturing of a drill bit (Kesavan and Ramnath, 2010). Tools made of alloys were obsolete because they fail to present the required hardness at elevated temperature during process. To improve the performance of a drill bit for desired operation, heat treatments and surface treatment operations are applied on the drill bit (Dallas DB, 1976).

Figure 3.3. Chip removal (Shaw and Cook, 1954)

Carbide drill bits are harder and more wear resistant compared to HSS drill bits. Carbide drill bits are usually used for cutting aluminium, cast iron and other nonferrous materials; however, same type of drill bits are used for drilling composites. Carbide drill bits offer benefits over HSS drill bits such as longer tool life, high spindle speed during operation and high material removal (Kesavan and Ramnath, 2010). However, carbide drills are more expensive than HSS drill bits. For large diameters holes, usually, carbide coating is applied on HSS drill bits. In composite drilling, the wear of a drill bit is completely different because of anisotropy of materials.

Another importance of coating is that they facilitate the cutting operation and increase the tool life. These coatings are applied by electroplating, chemical plating or arc deposition. The elements used for coating are usually nickel, tungsten, titanium and other similar materials to resist the harsh drilling environment in a process zone. Titanium Nitride (TiN) coating is often used because it reduces the friction and improves the tool life (Astashov, 2010).

For successive tool life, it should be noted that the hole depth also changes the method of drilling in terms of feed rate and rotational speed because the tool breaks when the

hole depth increases. For example, when the hole depth becomes equal to three or four folds of drill bit diameter, feed rate and spindle speed should be changed and also the periodic tool retrieval is important. This prevents the breakage of a drill bit and also reduces the chances of drill bit to stick into the workpiece (Dallas, 1976). Coolants are typically applied during drilling operation to reduce this, decrease machine time and increase the tool life. For the coolant to flow, special holes are provided in the drill bit body. The coolant is released at the cutting edge, reducing the temperature generated during the process. It has been reported that with the application of coolant the hole depth can be achieved eight times higher than dry cutting without changing feed rate and spindle speed (Dallas, 1976).

The geometry of a drill bit is usually optimised for a specific application (Galloway, 1957; Shyha et al., 2009; Palanikumar, 2011). The drill bits available in the market are, usually, provided with the operating parameters. The performance of a drill bit also depends on several other conditions such as the type of machine used to operate drill bit, workpiece properties such as porosity, anisotropy and inclination of workpiece. Moreover, the quality of a drilled hole could depend on the tool holding mechanism, tools chatter and process parameters (DeGarmo, 2003).

3.1.2 Performance challenge – Twist drill bit

New materials are consistently developed for high performance applications such as aerospace and automobile. These materials possess the properties such as high strength, hardness, thermal stability, anisotropy and corrosion resistance. High performance alloys, ceramics and composites are examples of such materials.

Improved mechanical and physical properties result in machining challenges. Material characteristics of composites such as anisotropy, inhomogeneity and low thermal conductivity introduce poor surface profile, cracking, delamination, splintering and chipping. Abrasiveness and hardness of the material also adversely affect the tool. In order to face these challenges, new machining and manufacturing techniques are being consistently developed (König et. al., 1990; Aspinwall, 2005). From drill bit point of view following challenges may arise;

- The cutting accuracy e.g. roundness, cylindricity and roughness could be influenced due to the relative softness of the drill bit with respect to the workpiece
- Burr formation in case of metals and delamination in case of composites could occur due to high drilling forces
- Wandering of drill bit can lead to bending and positional inaccuracies. The bending could cause breakage of the drill bits (Lee et al., 1987)
- Uneven drill wear along the cutting surfaces of a drill bit (Dallas, 1976)
- Hole-oversizing due to heat generation in the process zone and hole-undersizing due to rapid wear of drill bit (Zhixiong and Cheng 1999; Bayly et al., 2002)
- The frictional heat between drill bit and workpiece can cause the melting of a material, in case of soft materials e.g. 1050- aluminium, plastic
- Inconsistent formation of chip can block the coolant passage
- Chatter could be caused by the vibration motion of a drill bit due to torsional stiffness that leads to vibration at natural frequency of a drill bit, thus resulting into breakage of a drill bit
- New legislations to reduce the waste generation resulted into minimal use of lubricants (Envirowise, 2013). Thus drilling deep holes without lubricant is comparatively difficult
- Long chip formation requires chip breaking phenomenon to maintain the drilling quality as well as safety
- In some applications, deep holes are the requirements of industry thus the manufacturing of stronger drill bits puts another challenge on manufacturers

All of the mentioned problems result into the rejection of drilling parts. This increases the manufacturing time and increase the cost of a product.

These challenges can be handled by adopting another drilling technique e.g. ultrasonically-assisted drilling (UAD), laser drilling and water jet drilling. It has been proven that UAD has considerable advantages over conventional drilling. The technique uses the same twist drill bit (Thomas PNH, 2008). The details and the short history of this technique (UAD) are discussed in coming sections.

3.2 Ultrasonically-assisted drilling

Ultrasonically-assisted drilling (UAD) is a hybrid machining process in which high frequency (~ 20 kHz) vibration are superimposed on the drill bit or workpiece. The superimposing of high frequency vibration on the tool was first studied by Tatarinov (1910). It was reported that the application of 10 Hz vibration, in turning experiments, improved the chip formation. The experiments were conducted at low cutting speed ($100 \text{ rpm} <$). In drilling, low and sonic vibration were implemented in agricultural industry (Markov, 1966). The research addressed the problems faced by drilling with $\varnothing 0.2 - 2 \text{ mm}$ drill bits. Application of vibration, at a frequency of $50 - 600 \text{ Hz}$ with amplitude of $15 - 90 \text{ }\mu\text{m}$ along the drill bit axis (longitudinal vibration), improved the tool life, improved chip fragmentation and facilitated the machining feed rate. Later the vibrations were applied in different modes and the advantages and disadvantages of each mode were discussed (Bone G, 2005; Neugebauer and Stoll 2004; Zhang De-yuan et al., 1994).

3.2.1 Drill bit vibration

Vibrations are usually applied in the longitudinal direction of a drill bit. Researchers have reported several advantages such as drilling force reduction, improved surface quality and reduced tool wear is case of vibrating the drill bit in longitudinal direction. This work was summarized by Thomas (2008). The work of researchers using longitudinal vibration, superimposed on drill bit, is listed in Table 3.1. The table enlists the size of tool used, material of a tool, vibration frequency and vibration amplitude using the longitudinal vibration.

It has been reported that drill bit can also be excited in torsional modes of vibration and the advantages of UAD can be observed. Fuji claimed that their computer numeric control (CNC) machine can accommodate the drill bits $\varnothing 0.2 - 12 \text{ mm}$ and can be vibrated up to 27 kHz . (Fuji, 2011). However, this claim was opposed by Astashev and Babitsky (Astashev and Babitsky, 2007). They stated that torsional vibrations on drill bit showed no drilling forces reduction.

Table 3.1. UAD work - longitudinal vibration on drill bit

Research	Frequency (kHz)	Amplitude (μm)	Drill bit material	Drill size (mm)
(Shoh, 1970)	20.0	25	Not mentioned	3.26
(Fairbanks, 1975)	20.0	30	Not mentioned	6.35
(Zhang and Feng, 1991)	16.0	2.5	HSS	0.34
(Deng and Li1993)	Up to 25.0	16	HSS	1.60
(Zhang De-yuan et al., 1994)	Up to 22.0	15	Carbide	4.00
(Onikura et al., 1996)	40.0	3.5	Carbide	1.00
(Egashira et al., 2002)	40.0	0.8	Carbide	0.01
(Ohnishi et al., 2004)	75.0	1	Carbide	0.01
(Neugebauer et al., 2004)	Not mentioned	Not mentioned	Carbide	5.00
(Aoki and Nishimura, 2004; Aoki et al., 2005)	17.8	0.12	Carbide	8.00
(Azarhoushang et al., 2007)	21.0	20	Carbide	5.00
(Thomas, 2008)	22.0	12	HSS	8.00
(Baghlani et al., 2013)	20.3	Up to 10	Carbide	5.00

Mechanical and electrical designs were improved to decrease the nonlinearities in an ultrasonic system (see Section 4.1.2). Special controls were designed to reduce the nonlinearity problem. Although no research has been reported on controls of drill bit

excitation, in turning a study was conducted (Veronina, 2007). Along with improvements in electrical designs, careful mechanical-design consideration can improve the nonlinearities in an ultrasonic system. (see section 4.1).

3.2.2 Workpiece vibration

An alternative way of UAD is to vibrate the workpiece. However, this procedure has some limitations such as size of workpiece, workpiece tuning regarding ultrasonic vibration and high ultrasonic power generation (Neugebauer and Stoll 2004). The schematic of the setup is shown in Figure 3.4. Large workpiece needs more ultrasonic power to vibrate at high frequency and amplitude. Due to these limitations, this method of vibration application is not preferred from practical industrial implementation. Workpiece excitation was carried out in different ways such as along the direction of drill bit axis, perpendicular to the drill axis and in elliptical mode. Table 3.2 lists the type of vibration used to excite the workpiece.

Table 3.2. Workpiece vibration mode

Research	Vibration mode
(Huber, 1973)	Axial
(Takeyama and Kato, 1991)	Axial
(Chang and Bone, 2005)	Axial
(Chern and Lee, 2006)	Axial
(Ma et al., 2005)	Perpendicular to drill bit axis
(Bone, 2005)	Mix mode (longitudinal and torsional)

Figure 3.4. Schematic of workpiece excitation (Egashira et al., 2002)

3.3 UAD effects on tool

In UAD the tool used for drilling is generally twist drill-bit. Different characteristics such as thrust force, torque, tool life and material removal rates are affected when the process is changed from conventional drilling (CD) to UAD. As discussed in earlier sections UAD influences these characteristics and has positive influence compared to CD. Each of these is explained in detail.

It should be noted that the improvements in UAD are not always achieved because of nonlinearities of the process and system (refer to Section 4.2).

3.3.1 Drill-bit reaction

Drill bits possess large length to diameter ratio. The material of a drill bit is comparatively soft for the high aspect ratio of a drill bit. During operation, drill bits break, when drilling tough, hard and abrasive materials while drilling large diameter holes. The load is transferred in two ways: (i) axial load along the drill bit body due to feed and; (ii) torsional load (torque) due to rotation. A discrete advantage of UAD is that it reduces the drilling forces, both in terms of torque and thrust force, experienced by workpiece and drill bit. Experimental studies are evidence that UAD considerably reduced drilling forces on different materials. However, achieving the same level of force reduction each time, using the same setup, is a challenging task. The reduction in drilling forces on respective materials is shown in Table 3.3.

Although UAD has shown improvements in reducing the drilling forces, it is not necessary that if UAD reduces one component of force, i.e. thrust force, it also reduces the other component (torque). Experiments on Inconel – 718 revealed the decrease in torque, however, no reduction in thrust force was observed under ultrasonic excitation (Chen et al., 2006). Reduction in thrust forces, using different drilling conditions, i.e. feed rate and spindle speed, was reported by Zhang and Sun (1994). A study (Babitsky et al., 2007) on vibration excitation energy transfer suggested that different materials such as carbon fibre-reinforced plastics (CFRP), aluminium and glass can be drilled using UAD. It was reported that UAD can achieve up to 90% reduction in thrust force in all type of workpiece drilled during the experiments. However, it was also explained that it is difficult to achieve the same level of force reduction each time due to nonlinearities of the ultrasonic systems. In one of the figures (Figure 3.5), it was shown that drilling was initiated under conventional conditions and ultrasonic was turned on, after some time, at low feed rate. These experiments were carried out on 3 mm thick CFRP. It can be seen from Figure 3.5 that after introducing ultrasonic vibration to the tool, thrust force decreased by 90% compared to CD. It was also shown that thin strips of aluminium could be drilled without bending (see Figure 3.6). Under CD, aluminium strip bent more than 45 ° along the drill bit axis on both side, however, under UAD the

strip remained perpendicular to axis of drill bit (as happened in standard drilling) (Babitsky et al., 2007).

Table 3.3. Drilling forces on different materials

Work	Thrust force reduction (%)	Torque reduction (%)	Workpiece material
(Takeyama and Kato, 1991)	87	Not mentioned	GFRP
	80	Not mentioned	Pure aluminium
(Egashira et al., 2002)	60 – 70	Not mentioned	Glass
(Maet al., 2005)	67	Not mentioned	Aluminium (52S)
(Neugebauer and Stoll, 2004)	30 – 50	30 – 50	Al-Si alloy
(Onikura et al., 1996)	50	70 – 80	Aluminium copper based alloy
(Devine, 1985)	30	Not mentioned	Copper
(Devine, 1985)	30	Not mentioned	Cast iron
(Devine, 1985)	Not mentioned	65	Aluminium (6061-T6)
(Devine, 1985)	Not mentioned	25	Mild steel

It was suggested that under UAD, for higher depth of cuts, frequency needs to be tuned as the depth of cut varies (Zhang et al., 1994). In the experimental study, three different vibration schemes were used, i.e. no vibration (CD), constant frequency vibration at 21.5 kHz and variable frequency with respect to depth of cut. It was reported that with the increase in depth, frequency needs to be tuned for the same level of thrust force reduction. The effect of each experimental condition, in terms of thrust force signature, is shown in Figure 3.7. This research showed that the frequency tuning is necessary as the interaction (for example depth of cut) of workpiece and tool changes.

Figure 3.5. Drilling of CFRP (Babitsky et. al., 2007)

Figure 3.6. Drilling of aluminium strip: under UAD (a); under CD (b) (Babitsky et al., 2007)

3.3.2 Chip formation

It has been reported that the formation of chip changes under UAD. In some cases the chip removed in case of UAD was thinner compared to CD. Moreover, in UAD, chip was retrieved in short broken form (Fairbanks, 1975; Deng et al., 1993; Onikura et al., 1996; Suzuki and Yagishita, 2005; Devine, 2006). The chip breakage is encouraged, when drilling of large depth holes is required. For example, in case of titanium, the hole depth is limited to up to 3 to 4 times the drill-bit diameter before retraction. However, with UAD it was reported that the holes up to 8 times the diameter can be drilled in titanium without retraction (Devine, 1985). In aluminium same results were reported. It was observed that, due to chip breakage, the depths up to 20 times the diameter can be achieved without retraction (Devine, 1985). Later, in titanium drilling, at high speed drilling, it was found that in CD the chips were crumpled whereas in UAD the chip was uniform and conical.

Figure 3.7. Axial force vs. drill length (Zhang et al., 1994)

The change in chip behaviour in UAD compared to CD is summarized in Table 3.4. Change in chip behaviour for Inconel 738-LC is shown in Figure 3.8.

Figure 3.8. Chip formation of Inconel 738-LC (Azarhoushang and Akbari 2007)

Table 3.4. Chip characteristics

Research	UAD- chip characteristics
(Devine, 1985; Liu et al., 2005)	Longer, greater curl radius (metal)
(Devine, 1985)	Smoother surface and edges (metal)
(Devine, 1985)	Thinner (metal)
(Onikura et al., 1996)	Chip thickened by 30% (metal)
(Ma et al., 2005)	33 – 50% thinner (metal)
(Moriwaki et al., 1992)	Continuous chip (glass)
(Suzuki et al., 2004)	Continuous chip (ceramics)
(Azarhoushang and Akbari, 2007)	Broken chip (Inconel 738-LC)

3.3.3 Tool life

Tool life is one of the most important concerns of tool manufacturers. In several experiments, it was documented that tool life is increased with UAD (Fairbanks, 1975). However, it was opposed later and reported that the drill bit life decreases under UAD (Chang and Bone, 2004; Chang and Bone, 2005). It was analysed that UAD distributes the wear uniformly along the drill bit edges (Devine, 1985). Contrarily, in CD, the wear influenced the drill bit outer peripheral area. It was reported that the life of drill bit increases with UAD and in several cases, drilling was not possible with CD until UAD was switched on. This means that the blunt drill, from CD, was employed for successful drilling in UAD (Babitsky et al., 2007).

The effect of vibration amplitude was studied on alloy-18Cr2NiWA using HSS drill bit at different feed rates and spindle speed for micro drilling. It was observed that tool life was maximum at 0.5 μm amplitude (Zhang et al.1994,). The results are summarized in Figure 3.9. Azarhoushang and Akbari (2007) observed that the drill bit broke right after exit in CD for Inconel 738-LC. However, in case of UAD smooth and through holes were created.

In micro drilling of glass, carbide drills presented improved tool life under UAD compared to CD. Along with improved tool life, higher penetration rate was also observed (Egashira et al., 2002).

In case of UAD, the tool life is observed as material dependent. It was reported that the tool life may increase or decrease with the application of ultrasonic vibration. Micro drilling with 10.8 μm carbide drill bit on Duralumin, decrease the tool life with the application of UAD whereas with same drilling condition, when applied on stainless steel workpiece, the tool life was increased (Ohnishi O et, al., 2004). The effect of UAD on different materials, in terms of tool life/wear is shown in Table 3.5.

Figure 3.9. Drill bit life vs. vibration amplitude (Zhang and Feng, 1994)

A comparative study of UAD and CD on glass fibre-reinforced plastics (GFRP) with commercial epoxy LY-556 and hardener HT-972 showed that UAD reduces the tool wear by 40% compared to CD (Arul et al., 2006). In another study on same workpiece, the vibrations were applied on the workpiece. The low frequency was varied in steps from 100 – 280 Hz. The tool wear was decreased with the application of vibration (Ramkumar, 2003). Liu applied rotary ultrasonic drilling technique on CFRP using diamond coated hollow drill bits (Liu et al., 2012). A rotary ultrasonic combines the material removal of diamond grinding and ultrasonic machining. It was documented that the wear of the tool was decreased with the application of vibration.

Table 3.5. Tool life

Work	Tool life	Tool	Workpiece
(Neugebauer and Stoll, 2004)	Increased 20 times	Carbide	Aluminium silicon alloy
(Devine, 1985)	Increased 8 times	Not mentioned	Titanium alloy
(Huber, 1973)	Increased 3-5 times	Not mentioned	Titanium alloys
(Shoh, 1970)	Increased 3 times	Not mentioned	Titanium alloys
(Chen et al., 2006)	Increased 0.14 times	Carbide	Inconel 718
(Onikura et al., 1996)	Increased 0.05 times	Carbide	Duralumin
(Chang and Bone, 2005)	Decreased 0.05 times	HSS TiN coated	Aluminium alloy
(Cheng and Bone, 2004) (Cheng and Bone, 2005)	Decreased 0.35 times	HSS	Aluminium alloy (A1100-0)
(Chern and Lee, 2006)	Decreased	Tungsten steel	Stainless steel (SS41)

3.4 Hole quality in UAD

Similar to tool characterization, workpiece quality in terms of surface roughness, hole roundness, bur formation in case of metals and delamination in case of composites can also be used to qualify a machining process. In drilling process, depending on the type of drill bit used, process selection (UAD or CD) directly affects the quality of workpiece. Research is consistently focused on improving the hole quality with the minimum cost and effort. In the manufacturing process of composite assemblies, improved quality of hole can reduce the number of machining processes such as grinding, reaming by improving hole quality, e.g. roughness, circularity, delamination.

3.4.1 Hole-wall profile

It was documented that hole profile parameters such as hole roundness, straightness and size are improved by the application of UAD (Devine, 1985; Babitsky et al., 2007). Comparing the effect of UAD and CD on Duralumin, Onikura et al., (1996) claimed that at high feed rate the hole roundness was improved in case of UAD compared to CD. The hole size error was reduced by 25% in UAD. In another study it was reported that UAD can improve the hole oversizing by 60% relative to CD (Azarhoushang and Akbari, 2007).

The effects of vibration amplitude were analysed for the variation in hole diameter (Zhang et al., 1991; Zhang De-yuan et al., 1994). Constant frequency of 16 kHz was superimposed on HSS drill bit of $\varnothing 0.34$ mm. The vibration amplitude was varied from 0 to 2 μm at a different combination of feed rate and spindle speed. It was observed that for each set of feed rate and spindle speed the hole profile was optimised at 1 μm (see Figure 3.10).

Micro-drilling of stainless steel and aluminium alloy using cutting fluid revealed that hole oversizing can be improved by 83% in aluminium alloy with the help of UAD comparative to CD. The frequency was varied from 1 – 10 kHz at amplitude 10 μm . However, in hole roundness, no reasonable difference was observed (Chern and Lee, 2006). In case of aluminium, vibration amplitude was increased up to 10 μm at a frequency of 10 kHz and as a result, hole roundness was improved. However, this study resulted into different findings compared to (Zhang, 1991), i.e. with the change in amplitude from 1 to 10 μm , no optimum magnitude of vibration amplitude was observed.

(Azarhoushang and Akbari, 2007) agreed with (Chern and Lee, 2006) that change in vibration amplitude can affect the hole profile. Drilling was carried out on Inconel 738-LC with $\varnothing 5$ mm drill bit. They reported that the hole roundness and cylindricity improves with the increase in amplitude of vibration at constant frequency of 21 kHz. Although the agreement in research is clear that the variation in magnitude of vibration

amplitude affect the hole profile, no optimum amplitude was reported by (Azarhoushing and Akbari, 2007) which is contradictory to (Chern and Lee, 2006). Another agreement between both groups can be seen in terms of feed rate i.e. with the increase in feed rate, at a particular vibration characteristics, the hole profile deteriorates.

Figure 3.10. Hole diameter vs. vibration amplitude (Zhang et al., 1991)

3.4.2 Surface roughness

Similar to hole roundness, hole roughness is also an important qualifying parameter for a drilled hole. Surface quality is important for assembly, fluid flow and surface treatments.

In most of the research carried out for the comparison of surface roughness between UAD holes and CD holes, it was reported that UAD improves the surface quality (Devine, 1985; Deng et al., 1993; Babitsky et al., 2007).

It was observed that when UAD was applied on Duralumin, the axial surface roughness of a hole was improved by 80% compared to CD. Although no circumferential surface roughness improvements were observed at low feed rate, higher feed rate proved that UAD improved both axial and circumferential hole roughness (Onikura et al., 1996).

Improvements, in case of UAD compared to CD, in surface roughness were reported on stainless steel (Deng et al., 1993). The experiments were conducted using Ø1.6 mm drill bit and improvements in “Ra” value of surface roughness, in excess of 95%, were reported. In UAD of Inconel 718, the improvements were reported as 21% using a drill bit of Ø10 mm (Chern et al., 2006).

Chern and Lee applied vibration with 10 µm amplitude and 10 kHz on drill bit to drill aluminium alloy and found that the surface roughness was smoother in case of UAD compared to CD (Chern, 2006). The hole profile, drilled with Ø0.5 mm drill bit, is shown in Figure 3.11. (Deng et al., 1993; Onikura et al., 1996) found their observations in line with the research of Chern and Lee. They stated that the holes drilled were uniform and smooth in UAD whereas in CD the holes were rough, irregular and scratched. These observations are opposite to that of (Fairbanks, 1975). Fairbanks stated that the UAD-holes were brighter with fine scratching compared to CD-holes. Further, the surface of UAD-hole in aluminium alloy was hardened and burnished comparative to CD-hole surface.

A detailed research was documented by Azarhoushing and Akbari (2007). The study was conducted on Inconel 738-LC with different combinations of feed rate and spindle speed. The vibration amplitude was also varied from 0 – 10 µm at a resonant frequency using Ø5 mm drill bit. They reported that surface roughness was improved by 82% with the application of ultrasonic vibration. The optimum spindle speed, at which the maximum surface roughness can be achieved, was reported. Moreover, with the

increase in feed rate, decrease in surface quality was observed in UAD comparative to CD.

Figure 3.11. Hole wall surface (Chern and Lee, 2006)

In case of composite materials, different opinions exist. One group researchers (Li et al., 2003) reported that the application of vibration on drilling of laminated composites improves the surface roughness. However, (Aoki and Nishimura, 2004) oppose the claim and stated that in glass fibre-reinforced plastics (GFRP), the surface roughness increases in case of UAD. Application of UAD on metal matrix (AL/SiC) composite showed no change in surface roughness with or without the application of vibration on the tool (Liu et al., 2005).

3.4.3 Hole exit

In drilling process, when the drill bit exits from workpiece, the burr is usually formed in case of metals and delamination is encountered in case of composites. Drilling parameters are usually optimised to reduce these defects (Davim, 2008).

Burr formation

Burr formation is encountered in drilling of soft and ductile materials. It was believed that deburring process-cost accounts up to 30% of total production cost (Elbestawi et al,

1991; Bone 2005). Almost all researchers agreed that UAD reduces the burr formation (Devine, 1985; Babitsky et al., 2007; Azarhoushang and Akbari, 2007).

Devine study on aluminium alloy 6061, reported that deburring was reduced with the application of UAD and the exit became continuous and sharp (Devine J, 1985). Babitsky's experiments on aluminium alloy showed almost no burr formation in case of UAD compared to CD. The qualitative analysis was presented in the research i.e. a photograph was reported. This photograph of the workpiece under UAD and CD is shown in Figure 3.12.

Figure 3.12. Burr formation in aluminium alloy (Babitsky et. al., 2007)

A brief parametric study, in terms of feed rate, spindle speed and vibration characteristics in case of UAD was conducted by Chang and Bone. Diameter and height of burr formed during both UAD and CD was measured. It was concluded that the formation of burr is affected by the normal drilling parameters such as feed rate and spindle speed. A considerable reduction in burr formation can be achieved when all the parameters including vibration characteristics are optimised (Chang and Bone, 2005).

CD of high performance alloys such as Inconel and titanium alloys could result into the drill breakage due to the burr formation. The formation of burr could easily jam the drill

bit and due to extensive torque generation, drill bit can easily break. This breakage can be eliminated by the application UAD. Azarhoushang and Akbari (2007) agreed with this advantage of UAD.

Delamination

Delamination is defined as inter-laminar crack propagation under high magnitude of forces (Davim, 1985). In low vibration assisted drilling of workpiece vibration (Ramkumar et al., 2004), it was observed that using vibration decrease delamination in GFRP.

Arul conducted a study on woven glass fibre epoxy laminates at different frequency of vibration, superimposed on drill bit. He concluded that minimum delamination drilling-parameters were 18.85 m/min spindle speed, 0.02 mm/rev, 200 Hz frequency and 15 μm amplitude (Arul et al., 2006).

Liu has reported that delamination, in case of CFRP, decreases with the application of rotary ultrasonic elliptical machining/drilling (RUED) (Liu J et. al., 2012). Although no quantitative analysis was reported, the images presented the decrease in delamination. The results are shown in Figure 3.13.

Figure 3.13. Delamination in rotary ultrasonic elliptical machining (Liu et al., 2012)

3.5 Experimental considerations (came from chapter 7, 8 and 9)

3.5.1 Thrust-force evolution during drilling process

The thrust-force signature during the drilling process can be divided into four stages. These stages are shown in Figure 7.3. During the first stage (Stage I) drill bit approaches the workpiece and makes a contact with the workpiece. A rapid increase in the thrust force can be observed during this stage as a result of the extrusion action of the chisel edge of the drill bit. In several cases a sudden decrease in the first moment of the contact for the thrust force has been reported by researchers (Davim, 2009). This was considered as direct effect of the peel-up delamination. Other defects that may arise during this stage are skidding, wandering or the defect of the drill bit, which directly affect the hole quality and size.

Figure 3.14. Typical thrust force signature for drilling

During the second stage (Stage II) the workpiece experiences the complete engagement of the drill-bit lips. During this stage the thrust force remains almost constant. Occasionally, the sudden decrease in the thrust force can also be found during this stage, which is due to the fact that the drill bit enters into the other layer. Due to the presence of air gaps between the layers, the thrust force exerted by the extrusion of the chisel edge disappears momentarily then its magnitude picks up. It has also been observed that the good practice in manufacturing of composite materials could decrease and in some cases eliminate completely air gaps. This helps in decreasing such sudden drops in the thrust force. In drilling practices this drop is normally ignored and the average values during Stage II have been reported. Tool wear and delamination are associated with this stage because the workpiece experiences the maximum magnitude of the thrust force. The risk of delamination is high at the end of this stage because the last plies of the workpiece are pushed with the maximum thrust force by the chisel edge.

The third stage occurs when the chisel edge reaches the bottom layer of the workpiece. The magnitude of the thrust force drops significantly during this stage. The thrust force surges when the drill lips come out of the workpiece and drops to almost zero magnitude. When the drill bit penetrates completely the workpiece, then the process can be specified as a kind of reaming because the flutes engage completely with the workpiece and no cutting takes place. The thrust force after the complete exit of drill bit becomes almost zero. Delamination is possible during this stage but the risks are not as higher as in the Stage II. The risks of surface roughness are higher during this stage because the drilling process can cause the chatter. Once the tool exits the workpiece the problems of the surface finish and hole size tolerance could occur.

Stage IV occurs when the drill bit backs out from the workpiece. The process of reaming continues until the full drill bit backs out from the workpiece because it rotates. The thrust force remains constant (almost at the zero magnitude) but the problems of hole sizing and hole finish could occur during this stage.

3.5.2 Torque evolution during drilling process

A typical torque signature is shown in Figure 7.4. Unlike the thrust-force signature, the torque signature can be categorised into five stages.

Figure 3.15. Typical torque signature for drilling

During Stage I the torque increases in a same manner as the thrust force but the increase rate is smaller as compared to that of the thrust-force. When this increase is compared to the Stage II (when the drill bit is completely engaged with the workpiece) the rate of increase is higher because the moment arm of the torque increases consistently. Stage II for the torque is completely different from that for the thrust-force. The torque increases consistently until the half of the drill-bit lips starts exiting the last ply; at this stage the value of torque becomes constant for a short interval of time. The average peak value of torque during this stage (Stage III) is reported in this thesis.

Stage IV occurs when the torque start decreasing; this phenomenon happens when the drill-bit lips are half way out of the last ply. Then the magnitude of torque decreases sharply. In the thrust-force signature, entry and exit of drill-bit lips present almost the same increase and decrease, whereas for the torque, the signature of the drill-bit lip

entry is almost the same. However smaller in magnitude but at exit the decrease is sharper and the slope is much steeper.

The magnitude of the drilling torque stays high although the thrust force went to zero at the point of drill exit. The magnitude of this residual torque was observed to gradually approach zero with some additional time.

In experimental investigations on drilling of CFRP, analyses were carried out to quantify a thrust force and torque. Some studies dealing with the detailed analysis on drilling forces were also conducted, helping in the selection of the tools and optimising the drilling parameter (Lin and Chen, 1996; Faraz et al., 2009, Krishnamoorthy et al., 2012; Wang et al, 2013). The studies on vibration-assisted drilling suggested that the use of axial vibrations could lead to the maximum separation of workpiece and tool that results in reduction of drilling forces when compared to those exerted in conventional drilling (Wang et al., 2004; Makhdum et al., 2012a; Cong et al., 2012).

All the authors usually refer to the tool separation as a major factor of thrust force reduction in UAD (Maurotto, 2012; Muhammad, 2013). So it was used to explain the magnitude of forces reduction achieved in their experiments, still it should be noted that the experiments by the mentioned authors were conducted on turning. Another hypothesis used to explain the reduction in drilling forces is the reduction in friction in the UAD process. It is believed that ultrasonically-assisted drilling reduces friction during the cutting operation which reduced the temperature during UAD (Azarhoushang and Akbari, 2007). However, another group (MacBeath et al., 2006) claims that in case of ultrasonic cutting the friction increases and, hence, the temperature increases. The latter group performed some experiments on bones superimposing ultrasonic vibrations on the cutting blades. Thermocouples were used in these experiments, and it was observed that the temperature increased. It was also suggested that a new geometry of the tool is important in reducing the temperature. At the same time, research was conducted on Ti6Al4V by Punjana et al.,(2006) also supporting the fact that temperature in UAD increases.

Research conducted by Muhammad et al., (2012) on hard-to-machine alloys proved that pre-heating of a material increased the magnitude of thrust-force reduction in case of UAD hot-machining as compared to traditional UAD. The research conducted by Severdenko and Petrenko (1969) and Izumi et al.,(1966) concluded that ultrasonic energy reduced hardness of the material and the increase in its temperature. Similarly, tensile strength of aluminium was observed 8 – 10 times less when ultrasonic energy of 50watt/cm² was provided to the test specimen. The affect was equivalent to test conducted at 600 °C. This phenomenon was termed as acoustic softening (Langenecker, 1966). It was reported that transformation of ultrasonic energy into heat energy led to thermal softening of the material (Park, 2009). The tool-separation law cannot explain such a huge reduction in thrust forces or depletion of the magnitude of thrust-force reduction.

3.6 Temperature in drilling (came from chapter 8)

Temperature increase directly affects the machining quality. In machining process, a temperature increase can be controlled by means of different coolants or lubricants. The coolants are usually avoided in machining of CFRP because they result in swelling of the composite. Some specially designed coolants can be used; however, they are very expensive. Thus dry machining is mostly adopted; though there is a risk of damage caused by high process temperature. The latter can lead expansion of the cutting tool, and if the tool expands radially it affects dimensional accuracy (Weinertand Kempmann, 2004). Considering all these challenges, a thermal analysis of drilling of CFRP was carried out in the research work reported in this thesis.

Measuring the cutting temperature in the process zone has long been discussed and always considered as a challenging task. Temperature measurements, during the machining process could be carried out by two ways:(i) direct measurement procedure and (ii) indirect measurement procedure. In direct measurement procedures, thermocouples are embedded into a workpiece or in a cutting tool. In former case, they are embedded during the manufacturing stage of the composites (Takeshi et. el., 2013).

In our case, the tested materials were supplied by different companies; therefore, it was not possible to embed the thermocouples. Thermocouples could also be embedded into the drill bit (Weinert and Kempmann, 2004; Rawat and Attia, 2009). In our case, the drill bits were standard Jobber Carbide without holes for the coolant. Moreover, the drill bit vibrates at high frequency and its intermittent contact introduces additional complexities in measuring the temperature of the workpiece. Therefore the data measured with thermocouple for UAD cannot be obtained.

Indirect methods of temperature measurement have gained substantial popularity and are adopted in the research work. These types of temperature measurements can be performed by using EMF (electro-magnetic field) method or thermal camera. In the EMF method, the field generated at the interface of tool and workpiece is used to evaluate the temperature (Grzesik and Nieslony, 2000). In UAD the tool vibrates at high frequency, producing the EMF around it. This affects adversely the EMF generated at the interface between tool and workpiece. Therefore, the clear signal cannot be achieved to measure the temperature. Another challenge in the drilling process is that the drill bit tip is inside the workpiece: thus, the tool-workpiece interface cannot be captured during the process. Thermal imaging procedures involve the use of an infrared camera. However, the infrared method cannot measure the temperature inside the workpiece. The temperature is measured on the surface, where the chip exits the workpiece. The surface temperature at the visible and focused zone can be recorded accurately after a proper calibration of the infrared camera. The magnitude of emissivity of the material is also of prime importance in this method because the camera evaluates the temperature on the basis of it (Muraka et al., 1979; Muhammad et al., 2012). Emissivity of the material is defined as the attribute of it to emit infrared radiation from its surface. It could be elaborated as the ratio of the heat energy radiated by the body made of this material to that by a black body under the same thermal conditions.

After this discussion, it is clear that measuring the temperature during drilling process is difficult task. The temperature can be measured in the cutting zone; however, the measurements can be taken on the surface. These measurements could give an approximate estimation about the temperature of the chip and drill bit surface.

3.7 Summary

In Chapter 2, the importance of the composite materials, especially, CFRP was discussed. Nowadays, CFRPs are gaining superiority over metals. In this chapter a brief overview of drilling process, especially of UAD, was presented. The contribution of different researchers in the field of UAD was summarised and it was found that researchers have studied the effect different vibration-parameters such amplitude and frequency on different materials. Moreover, drilling variables such as affect of feed rate and spindle speed were also studied. However, from all the review, mentioned in this chapter, it can be easily concluded that UAD was conducted on metals; whereas, in the case of composite, the knowledge is limited and further investigation on UAD of composites is necessary. The answer to the question such as decrease in forces in case of UAD on composites, vibration effects on delamination, surface roughness, temperature measurements, circularity and hole tolerances are yet to be answered.

Moreover, in case of UAD on CFRP, a very basic research was carried out. From literature survey of UAD, it can be concluded that tool life, surface quality, circularity and most of the drilling associated damages are dependent on the process parameters such as spindle speed, feed rate, type and properties of workpiece and drill bit, and on vibration characteristics such as frequency and amplitude. UAD can potentially improve the drilling quality in CFRP.

Later, procedure to record the drilling forces is presented and, different stages during the drilling are described. The effect of each drilling stage on drilling forces is presented.

A brief survey about the temperature measurements is conducted. Different methods, used to measure the temperature during drilling process, are discussed. Temperature measurements, with the help of infrared thermal camera, are suggested. It cannot measure the temperature inside the cutting zone, however, the temperature can be measured on the surface, and also the drill bit and chip temperature can be recorded with this method.

However, nonlinearities can create several problems during UAD. These nonlinearities are usually introduced in a system due to inherent nonlinear- properties of transducers. Therefore, it is important to consider different problems that were encountered by many researchers in the field of transducer design. Moreover, reproducibility of results, in UAD has been always questionable. To design a transducer that can be used for reproducible results it is necessary to discuss all the challenges that could arise during the design of a transducer which are addressed in the next chapter.

CHAPTER4

ULTRASONIC TRANSDUCERS

Ultrasonic transducers are devices that convert electrical energy into mechanical vibration at different sets of frequency. The frequency of mechanical vibration is dependent on electrical input signals and vibration amplitude depends on power of a transducer and its mechanical design. Transformation of electric signals into mechanical vibration can be achieved by two means: (i) magnetostrictive effect; (ii) piezoelectric effect. In magnetostrictive transducers, the magnetostrictive properties of the materials (nickel, cobalt and iron) are used to convert electric energy into mechanical one. In such systems, a coil is wrapped around the magnetostrictive material and its excitation depends on the applied current. The operating transducer first converts the electric energy into magnetic energy and then the latter into mechanical vibrations. These

transducers usually operate at a frequency below 30 kHz. A magnetostrictive generator is used to operate the transducers.

The wrapping of a coil around the material makes the use of magnetostrictive transducer unsafe because the current flows at high frequency and amperage. (Stefanite, 2008). This double conversion introduces extra losses and the efficiency of such transducers cannot be higher than 50%. Moreover, these types of transducers are inherently limited to operate at a frequency below 30 kHz due to limitations in size. The operation at frequency below 30 kHz introduces noise issues because these transducers operate at first sub-harmonic frequency (half of the vibrating frequency). Thus, the first sub-harmonic operating frequency is always audible (loud) to human ear. The technology used to operate magnetostrictive generator is more prone to failure because of high magnitude of current and switching frequency. Sweeping frequency is preferred in ultrasonic application, and magnetostrictive generators do not offer the option of sweeping the frequency because of their higher mass.

On the other hand, piezoelectric transducers claim a number of advantages over magnetostrictive transducers. A piezoelectric material expands and contracts when the polarity of the electric input is changed, and the magnitude of expansion and contraction depends on the input current and vice versa. This is also known as piezoelectric phenomenon. Piezoelectric materials are directly connected to the electric source which provides more safety compared to other types of transducers. The electric energy is directly converted into vibrations; this makes the transducer more efficient. Usually, the piezoelectric transducers are 95% efficient. The operating range could be from 1 Hz to several MHz. These transducers operate at the same frequency of the input current; therefore, transducer operating in ultrasonic range is not audible. The generators used to excite the piezoelectric material are more reliable compared to the generators used to excite the magnetostrictive materials (Joshi, 2010).

The materials presenting piezoelectricity are quartz and Rochelle salt as well as piezoceramics such as barium-titanate and lead zirconate-titanate (PZT) (Newnham, 2008). Piezoelectric ceramics have found applications in power ultrasonics. The

transducers using piezoelectric ceramics as a source of excitation are efficient compared to other transducers. The transducers are usually tuned at set frequency of the transducer with a narrow bandwidth. Simultaneously, the main power supply at 50 Hz or 60 Hz is converted by generator to the tuned frequency and the voltage and current are optimised for performance of a transducer; whereas, an amplitude of vibration in such systems is normally amplified using different tools such as concentrators. A concentrator, or horn, is a device of a specific shape such as conical, step or exponential used to amplify the vibration amplitude at the face of a transducer (see Figure 4.1).

Figure 4.1. Horns for amplitude magnification (Arnau, 2008)

Ultrasonic transducers are used in different applications such as cleaning, food cutting, welding and machining (Neppiras, 1972; Rawson, 1998; Shoh, 1976; Graff, 1975). Ultrasonically-assisted machining is the material removal process used to shape various materials including those with low ductility and high hardness such as inorganic glasses, silicon nitride, nickel/titanium alloys and rock (Brehl and Dow, 2008; Muhammad, 2013; Maurotto, 2012; Makhdum et al., 2012b).

The vibration amplitude and vibration frequency depends on the application. The horns are optimised for different applications such as sonochemistry, ultrasonic welding, ultrasonic machining and ultrasonic cleaning (Arnau, 2008).

4.1 Design of ultrasonic transducers

It was not possible to use the ultrasonic devices for research and industrial applications without stepped and tapered half-waveguide horns. The purpose of these horns is to amplify the amplitude of vibration. Balamuth (1954) presented a first analytical and numerical model for the design of stepped and tapered horns. He concluded that the stepped horns provided the maximum vibration amplitude at a transducer face. The major recommendation for the modelling was that the cross-sectional area of a horn should be kept below a quarter wavelength. It was claimed that the model predicted the actual behaviour of a horn. However, the lateral deformation that occurs due to the Poisson's effect was ignored (Balamuth, 1954). After analytical and experimental study, Mekulov (1857) concluded that tapered and catinoidal horns can achieve higher amplitudes. In this work limitations of the gained amplitude due to strain of a material were also discussed. Latter Merkulov and Kharitonov (1959) presented their analytical design process and experimental data for complex horns. It was claimed that this new design could gain higher amplitudes than ever achieved before. Analytical and experimental data was found in good correlation in terms of amplitude magnification. However, the analytical predictions and experimental data for resonant frequency could differ due to the complex shape of horn.

The design techniques of mentioned authors developed the basic rules for the ultrasonic-horn designs. Despite these achievements, a designer had to optimise the horn profile and dimensions before the calculation of maximum stress values during the operation. A great care needed to be taken that the operational stress of the horn would not increase the maximum stress of the material. To keep the operational stress below the ultimate stress of the material, the design process used to be repeated until satisfactory design.

This problem was solved by Eisner and Seager (1965). They proposed a numerical approach, which used the requirements for a horn such as frequency and amplitude during operation, instead of starting from the profile of a horn. This method helped in optimising the design requirements and also ensured that the maximum operating stress would not go beyond the stress elastic limits. During the design process, the mechanical properties were used as input into the model, which solved the problems of redesigning.

Later, an analytical model was developed by Amza and Drimer (1976). Using this model, a designer can choose the material as well as the type of horn (conical, exponential or stepped). It was reported that the predicted longitudinal frequency could deviate from experimental values of frequency. To minimise this problem, the authors recommended using a length-correction factor to alter the dimensions of a horn by changing the nodal point position and vibration distribution over the body of a horn. However, the application of thick coating on the working face of a horn could dwarf the correction factor.

Different types of horns have been optimised for different applications. It is not necessary that an efficient horn for one application could be efficiently used for the other. For example, blocked horns are used for ultrasonic welding. Such a horn applies concentrated and uniform acoustic energy and pressure at a point/area of application. These types of horns have a wide cross-section of the output horn and they have been used for industrial applications since 1970's. The details about the design of such horns were discussed in details by Derks (1984). He used a finite element model to design output horn.

The model was validated with experimental data. The design rules were then set by Adachi et al. (1985) for design simplification of design for block horns to achieve the uniform amplitude at output face. The design approach was successful in achieving the uniform amplitude by employing a careful dimension control and separating the slot-numbers that are cut in a block. However, this approach could not provide the desired type of amplitude reached. Alternatives to block horns in ultrasonic applications,

conical and stepped horns, were found efficient for machining applications (Thomas and Babitsky, 2007).

It should be noted that the design rules were almost same for each type of a transducer. Finite-element modelling for design of ultrasonic horns gained popularity in 1980's. After Adachi et al., a similar modelling approach was used for the design of horns. The new model differed from the old one because the neighbouring modes of resonant frequency could also be evaluated. This helped in understanding the influence of neighbouring modes on the tuned mode of vibration. Koike and Ueha (1993) further introduced the transient response in their models which was proposed for blocked horns and Langevin transducer. A complete assembly of a transducer was considered, for the first time, during the modelling. The model was capable of determining the transient stress response for tool failure during the unloading conditions. Although the cause of tool failure was not the transient stress, a good correlation was found between the simulated and experimental values. This was the first attempt to develop a complete finite-element analysis (FEA) considering the major complexities that arise during the transient analysis of transducers. Then the design approach changed and researchers started to address the frequency of a transducer and used frequency analysis.

A frequency analysis was conducted for a radial-mode cylindrical-horn. These types of horn are used in a metal forming industry. The analysis findings were based on a combined approach of FEA, experimental modal analysis and measurements with electronic speckle pattern interferometry. The FEA-based model offered redesigning capability by shifting the neighbouring resonant frequencies away from the desired frequency. Thus, the model coupling could easily be separated from the tuned vibration frequency. The model was the first attempt to validate FEA results with experimental data achieved using non-contact measurement instruments (Chapman and Lucas, 1990).

Similar to block-horn design techniques, these methods were adopted in a food-cutting industry, where guillotine blades were used for cutting. The design considerations were made on a uniform vibration amplitude and maximum stress concentration. This was done to avoid cutting blade-failures (Rawson, 1998). It is shown in literature that block

horns were used to operate multiple tools, attached to a large surface area of a block horn. This could increase the process efficiency. For example, in spot welding, the use of multiple tools increased the number of welds and a weld could be completed in single action by using only one transducer. The implementation of multiple tools using a single transducer decreased the initial setup and running cost. Similarly, in the food-cutting industry multiple cuts could be achieved using a single transducer. Although several patents were registered, due to the failure of devices which were linked to non-linearity of the systems, the devices were not viably used for industrial applications (Rawson and Morris, 1993; Hamilton, 1995). Hence, FEA and experimental methods were used to improve the performance and reliability of cutting blades (Cardoni and Lucas 2002; Cardoni et al, 2004).

Although designs of transducers have been addressed since the first application in machining, FEA of transducers for machining operations gained the popularity only in 2000's. The researchers addressed the same issues such as tool wear and non-linearity as encountered during the design of transducers for welding and food cutting. The transient response of the drill bit was studied by Thomas and Babitsky (2007). The authors proposed a three dimensional finite element model to understand the response of a twist drill bit under vibration. Shuyu (2005) studied the response of a transducer under different loading conditions such as drilling and other machining applications. The design was generalised for all the applications of ultrasonic transducers. However, the generalized designs cannot be used to transducer designs for the machining applications. The advantages of ultrasonic vibrations with regard to drilling were studied for the first time by Babitsky et al. (2007); Astashev and Babitsky (2007). It was the first finite element study conducted to understand the effects of ultrasonics, directly, on the reduction in thrust forces in ultrasonically-assisted drilling (UAD).

It can be concluded that all the researchers used the Langevin transducer for machining applications. The Langevin transducer consisted of a horn, piezoelectric discs sandwiched between two pieces of metals and a bolt. The bolt is used to compress other components and also holds the assembly. All the transducer's components are made

from the materials offering maximum acoustic coupling. A typical Langevin transducer with exponential horn for amplitude amplification is shown in Figure 4.2.

Figure 4.2. : Langevin transducer (Wang et al, 2011)

4.1.1 Use of multiple vibration modes

A longitudinal mode of vibration was used in early ultrasonic devices. However, it was reported in the form of patent that the ultrasonic transducer's effectiveness could be enhanced using a torsional mode of vibrations in drilling, machining and welding applications (Mason, 1964). Rozenberg (1969) enhanced the design of ultrasonic transducer. He developed a transducer, which was capable of converting a partial longitudinal motion into torsional motion.

Thus, a multiple-mode transducer was developed (Rozenberg, 1969). Although the transducer converted a part of its longitudinal motion into a torsional one, the conversion efficiency was very low, and several design problems were also encountered. As published in recent years, composite modes of vibration are achievable through transducer's architecture by using multiple piezoelectric rings with different pole orientations. Multiple modes could also be achieved by changing horn geometry by

introducing slots or spiral cuts. These transducers are useful in welding application as they increase the material thickness and weld strength (Tsujino et al, 1996; Tsujino et al, 2000). It can be seen that the composite vibration mode found the application in surgery. For example, in contact eye surgery, composite modes of vibration are used for enhancing the emulsification of the lens (Boukhny and Chon 1997; Wuchinich, 2007). The multiple modes of vibration are also used in ultrasonic motors, and it was claimed that the power and performance of ultrasonic motors were improved by introducing multiple modes of vibration (Tomikawa et al, 1990; Tsujino et al, 1996)

Similarly, in ultrasonic drilling the improvements were reported by using the multiple vibration modes (Harkness et al, 2009; McFall et al, 1961). In ultrasonically-assisted drilling, it was reported that even if the transducer vibrated in a longitudinal mode, pre-twisted geometry of drill bit inherit the torsional mode of vibration from its pre-twisted geometry. This results in the combination of longitudinal and torsional modes of vibration. This combination improves the quality of drilling and increase the tool life (Thomas, 2008; Makhdum et al., 2012b). These modes are shown in Figure 4.3.

4.1.2 Nonlinearity of ultrasonic systems

In studies, ultrasonic systems were represented by linear systems, and mathematical approximations were made to solve the dynamic problems because it is easier to achieve the approximate results. Still, it is important that all the ultrasonic systems are defined as nonlinear systems. From elementary mathematics point of view, the change of state of a linear system is always proportional to the applied load and energy. However, this is not true for nonlinear systems. It has been observed for nonlinear systems that they might behave linearly in initial stage but ultimately a point was reached where the rate of change ceases being proportionate and becomes disproportionate. Although all the systems are ultimately nonlinear, significant approximation in terms of amplitude and frequency can be evaluated for linear systems (Thomsen, 1997). Mathematical modelling of nonlinear systems is challenging because the nonlinearity sources can arise from different origins. Separation of nonlinearity sources from linear ones is difficult in

terms of mathematical modelling (Matheson, 2012). The major sources of non-linearity are:

Geometric nonlinearities could stem from deflection, rotation or other kinematic characteristics;

Material nonlinearities could be the result of non-linear relationships between stress and strain;

Physical configuration nonlinearities could arise from existence of another component, operating linearly, e.g. discontinuous coupling.

Figure 4.3. Combined modes of vibration (Thomas, 2007)

Since the first invention of piezoceramics, it has been reported that all the ultrasonic devices behaved nonlinearly, when excited above the linear threshold (Negishi, 1960). One of the major reasons for these nonlinearities was discussed by Jaffe and Berlincourt (1965). They stated that a piezoelectric charge constant lie within the linear region; however, this linear region was observed only under a low level of vibration of corresponding to low stresses and strains. It was reported that this level lies at vibration frequencies lower than 1 kHz. However, in power ultrasonics the devices are operated above 15 kHz. It is impossible to achieve the maximum vibration amplitude at lower frequency since it can only be experienced at resonance frequencies. Other reasons for these nonlinearities were considered as electromechanical loss factor (Q_m^{-1}) and dielectric loss factor (δ) that originated from deformations associated with piezoelectric ceramic, horn material, and the change in elasticity of transducer-components at high vibration. It was also reported that a loss factor is dependent on strength of electric field and temperature (Gerthsen et al, 1980; Takahashi et al, 1994; Beige, 1983; Mukherjee et al, 2011). It should be noted that although elastic, dielectric and piezoelectric terms are temperature dependent, they are less sensitive compared to the loss factor for the evaluation of amplitude values (Albareda et al, 2000; Umeda et al, 2000a; Umeda et al, 2000b).

Experimental characterization of piezoelectric materials has been carried out using a constant-current method. This method studies the effects of high amplitude on the level of heating. It was documented that heating had a significant effect on dielectric and mechanical losses. Heating also changes magnitudes of elastic, dielectric and piezoelectric terms (Hagemann, 1978; Beige, 1983). In another research, an experimental method and a system were developed for isolation of high-amplitude effects from the electric field strength and increase in temperature of piezoelectric ceramics (Umeda et al, 2000a).

It is obvious that the nonlinear behaviour of piezoelectric ceramics is driven by high levels of vibration, which results in amplitude saturation, frequency softening, and amplitude jumps and generation of harmonics. However, when the nonlinear terms are approximated as linear terms in simulations for transducer modelling, it is impossible to

avoid the nonlinearities during operation of a transducer (Guyomar et al, 1994; Uchino 1998). In these studies the response of a Langevin transducer was observed in the experiments, and it was found that the experimental response was comparable with simulated results. The nonlinearities during the operation of a transducer were reported. The limitations of modelling nonlinearities in ultrasonic transducer systems were further discussed in details by Blackburn and Cain (2006); Blackburn and Cain (2007); Guyomar et al. (2011).

Since a transducer is composed of piezoelectric ceramics and other non-piezoceramics materials such as backing section and tools (see Figure 4.2), additional nonlinearities also arise at high vibrations due to non-piezoceramics. It was discussed that in titanium alloy, mechanical losses (Q_m^{-1}) were independent of frequency and temperature at low strain levels. When the strain level was increased to anelastic deformation (stress and strain nonlinear point) Q_m^{-1} became dependent on the vibration conditions. After this point, Q_m^{-1} increases exponentially, and component failures happened (Puskar, 1982; Campos-Pozuelo and Gallego-Juarez, 1995). It was also reported that fine annealing of non-piezoceramic materials could improve the mechanical losses in transducers. This is because of pinning of dislocation loops. Conversely, previously strained materials allow free dislocation and cause frequency softening due to reduction of stiffness (Mason, 1956; Mason and Wehr, 1970). Experiments were conducted to evaluate a critical value of strain for steel, aluminium and titanium alloys to determine strain values that these materials can experience before the critical increase in Q_m^{-1} (Puskar, 1982; Campos-Pozuelo and Gallego-Juarez, 1995).

Almost all ultrasonic devices are composed of several components such as horn, backing section and working tools. As discussed, these components add up the nonlinearities, at high-vibration conditions, to the piezoelectric nonlinearities. It is well known that a nonlinear behaviour could also be a result of physical configurations in any dynamic systems (Thomsen, 1997). The instabilities could arise due to nonlinearities, and these result in shifting the frequency jump, amplitude depletion and modal interactions. All these mentioned issues could arise even if all the components

are tuned before assembly. These difficulties cannot be ignored and cannot be coped with the linear analytical or finite element-models (Mathieson, 2012).

Still, the way to minimise all these nonlinear problems is redesigning the geometry of components for a desired application until the nonlinearities disappear for particular operational conditions (Cardoni, 2003). It is important to conduct the research to understand the geometry effects, device-manufacturing procedure, selection of material.

4.2 Summary

The evolution of transducer design was discussed in this chapter. Challenges in the design of ultrasonic transducer were reviewed. The design of a transducer, for any particular application such as drilling, is a complex task. Each part of a transducer should be designed carefully, and the mechanical contacts and pressure between every part play a critical role in the performance of a transducer. A small variation in size and shape could jeopardise the desired results. Therefore, in the field of ultrasonically-assisted drilling, complex drill bit geometry is important to be studied together with other components of a transducer for its efficient design. This could be achieved by using a finite-element model.

From literature survey, it is obvious that for a design of ultrasonic drilling-transducers both approaches, i.e. using (i) vibration characteristics; or (ii) material properties e.g. elasticity can be used as an input. However, in most of the cases, it was suggested that material properties as an input can give the better predictions. In our case, material properties were used as an input for modelling, and geometry of a transducer-system was improved to achieve the desired frequency. The modelling procedure is explained in next chapter.

CHAPTER5

NUMERICAL MODELLING: PROBLEM FORMULATION AND PARAMETRIC STUDIES

In this chapter, a need to develop a finite-element model is discussed. First, the problem is formulated and then its solution is discussed briefly. Free-vibration and drilling experiments were conducted on existing-transducer to replicate the results by Thomas (2007). FE model, developed in this chapter, was verified with free-vibration experimental data. The details about free-vibration experiments are given in the next chapter.

5.1 Problem Formulation

As discussed in chapter 3, when ultrasonic vibrations are superimposed on a drill bit, during drilling operation, the level of drilling forces decreases compared to conventional drilling (CD) and the process is called ultrasonically-assisted drilling (UAD). To study this effect of vibration, experiments were conducted with the existing-transducer (see Figure 5.1) used by Thomas (2007) at the same experimental parameters i.e. feed rate, spindle speed, vibration frequency and amplitude using the same workpiece (aluminium) and drill bit. The experimental results were in line with Thomas (2007). Same level of thrust force and torque was observed in both CD and UAD with the force reduction of 70% in UAD compared to CD. Later, the experiments were conducted on steel and a descent reduction in drilling forces was observed in UAD compared to CD. However, when the experiments were carried out on CFRP, no reduction in drilling forces was observed.

Figure 5.1. Existing ultrasonic transducer (Thomas, 2007)

To elucidate the problem of not achieving drilling forces reduction in UAD on CFRP (compared to CD), drilling experiments were conducted on the same size (geometric dimensions) of workpiece consisted of aluminium, steel and CFRP at the same experimental conditions. This was done to investigate the effect of size and shape of the workpiece on the performance of existing-transducer.

The schematic of the experimental setup is shown in Figure 5.2. The experiments were carried out at 260 rpm and 50 mm/min feed rate. The thrust force reduction in case of aluminium, steel and CFRP (UAD vs. CD) was recorded in the excess of 70%, 50% and 15% respectively. Further, the experiments were conducted at lower level of feed rate and spindle speed but no improvement in CFRP results was observed.

Figure 5.2. Schematic of drilling experiments

As the response of different materials is different to the same level of vibration due to the difference in the stiffness of the materials (Astashev and Babitsky, 2007), therefore the reduction in drilling forces, with the same transducer, could be different for different materials.

To investigate this, natural frequencies of first bending mode was studied for the workpiece with the same geometric dimensions for aluminium, steel and CFRP using finite-element software Abaqus. The workpiece was modelled in 3D using Abaqus 9.11. The same geometry was assigned mechanical and physical properties for aluminium, steel and CFRP, one at a time throughout one study. Aluminium and steel properties were assigned as they are presented in Table 5.3. For CFRP, it was assumed that CFRP is solid homogenous material. This assumption was made on the basis that the cutting operation could only progress when the maximum shear stresses of the material are

dominated by the cutting force. As the carbon fibre has maximum magnitude of mechanical properties in fibre direction, therefore, the properties in fibre direction were assigned. These properties are given in Table 5.1.

Table 5.1. Mechanical properties of carbon fibre in axial direction

Property	Magnitude
Young's modulus (GPa)	150
Poisson's ratio	0.25
Density kg/m ³	1600

Mesh convergence study (discussed in section 5.5) suggested that the tetrahedral element, with the element size of 2.5 mm, was significant for the geometry of workpiece. It should be noted that tetrahedral mesh and Lanczos solver were used throughout the FE modelling because the previous studies (Mathieson 2012; Li et. al., 2011; Hunter et al., 2008; Ostasevicus et al., 2012) suggested this solver gives reliable results and for this type of frequency analysis; also for the eigenfrequency study, the difference in element type does not, significantly, affect the results.

Figure 5.3. Boundary conditions and geometry of workpiece

The geometry of the workpiece was assigned the static boundary conditions at the regions where the workpiece was clamped during the experiments. The boundary conditions are shown in Figure 5.3. The frequency of first bending mode was evaluated using Abaqus. This mode for aluminium, steel and CFRP was observed as 5.7 kHz, 7.2 kHz and 11.8 kHz, respectively. These are shown in Figure 5.4.

Figure 5.4. First bending mode of: aluminium at 5.7 kHz (a); steel at 7.2 kHz (b) and CFRP at 11.8 kHz

The difference in the frequency of first bending mode of each material revealed that CFRP presented the same mode at a frequency double in magnitude as compared to aluminium. After this study, it was suggested that a transducer with the operating frequency, two times higher than the existing-transducer, could lead to the same level of drilling forces reduction in CFRP, as obtained in aluminium. Hence, the design and development of new transducer systems was carried out.

As discussed, maximum thrust force reduction in vibration assisted-drilling can be achieved when the relative vibrations between the tool and the workpiece are predominantly restricted in the axial direction of the tool axis (Wang et al., 2004; Chang

et al., 2009; Alam et al., 2011; Makhdum et al., 2012b). Therefore the study is based on the longitudinal modes of vibrations in which the eigenfrequency analysis was conducted. As the eigenfrequency analysis can be used to extract the eigenmodes in a longitudinal mode of vibration, therefore this type of analysis was chosen for the design of transducer: to be used in ultrasonically-assisted drilling. It has also recently been studied that all the other characteristics of transducer e.g. vibrational amplitude are optimised at the natural modes of frequency corresponding to the relevant eigenmodes (Ostasevicius et al., 2012). In achieving the longitudinal mode of vibration, the transducer assembly and acoustic matching of the components, in an assembly, plays an important role.

5.2 Transducer assembly and acoustic transmission

Different components are joined together to construct a transducer. A typical Langevin transducer is composed of front mass (horn or concentrator), piezoelectric ceramic discs, back mass and a fixing bolt to hold the assembly together. The assembly is made such that the parts can be joined together and disassembled easily. A transducer is pre-stressed with the help of a bolt or threads to hold the components together. The applied torque (by means of the bolt) on each component plays a critical role as the stiffness in each part significantly affects the performance of the transducer.

The performance of the transducer can also be affected by the acoustic mismatching of the parts due to shape and material properties of the components. The waves propagating through a solid depend on the shape, stiffness and density of the material. When the sound waves pass from one medium to another, at the boundary of the two mediums, they transmit both into the second medium and also reflected back to the initial medium. The maximum transmission from one medium to another can be achieved if both media are well acoustically coupled (Gellego-Juárez, 1989; Abdullah, 2009). There are two ways to achieve this: a) by experimental methods; b) by numerical modelling. The latter was chosen for this course of study because the experimental method involves more time and effort. Another advantage of numerical modelling, over

experimental techniques, is that the behaviour of the transducer can also be studied at different locations and regions within the body of a transducer. This is impossible using only experimental techniques.

5.3 Mesh convergence of stepped concentrator

In the previous section, it was discussed that transducer is composed of several parts. The concentrator or front mass plays an important role in magnifying the vibration amplitude. Several authors (Babitsky et al. 2007; Wang et al., 2011; Cardoni and Lucas 2002; Cardoni et al, 2004) dedicated their research to investigate the optimum size and shape of the concentrator to achieve desired vibration characteristics. Moreover, the tools are also attached to the concentrator therefore this part of a transducer was chosen to study the mesh convergence.

The 3D model of a concentrator was developed in Abaqus software and, the mechanical and physical properties were assigned to the structure. There are different types of 3-D stress elements offered by Abaqus™6.11-1. However, tetrahedral (tet) (C3D10) elements were used throughout this study. Moreover, the drill bit geometry and the fixing bolt exhibits both complex shape and sharp contours. The shape of the backing-section and transducer concentrator is not as complex as drill bit but they present the sharp contours. Tetrahedral quadratic elements offer an efficient way, they can predict the required results in an effective way and the good correlation between the simulation and experimental results can be predicted (Abaqus, 2011; Wang et. al., 2004 and Pain et. al., 2011). As mentioned earlier, for the eigenfrequency analysis, the element type does not affect the solution significantly. The fixed boundary conditions were applied at the base on first step (refer Figure 5.5). Lanczos solver was used and also suggested by many researchers (Mathieson 2012; Li et. al., 2011; Hunter et al., 2008).

Lanczos solver is an implicit algorithm which is used to compute a definite number of eigenvalues in any part of the spectrum of a generalized symmetric matrix eigenvalue problem. In Abaqus™ the Lanczos procedure consists of a set of Lanczos “runs,” and in each run a number of iterations called steps are performed. This algorithm solves the

linear system of equations with minimum number of steps. For each Lanczos run the following spectral transformation is applied:

$$[M]([K] - \sigma[M])^{-1}[M]\{\phi\} = \Theta[M]\{\phi\} \quad 5.2$$

where σ is the shift, Θ is the eigenvalue, and $\{\phi\}$ is the eigenvector. This transformation allows rapid convergence to the desired eigenvalues (Ericsson and Ruhe, 1980; Simon 1984; Abaqus™ 6.11, 2011).

The concentrator structure was divided into elements. The number or the size of the elements influence the solution i.e. too many elements take too much solve time but the predictions are close to the real problems whereas too few elements result in deviation in approximation but the solution time can be decreased. For the balance between solution time and accuracy different mesh size resulting in different number of elements were used. For example where the high mesh density was used the accurate results can be obtained and vice versa. The resonance frequency-convergence was studied for, number and size of the mesh for concentrator. The simulated results revealed that once a suitable mesh was employed the constant frequency for the longitudinal modes was observed. Two mesh densities with tetrahedral mesh type are shown in Figure 5.3.

Figure 5.5. Mesh densities of tet-mesh: element size 20 mm, 529 number of elements (a); element size 3.5 mm, 51,416 number of elements (b)

The mesh convergence was achieved at 6.0 mm element-global-size. The first second and third longitudinal modes for this size of element were found at 9.126 kHz, 18.610 kHz and 32.454 kHz respectively (presented in Figure 5.6). It is recommended to use the element-global-size for the same shape and geometry below 6.0 mm. It can be seen from Figure 5.6 that other two modes of vibration were also stabilised at the

same element-global-size where the first longitudinal mode. Therefore, it is recommended that the frequency of first longitudinal mode can be used for mesh convergence study in order to reduce the time and effort. Moreover, it can be seen that the element size does not affect the mode-frequency significantly i.e. with the change in element size from 3.5 mm to 6 the change in frequency was observed less than 5 Hz (see Figure 5.6). The three longitudinal modes of FE model are presented in Figure 5.7.

Figure 5.6. Mesh convergence with tetrahedral mesh for concentrator: (a) first longitudinal mode; (b) second longitudinal mode; (c) third longitudinal mode

Figure 5.7. Three longitudinal modes of vibration for concentrator: (a) first longitudinal mode at 9.125 kHz; (b) second longitudinal mode at 18.610 kHz; (c) third longitudinal mode at 32.945 kHz

The mesh convergence for all the other parts of transducer was also carried out independently because the shape and density of most of the parts was different. As discussed in Chapter 4 that the difference in shape and density could contribute to non-linearities therefore each part was studied independently for mesh convergence. Moreover, the behaviour of the piezoelectric ceramics is completely different i.e. orthotropic. Hence, modelling procedure for piezoelectric ring was comparatively different. All the components were assigned the fixed boundary conditions at one end whereas the other ends of all the components were left free.

It was expected that first twenty numbers of eigenmodes would be sufficient to have at least 2 or 3 longitudinal mode of natural frequency. Therefore, twenty eigenvalues were

requested in the solver. Tetrahedral mesh and the mechanical properties shown in Table 5.2 were used. After simulation, it was observed that these modes include bending, rotational, transverse and longitudinal modes. The first twenty modes of vibration also included the three longitudinal modes. Only the first longitudinal mode of each component of transducer is reported here. As in case of ultrasonically-assisted drilling the longitudinal mode of vibration achieves the maximum thrust force reduction, therefore, the focus of this study was on longitudinal mode of vibration. Moreover, the piezoelectric rings, predominantly, vibrate along the thickness direction due to crystals aligned in this direction; therefore, the focus of study was on longitudinal modes.

Table 5.2. Mesh convergence for different components of transducer

Component	Element-global-size (mm)	Frequency of first longitudinal mode (kHz)
Backing section	4.5	19.21
Fixing bolt	2.0	20.99
Piezoelectric ring	2.5	150.44

The mesh convergence for fixing-bolt, backing section and piezoelectric ring was achieved below 2.0 mm, 4.5 mm and 2.5 mm element-global-size respectively. The first longitudinal mode of vibration for these components were observed at 19.21 kHz, 20.99 kHz and 150.44 kHz respectively (see Table 5.1). It was observed that the first longitudinal mode of all the components including the concentrator was closer to each other and was below 20 kHz. However for piezoelectric ring the first longitudinal mode was observed at 150.44 kHz. This frequency (150.44 kHz) is in excess of eight times in comparison to the frequency of first longitudinal mode of other components. The longitudinal mode at higher frequency supports the idea that the modes of vibration are dependent on the shape and properties of the components. In Figure 5.6, it can be seen that all the other components except the piezoelectric rings have high length to diameter ratio (>1). This indicated that the higher is the length to diameter ratio, the lower is the Eigen frequency. It can be concluded that the length to diameter ratio of the component strongly affects the frequency of the vibration modes.

5.4 FEA study and mesh convergence for transducer

The different parts of the transducer were assembled in Abaqus™ 6.11. The boundary conditions and the contact definitions were assigned carefully. The transducer with its respective parts is shown in Figure 5.8.

Figure 5.8. Schematic of the transducer

A standard M – 16 bolt was modelled with nominal dimensions consisting of the countersunk hexagonal-head. The backing section was modelled with the external diameter of $\varnothing = 60$ mm and length of $l = 65$ mm with the counterbore ($\varnothing_{\text{Large}} = 30$ mm, depth = 20 mm and $\varnothing_{\text{small}} = 20$ mm thru) to provide the support for bolt and hold the other parts of the transducer together. Standard Morgan™ piezoelectric PZT – 807 rings of dia $\varnothing = 50$ mm, $t = 4$ mm were modelled for numerical analysis. The mechanical properties of each part are given in Table 5.3.

Table 5.3. Mechanical properties of different parts of the transducer

Part	Material	Property	Magnitude
Concentrator and backing section	Aluminium	Young's modulus	70,000 MPa
		Yield stress	290 MPa
		Poisson's ratio	0.25
		Density	2600 kg/m ³
		Young's modulus	70,000 MPa

Piezoelectric rings	ceramic	PZT807	Yield stress	75 MPa
			Poisson's ratio	0.29
			Density	7600 kg/m ³
			Young's modulus	300,000 MPa
Bolt		Annealed steel ANSI	Yield stress	350 MPa
			Poisson's ratio	0.27
			Density	7700 kg/m ³

Considering orthotropic, piezoelectric and dielectric properties

As piezoelectric ceramics are different in mechanical and electrical behaviour compared to other conventional metals therefore a separate mesh convergence study and FE model was generated to analyse the behaviour of piezoelectric rings. In the previous section, the piezoelectric material was defined by 3-D stress elements which were changed to piezoelectric elements in this section to analyse the behaviour of piezoelectric ceramic in close approximation to real problem. The properties for piezoelectric rings (PZT-807) were obtained from the supplier (Morgan Technical Ceramics TM). The suppliers provide the material properties in a different format to that accepted in FE code Abaqus. Therefore the properties were converted into FE format by using the method explained by (Al-Budairi, 2012). To define piezoelectric elements in Abaqus, density, dielectric, elastic and piezoelectric properties were assigned as an orthotropic behaviour. The elastic, piezoelectric and dielectric properties are given in Table 5.4, 5.5 and 5.6 respectively. The element type was chosen as Piezoelectric element (C3D10E) tetrahedral mesh type. After defining piezoelectric properties for piezoelectric elements, a coordinate system was assigned to the geometry of piezoelectric ring with the vibration-direction along the thickness of the ring. The orientation of orthotropic behaviour was constrained in the direction of defined coordinate system by defining the orientation in Abaqus (see Figure 5.9).

Table 5.4. Elastic moduli of piezoelectric rings

Elasticity (orthotropic) $\frac{N}{mm^2}$	
D_{1111}^E	96800
D_{1122}^E	-5900
D_{2222}^E	96700
D_{1133}^E	20600
D_{2233}^E	20500
D_{3333}^E	70600
D_{1212}^E	35000
D_{1313}^E	35000
D_{2323}^E	35000

Table 5.5. Piezoelectric strain of piezoelectric rings

Piezoelectric (orthotropic) $\frac{C}{N}$	
d_{111}	0
d_{122}	0
d_{133}	0
d_{112}	0
d_{113}	0
d_{123}	2.94×10^{-10}
d_{211}	0
d_{222}	0

$d_{2\ 33}$	0
$d_{2\ 12}$	0
$d_{2\ 13}$	$2.94\ E^{-10}$
$d_{2\ 23}$	0
$d_{3\ 11}$	$-9.3\ E^{-11}$
$d_{3\ 22}$	$-9.3\ E^{-11}$
$d_{3\ 33}$	$2.6\ E^{-10}$
$d_{3\ 12}$	0
$d_{3\ 13}$	0
$d_{3\ 23}$	0

Table 5.6. Dielectricity of piezoelectric rings

Dielectric (orthotropic) $\frac{F}{mm}$	
$\epsilon_{11}^s = D_{11}^s$	$6.9\ E^{-06}$
$\epsilon_{22}^s = D_{22}^s$	$6.9\ E^{-06}$
$\epsilon_{33}^s = D_{33}^s$	$4.98\ E^{-06}$

Figure 5.9. Orthotropic behaviour assignment

All the parts of transducer were held together with the help of fixing bolt and high torque was applied to the bolt to hold the parts and assure the vibration transmission. Therefore, it was assumed that each connecting surface of all parts had maximum friction between each other. To achieve this in FE the contact conditions between each connecting surface were assigned as rigid contact. This contact condition offers the maximum possible friction between the two surfaces.

Instead of conducting the mesh convergence study for the complete transducer it was preferred to run the simulation with two different types of mesh densities and then compare the results. It was observed that, for the mesh consisting of higher number of elements (low element-global-size for each component) the solution time increases. In both of mesh densities the first, second and third longitudinal mode of vibration were observed with the percentage difference of 0.61%, 0.08% and 0.4% respectively (see Table 5.6). Whereas with such a small difference in the resonance frequency the solution time (CPU time), with higher mesh density, increases by 81.02% (refer [to](#) Table 5.6). Therefore it is recommended that the mesh density for each part of the assembly should be selected as high element-global-size after the convergence point. For example the mesh convergence for the concentrator was achieved at 6 mm element-global-size which is suitable for the further study. The three modes of vibrations of the transducer are shown in Figure 5.10.

It can be seen from Figure 5.10 that these three modes of vibration are almost longitudinal at the end of the transducer. However if the effect is studied locally through the body of the transducer then the different nodal points present the different direction of displacement vectors. This can be explained by plotting the direction of displacement vectors (see Figure 5.11). It is clear from Figure 5.11 that for first longitudinal mode, most of the displacement vectors are in horizontal direction but some of the vectors are at the first step of the concentrator, are presenting the 3D effect such as vibrational dilation in different directions.

Table 5.7. Mesh densities for transducer

Mesh density

Part	Element-global-size (mm)	Element-global-size (mm)
Concentrator	6.5	4.7
Bolt	2.5	2
Piezoelectric ring	2.4	1.4
Backing section	4.3	3.4
Total number of elements	36181	105172
Total solution time (Sec)	458.5	2423.6
First longitudinal mode (kHz)	15.184	15.245
Second longitudinal mode (kHz)	20.326	20.356
Third longitudinal mode (kHz)	32.652	32.524

Model visualization relative displacement vector sum

Figure 5.10. Longitudinal modes of vibration for complete transducer at low mesh density: (a) first longitudinal mode @ 15.184 khz; (b) second longitudinal mode @ 20.326 khz; (c) third longitudinal mode @ 32.652 khz

Figure 5.11. Displacement vectors at different longitudinal modes: (a) at first longitudinal mode; (b) at second longitudinal mode; (c) at third longitudinal mode

This phenomenon is more dominant in second longitudinal mode. It increased at the third longitudinal mode resulting in higher dilation compared to the second and third longitudinal mode. This figure reveals that the 3D effects are present in every mode of vibration on the complete body of transducer. However these volumetric swelling effects result into a pure longitudinal vibration at the end of the transducer (point of interest, where the drill bit is attached). Another interesting behaviour can be observed in this figure that at some nodes the displacement vectors are pointed in opposite direction. This represents that for all nodes, it is not possible to vibrate in the same direction at same time to propagate the longitudinal vibration throughout the transducer. Figure 5.11 (c) shows that at various locations along the length of the transducer, the effect of resultant vibration is zero. This is due the fact that the displacement vectors are same in magnitude but opposite in direction. It can be concluded from Figure 5.11 that the vector displacements change their direction with the each increase in eigenfrequency for the same mode of vibration. For example the first longitudinal mode presents less 3D affects in terms of vector displacement directions as compared to the second and third longitudinal mode. However interestingly, the comparison of percentage difference of longitudinal mode between one-dimensional theory and FE model showed that first and third longitudinal modes are within a range of 5% error. Whereas, the second longitudinal mode showed 22% difference. From the previous experimentation on the same transducer, it was observed that the maximum amplitude corresponds to the second longitudinal mode (Thomas, 2007). Therefore the difference of 22% in the second longitudinal mode is not acceptable.

5.5 Summary

The study of eigenfrequency of workpiece (Section 5.1) suggested that for different materials, the eigenfrequency of are different for the same mode of vibration. This frequency is dependent on the material properties. The mesh convergence study revealed that the eigenfrequency of a component does not vary significantly with the change in type and size of the mesh, therefore, any type of mesh and element size could

provide the reasonable results. However, for more specific studies, mesh convergence study should be carried out in order to achieve the significant results.

From this study, it can be expected that for the pre-twisted geometry of the drill bit, the direction of displacement vectors cannot be perfectly horizontal. This behaviour of the drill bit indicates that the drill bit, under the ultrasonic excitation, transfers the ultrasonic energy not only in horizontal direction but in different directions at various time intervals. This makes it primarily important to study the behaviour of drill bit together with the transducer. The transducers were optimised with the drill bit and this optimisation is explained in Chapter 6.

Furthermore, once the mesh convergence study is carried out for individual parts of the transducer then the converged-mesh of each part can be used to study the transducer assembly, provided the contact definitions are assigned carefully to the assembly. From the mesh convergence study it can be assumed that with Lanczos solver and tetrahedral elements, the geometries under consideration converge at the element-global-size corresponding to 10,000 number of elements (see graphs in appendix 5.1). As components have different size such as piezoelectric rings, concentrators and drill bits therefore this assumption is helpful in further studies.

CHAPTER 6

NUMERICAL MODELLING: VALIDATION AND PREDICTION FOR NEW TRANSDUCER SYSTEMS

In this chapter the finite element (FE) model predictions (Section 5.5) are compared with the experimental data. The procedure used to excite the transducer is explained briefly. Furthermore, three new transducer systems are designed using the same FE model and then manufactured. The purpose of designing the new transducer systems was to develop a transducer with sufficient power to drill through carbon fibre-reinforced plastic (CFRP). Different sizes of drill bit were to be used and vibration modes were analysed using the drill bit together with the transducers.

6.1 Experiments on existing transducer for extracting the resonance frequency

Experimental data were collected through series of experiments. The electronic devices used to excite the transducer are explained. These devices and their functions are explained below:

6.1.1 Transducer excitation

The signals commonly used to excite ultrasonic devices are swept sine waves. Standard electric power is converted into swept sine waves for the tuned frequency of a transducer. The tuned devices could excite between 0 Hz and 80 kHz. The electric power is supplied at standard frequency and voltage i.e. 50 Hz and 230 V respectively. The electric power (frequency and voltage) was converted into operating frequency and voltage with help of different electrical devices. The block diagram of amplification system is shown in Figure 6.1.

The standard electric energy available in the UK is provided at 230V at 50 Hz frequency (Wilson, 2011) whereas the transducer operates around 200 V at a frequency ranging from several hundred Hz to several thousandHz. Therefore the power was converted from standard voltage and frequency to the operating voltage and frequency of the transducer. To achieve the power conversion a circuitry was designed at Loughborough University in previous experimentation for both drilling and turning with considerable advantages (Varonina et al., 2008; Thomas, 2008). The system used in the previous experimentation was slightly modified and used for the electrical power conversion. Modifications were carried out to use isolatory unit before matchbox. This was done to purify the electric signals from universal amplifier.

Figure 6.1. Electric power flow diagram

Function generator GW Instek™ model SFG – 2110 was used for the conversion of the frequency from 0.1 Hz to 10 MHz. Typically, the UAD experiments were performed in the range of 17 kHz to 40 kHz. As discussed, the ultrasonic transducers are operated using swept sine waves. The function generator was also employed to the square wave form into swept sine wave form. The output voltage achieved using the function generator was measured around 2.5 V (peak to peak).

The power output from function generator was not sufficient to be used for the transducer's excitation therefore a power amplifier was manufactured in Loughborough University to produce a powerful signal, adequate to operate ultrasonic transducer. The power output from the amplifier was 80 V (peak to peak). The electric wave out of the amplifier could contain DC current component. Since the matchbox operates with AC signals, an isolatory Unit was manufactured and used. The Isolatory System was composed of 16 μF capacitance which ensured the supply of current to be pure AC for further processing.

A standard matchbox model number EVB – 2 was used. It comprises of an inductor and a transformer. The inductor was used to shunt the piezoelectric ring's capacitance

whereas the transformer was used to step up the voltage. The transformer stepped up the voltage from 80V to 200V, powerful enough to operate the transducer.

6.1.2 Experimental setup

A series of free-vibration experiments was conducted on the existing transducer to extract the values of resonance vibration-amplitude at the tuned resonance-frequency. The transducer used in these experiments was same as used for the FE study in Chapter 5.

Free vibration tests at resonance frequency were conducted on the transducer. Free-vibration test can be defined as the measurement of the vibration characteristics when the transducer is excited without any drilling tool. The resonance conditions such as vibration frequency and amplitude of a transducer vary depending on the geometry, material, and the pressure of each component on each other (exerted by fixing bolt). At each resonance frequency the transducer experiences different amplitude value along the transducer axis. As the transducers are designed to experience the maximum vibration-amplitude at the transducer head therefore the vibration amplitude was measured at the transducer head (refer section 5.5). These measurements were taken with the help of single beam laser vibrometer. The transducer was tuned to experience the vibration amplitude. The value of frequency corresponding to each magnitude of vibration amplitude was recorded for comparison with FE model.

A test bench was designed and manufactured to conduct the free-vibration test which is shown in Figure 6.2. The transducer was placed on the test bench without any clamping to analyse the free behaviour of the transducer. The transducer was connected to the electric power supply. It was tuned at the resonance frequency. A laser-reflecting tape was attached at the second step of the transducer. The vibration amplitude was measured with a Polytec GmbH™ (model number OFV – 3001) vibrometer at a tuned frequency. This vibrometer was able to measure the vibration amplitude with the resolution of 0.08 μm . The laser beam was focused on the reflecting tape and then it displayed vibration-amplitude on the oscilloscope in units of voltage. The vibrometer

was calibrated and the vibration amplitude in terms of μm was recorded. The details of the vibrometer are given in Table 6.1.

Figure 6.2. Test bench for free vibration test

Table 6.1. Laser vibrometer specifications

Manufacturer	Polytec GmbH
Model number	OFV-3001
Technology	Laser Doppler
Resolution (μm)	0.08
Linearity error	0.1% of full scale
Max velocity (m/s)	10

6.2 Experimental results and comparison with FEA

The amplitude for first, second and third resonance mode was recorded as $4\ \mu\text{m}$, $18\ \mu\text{m}$ and $3\ \mu\text{m}$. The frequencies for first, second and third longitudinal mode were $14.2\ \text{kHz}$, $19.8\ \text{kHz}$ and $32.5\ \text{kHz}$ respectively. The corresponding values in FE model were $14.8\ \text{kHz}$, $19.4\ \text{kHz}$ and $31.7\ \text{kHz}$. The percentage difference between FE model prediction and experimental results was evaluated as 4.2% , 2.0% and 2.8% for first,

second and third longitudinal mode of vibrations. These results are also given in Table 6.2 with the corresponding percentage difference.

Table 6.2. Comparison of experimental and FEA resonance frequency

Longitudinal resonance mode	Experimental vibration frequency (kHz)	FEA vibrational frequency (kHz)	Percentage difference
1 st resonance mode	14.2	15.2	6.5%
2 nd resonance mode	19.8	20.3	2.5%
3 rd resonance mode	31.5	32.6	3.4%

From experimental observations the magnitude of vibration amplitude for second longitudinal resonance mode was higher than that of first and third longitudinal mode. As the UAD takes place at high amplitude values therefore the first and third longitudinal modes could be ignored. It was suggested in the former experiments (Thomas PNH, 2007) that the first and third longitudinal modes of vibration can be neglected from drilling aspects. This is because the small magnitude of vibration amplitude is not adequate to present thrust force reduction with respect to convention drilling technique.

The reason for the lower amplitude at first and third resonance frequency could be;

1. The particles might not be in complete harmony with each other
2. The resonance might not be completely constructive
3. The travelling sound-waves might be out of phase with each other
4. At these resonance frequencies, non-linearities may arise and acoustic mismatching might happen between the components of the transducers
5. The wave-amplitude might not be maximum at the end of the second step of the transducer but somewhere else in the transducer structure

The FE model predictions of frequency (section 5.5) showed promising results when compared to the experimental frequency results. This model was further used to design three new transducers systems for drilling in carbon fibre-reinforced plastics (CFRP) using different diameter drill bits.

6.3 Design and optimisation of drilling transducers for carbon fibre-reinforced plastics

A literature review of transducer design showed that FE model of transducer has been developed for only the transducer without much regard for the complete assembled components (Safari and Aktogan, 2008). For example, the complicated geometry of drill bit together with transducer, as a single system, has not been explicitly studied. This is significant because a slight geometry change can considerably influence the performance of an ultrasonic system. In this chapter FE model, for the design of ultrasonic transducer is discussed and studied. This FE model was validated with the experimental results achieved through a series of experiments conducted on an existing transducer which is discussed in next chapter. Then, the developed model is used to design a transducer for ultrasonically-assisted drilling to achieve efficient machining performance.

Figure 6.3. Commercial transducer

Firstly, a commercially available transducer (see Figure 6.3) was optimised for drilling in CFRP. This transducer was capable to accommodate Ø 3 mm and Ø 6 mm drill bit. Later, a transducer was designed and manufactured for Ø 12 mm drill bit. In both cases the drill bit was analysed using finite-element, together with the transducers. The transducer systems used to accommodate Ø 3 mm, Ø 6 mm and Ø 12 mm drill bits were assigned the names as “System I”, “System II” and “System III” respectively.

6.3.1 Optimisation of transducer systems

This study is divided into two sections. In the first section a commercially available transducer (Transducer A) was optimised to accommodate Ø 3 mm and Ø 6 mm drill bits. In the next section a bigger transducer to accommodate Ø 12 mm was designed and manufactured.

The free-vibration tests were carried out on Transducer A without drill bit. The resonance frequencies were observed as 21.1 kHz, 29.7 kHz and 33.5 kHz for first, second and third longitudinal mode. The potential of the transducer to vibrate at high frequency revealed that it should be able to resonate the drill bit at high frequency. To investigate this, FEA study was conducted.

Trial and error method was used to optimise the shape of an adapter to achieve the longitudinal vibration modes at the tip of drill bit. This was done by optimising the size and shape of the adapter (to be connected to the transducer shown in Figure 6.3). First the shape of the adapter was optimised by running a series of FE simulations and, then the size of adapter was optimised. The details about the FE methodology is given in next section. The shapes of the adapter i.e. conical, stepped, exponential and, a combination of different shapes were studied using Abaqus adopting the FE-model developed in Chapter 5. After a series of simulations, it was found that Conical adapter presents the required mode for Ø 3 mm drill bit. The shapes of the adapter studied are shown in Figure 6.4 and 6.5. In these figures optimised shape that demonstrated the desired vibration characteristics is marked with green tick sign and, those which failed are marked as red cross in the corresponding box. Same methodology was used

optimise the adapter for $\varnothing 6$ mm drill bit. However, instead of Conical adapter, Step adapter was found to show the promising results with Conical adapter and drill bit was considered as a single system.

Figure 6.4. Shapes studied for optimisation of maximum vibration for $\varnothing 3$ mm drill bit

Figure 6.5. Shapes studied for optimisation of maximum vibration for Ø 3 mm drill bit

Transducer A was made of mild steel. Its properties were obtained from the supplier (NDT, 2012) and 3D model of the transducer was modelled in Abaqus 6.11. This transducer consisted of four piezoelectric rings in the stake, for high performance applications. Jobber Carbide Dormer™ twist drill bits (Ø 3 mm, and Ø 12 mm) was

modelled in Solidworks™ and then imported in Abaqus for FE studies. The Ø 6 mm drill bit was supplied by the Advanced Manufacturing Research Centre, UK (AMRC) and modelled in Solidwork. Since aluminium offers favourable acoustic coupling properties for carbide and steel, the geometries of adapters were assigned aluminium properties. The same grade aluminium was used as studied in section 5.2. A mesh convergence study was conducted similar to section 5.2. The convergence point for each component with corresponding number of elements and frequency of first longitudinal mode is given in Table 6.3. The surfaces of each component of transducer, in an assembly, were connected using surface-to-surface rough contact (Abaqus 9.11). As it was observed in section 5.4 all the other modes of vibration converge for the same element size where the first longitudinal mode was observed therefore the first longitudinal mode is reported here.

Table 6.3. Mesh convergence parameters for transducer components

Component	Element size (mm)	Number of elements	Frequency of first longitudinal mode (kHz)
Ø 3 mm drill bit	0.6	12,859	57.2
Ø 6 mm drill bit	1.2	11,601	21.7
Ø 12 mm drill bit	1.5	10,975	17.4
Step adapter	2.6	10,976	24.9
Conical adapter	2.5	12,650	27.9
Concentrator (Transducer A)	4.0	11,647	22.2
Concentrator (For 12 mm drill)	5.5	11,015	17.1
Piezoelectric rings Ø 50 mm	1.7	12,228	150.4

Backing section (Transducer A)	2.8	10,719	5.3
Backing section (For 12 mm drill)	5.8	11,648	33.8
Fixing bolt	3.0	12,176	29.3

The transducer, to accommodate $\varnothing$ 12 mm drill bit, was designed with ANSI M20 bolt, backing section of steel, concentrator of aluminium and two standard piezoelectric rings of $\varnothing$ 100 mm PZT – 807 ceramic grade (supplied by Morganelectroceramics™). The corresponding properties were assigned to each component of the transducer. The 3D models of the transducer systems i.e. “System I” and System II” are shown in Figure 6.6. The pre-manufactured parts are shown in light grey and optimised parts that were designed and manufactured are shown in black.

The modes of vibrations were studied and analysed. Second longitudinal mode of vibration for System I, System II and System III were observed at 28.1 kHz, 32.6 kHz and 21.4 kHz respectively. The vibration mode for each system is shown in Figure 6.7. It can be seen that all systems show the maximum longitudinal displacement at the tip of the drill bit. For all types of twist drills the vibration mode presents the twisting of the drill bit along with the longitudinal vibration. This twisting phenomenon is inherent from the pre-twisted geometry of the drill bit. For $\varnothing$ 3 mm and $\varnothing$ 6 mm drill bit only one twist was observed which was present on the tip of the drill bit. Whereas, the twists for drill bit for $\varnothing$ 12 mm were observed at two positions along the length of the drill bit.

For $\varnothing$ 12 mm drill bit, the second twist could be due to the length of the drill bit. In order to avoid the second twist of the drill bit, the study was also conducted by keeping the drill bit shorter in length. However, the shorter length of the drill bit could not present maximum vibration effect at the tip of the drill bit and also the vibration modes were not stable (see Figure 6.8). The experiments were also conducted with the shortened drill bit, however, no resonance was observed. It supported the evidence that the vibration modes and Eigen frequency of the system are dependent on the stiffness

and the geometry of the object. It could also be concluded from this study that the twisting of the pre-twisted structures cannot be avoided. Therefore, the primary longitudinal vibrations are overlapped by the secondary twisting motion of the drill bit.

Figure 6.6. 3D models of the transducer systems: (a) System I: Optimised conical adapter for Ø 3 mm drill bit ; (b) System II: Optimised step adapter for Ø 6 mm drill bit; (c) System III: Designed and manufactured for Ø 12 mm drill bit

It can also be seen from the Figure 6.7 that the first step, piezoelectric rings, backing section and fixing bold are almost stationary (not representing any vibrational effect) at these modes of vibration. Moreover, the vibrations are only amplified at the tip of the drill bit representing the maximum longitudinal displacement.

Figure 6.7. Second longitudinal mode of vibration: (a) system I @ 28.1 kHz; (b) system II @ 32.6 kHz; (c) system III @ 21.4 kHz

It was concluded from FE model that the pre-manufactured transducer could accommodate $\varnothing 3$ mm and $\varnothing 6$ mm drill bits using Conical and Step adapter. To accommodate $\varnothing 12$ mm drill bit a new transducer needed to be manufactured.

Model visualization vector sum (U)

Figure 6.8. Second longitudinal mode of vibration: (a) standard size of drill bit; (b) Half size drill bit

6.3.2 Free-vibration experimental results and comparison with FEA

The conical and step adapters were manufactured according to the dimensions (as analysed in FE). The dimensions of the adapters are shown in Figure 6.9. The concentrator and backing section for the transducer to accommodate $\varnothing 12$ mm drill bit

was manufactured and then it was assembled using ANSI M20 bolt. The concentrator and the backing section were made of aluminium and steel respectively.

All transducer systems i.e. System I, System II and System III presented different vibration characteristics in terms of frequency and amplitude. It was observed during the experiments that the magnitude of the resonance frequency was decreased with the increase in the size of drill bit. It should be noted that the geometry of the adapters was also different for System-I (with Ø 3 mm drill bit) and System-II (with Ø 6 mm drill bit). The magnitude of the vibration amplitude also decreased with the increase in the size of the drill bit. The transducer system used to accommodate Ø 3 mm drill bit consisting of Conical adapter presented the resonance frequency of 30.25 kHz with amplitude of 18 µm. For Ø 6 mm with Step adapter and same transducer the resonance frequency was observed as 27.8 kHz and amplitude as 12 µm. Whereas, for the larger drill bit i.e. Ø 12 mm, the vibration response was different i.e. the amplitude of vibration was found from 12 – 18 µm at the frequency span of 22.1 – 26.8 kHz. This represents that for System III, the vibration response was more stable compared to System I and System II. The resonance response of all the systems is given in Table 6.4.

6.3.3 Comparison with FE predictions

It was observed that experimental resonance value of frequency is higher than FE prediction. This phenomenon was also observed by (Cardoni et al., 2004). Another finding was that the percentage error between FE model and experimental values of frequency was increased with attachment of the drill bit to the transducer. This is due to the fact that system becomes comparatively complex due to the complex geometry of drill bit and extra mass attached to the system. The results are shown in Table 6.5.#

The reason for comparatively higher error could be the extra grip screws attachment that was used to secure the drill bit firmly to the transducer. The screw-pressure was represented in the simulation as a Surface to Surface Rough interaction (Abaqus 9.11). This could lead to extra inaccuracies in the model and result into the extra error.

(a)

REVISION HISTORY			
REV	DESCRIPTION	DATE	APPROVED

NAME	DATE	Solid Edge	
DRAWN LTJ	05/03/12	TITLE	
CHECKED		Holder, 12mm	
ENG APPR		SIZE: Dwg No	
MGR APPR		A4 LTJPC 0003	
UNLESS OTHERWISE SPECIFIED		FILE NAME: 12mm Holder.dft	
DIMENSIONS ARE IN MILLIMETERS		SCALE: WEIGHT: SHEET 1 OF 1	
ANGLES ±XX°			
2 PL ±XXX 3 PL ±XXXX			

(b)

Figure 6.9. Dimension for: conical adapter (a); step adapter (b)

Table 6.4. Experimental results vs. FEA results

Transducer system	Resonance frequency (kHz)		Difference
	Experimental	FEA	
System 1 with Ø 3 mm drill bit	30.25	28.1	7%
System 2 with Ø 6 mm drill bit	27.8	32.6	14%
System 3 with Ø 12 mm drill bit	22.1-26.8	21.4	3.1-20%

The transducer to accommodate Ø12 mm drill bit presented the wide span of experimental resonance frequency (22.1 – 26.8 kHz) with the amplitude from 12 – 15 µm. However, in FE model this mode of vibration was observed at the resonance frequency of 21.4 kHz. This stability of frequency favours the drilling experiments because when the drilling load is applied on the vibrating drill bit, the vibration amplitude depletes. To reduce this problem the resonance frequency needs to be tuned again, when the engagements happens between workpiece and the drill bit. If frequency is stable then it favours the drilling process and no further tuning is required during the process.

6.4 Summary

Free-vibration experimental setup was explained in this chapter. A comparison of second longitudinal mode of vibration-frequency between FE-model and experimental data was presented. It was found that FE-model developed in Chapter 5 predicts the desired mode of frequency with an error of less than 15%.

For the given transducer i.e. transducer A, a conical adapter could lead to the drilling forces reduction using Ø3 mm drill bit in UAD compared to CD and, step transducer was suitable for Ø6 mm drill bit.

However, for Ø12 mm drill bit a new design was suggested in this chapter on the basis of FE-model predictions. This was predicted that these designs could lead to the reduction of drilling forces. The drilling experiments were conducted successfully using these transducer systems. The details of these experiments are given in the next chapter.

CHAPTER 7

STUDY OF DRILLING FORCES

As discussed in Chapter 2, carbon fibre-reinforced plastics (CFRP) are used in the aerospace and automobile industry; advanced manufacturing techniques make the production process cost-effective. The use of CFRP is supported by their mechanical properties that can be customised to offer improved resistance to applied load and hostile environment. As discussed in Chapter 3, the parts made of CFRP are often needed to be drilled to facilitate their assembly. However, during drilling, a drill bit exerts high drilling forces on the components. Thus, the magnitude of drilling forces is one of the key factors to assess the machinability. An important feature is a critical magnitude of drilling force (Hocheng and Tsao, 2006; Krishnaraj et al, 2012; Davim, 2009), beyond which the delamination and other defects such as laminate cracking and spalling are observed to initiate. These drilling-induced damages caused by excess of drilling forces can result in damaging the parts that are usually discarded. This results in an increased manufacturing time.

The current study deals with a comparison of thrust forces induced by ultrasonically-assisted drilling (UAD) and conventional drilling (CD) with different drilling parameters. Three different sizes of drill bits were used and three different materials were tested. The transducer systems designed in Section 6.3 were used for different sizes of drill bits. Details about each transducer system are given in Chapter 6. The choice of workpiece and drill bits is discussed in next section based on practical considerations.

The suggested approach differs from the previous experimental works on UAD (Won and Dharan, 2002): no pilot drill was used for Ø12 mm drill bit. Moreover, in the history of ultrasonically-assisted drilling, Ø12 mm drill bit was used for the first time to study the drilling-induced forces in comparison with CD (which is of high importance for the aerospace industry).

7.1 Experimental setup

In this section the workpiece, tools and machining setup are introduced, which were used during the experimentation.

The lathe machine (model HarrisonM – 300) was used in the experiments. The choice of this machine was made on the basis of its better feed rate, spindle-speed (rotational speed) control and the flexibility of assembling the transducers. A transducer mounting tube was manufactured and fitted on the universal chuck of the lathe. The transducer chosen for each experimental phase was mounted in the mounting tube. The electric power was supplied through the slip rings to the transducer. The workpiece was clamped in the special fixture mounted on the dynamometer for force measurement on the saddle of the lathe.

A two-channel Kistler™ 9271A dynamometer was used to record the levels of thrust force and torque. This dynamometer was mounted on the cross-slide of the lathe on an angle plate. Different fixtures were made to accommodate different workpiece, and those fixtures were mounted on the dynamometer so that the thrust force and torque

could be recorded. The dynamometer was calibrated for thrust forces and torque before conducting the experiments. The used experimental setup is shown in Figure 7.1.

Figure 7.1. Drilling setup for Ø3 mm drill bit

The data from dynamometer were amplified by a charge amplifier. The data from amplifier were inputted to Picoscope™ oscilloscope 4424 and, finally, it was recorded on a personal computer. Then, the files in oscilloscope format were converted into a .txt file, which was further processed using a custom-made program in Matlab™.

Three types of workpiece were used in the experiments. The experiments with drill bits of Ø3 mm and Ø6 mm were conducted on T700/M21 quasi-isotropic 10 mm-thick workpiece (WP1). This material is used for high-performance application in aerospace industry. These twist drill bits were Jobber carbide TiN coated, whereas those with Ø12.5 mm was supplied by Airbus™. Shapes of drill bits are shown in Figure 7.2. The second type of material was woven 10 mm thick CFRP composite provided by AMRC (WP2). Due to the requirements of AMRC only Ø6 mm bits were used on woven composite. The drilling experiments with Ø12.5 mm were conducted on 4 mm-CFRP cross-ply laminates (WP3) manufactured in Loughborough University. The ply

thickness and orientation studied under the microscope for each material is presented in Table 7.1.

Figure 7.2. Drill bits used in experiments: (a) Ø3 mm Jobber carbide two flute drill; (b) Ø6 mm Jobber carbide two flute drill; (c) Ø12 mm provided by Airbus™ two flute drill

Table 7.1. Workpiece used during experiments

Type	Material	Stacking order	Thickness
WP1	T700/M21 quasi-isotropic	$[(0/45/90/-45/_{2s}0)_{2s}]_{2s}$	15 and 10 mm
WP2	Woven type aerospace grade	Confidential	10 mm
WP3	Cross-ply manufactured in Loughborough University	$[0_4/90_4]_{2s}$	4 mm

The distance between neighbouring holes was kept constant and was double the diameter of the hole. This helped in analysing the damage caused by each drilling technique. Thickness selection (elaborated in Section 7.3) was driven by the

requirement to achieve the full engagement of the drill-bit lips during the hole making. This primary selection was made to study the maximum thrust forces caused by drilling. It should be noted that all the experiments were conducted in dry cutting conditions. These conditions are favoured by the industry as they are considered as environment-friendly (Weinert et al., 2004b).

In case of epoxy-matrix composites the coolant may cause the swelling of the polymer and chemical reactions could take place in certain functional groups of macro-molecules. As the coolant spreads over the entire workpiece during the process, the mentioned defects not only affect the hole quality but the entire workpiece. This spread of the coolant over the entire workpiece causes the weakening of the composite in terms of reducing its strength. This is a result of lower adhesion within the polymer material and cohesive forces at the interface (Weinert and Kempmann, 2004a). All these challenges could be avoided using the dry machining technique capable of lowering drilling forces and producing high surface quality. UAD has presented such an attractive alternative.

The thrust force and torque signatures during drilling process are explained in Section. 7.2. The used experimental setup is summarized in Table 7.2.

Table 7.2. Summary of experimental setup

Machine tool	Lathe M – 300 Harrison
Experimental condition	Dry cutting condition
Force measurement equipment	Kistler™ 9271A dynamometer +2 channel acquisition cable +single amplifier + Picoscope™ oscilloscope 4424
Data acquisition software	Picoscope™ 6.0

	+Matlab™
Workpiece WP1	T700/M21 quasi-isotropic 15 mm thick Airbus™
Workpiece WP2	Woven 10 mm thick supplied by AMRC
Workpiece WP3	Cross-ply manufactured at Loughborough University 4 mm thick
Drill bit D1	Two flute Jobber carbide Tin coated twist drill $\varnothing = 3$ mm
Drill bit D2	Two flute twist drill $\varnothing 6.35$ mm provided by AMRC
Drill bit D3	Two flute Jobber carbide Tin coated twist drill $\varnothing 6$ mm
Drill bit D4	Two flute $\varnothing 12$ mm supplied by Airbus™

7.2 Planning of experiments

The purpose of experiments in this study is to investigate the levels of thrust force and torque exerted by the drill bit on composite during the drilling process. The drilling process - from the drill entry to full engagement and drill exit from the material is characterised by changes in the thrust force and torque. As the employed software recorded the data in terms of voltage and time, the calibration was used to evaluate the corresponding thrust force and torque in respective units – N and N.cm, respectively. When the full drill-bit engagement happened during the drilling process, the values of the measured thrust force became nearly constant. Whereas the values for the measured torque for conventional drilling during the full engagement of the drill bit increased, it became constant after a short interval of time before the drill bit exit. These values at the maximum level, during the full drill bit engagement over a time frame were averaged and reported. The first level of comparison between UAD and CD was provided based on these values. It was observed that the profile of thrust force and torque was not changed with the change in the feed rate and spindle speed but the magnitude of forces and time required drilling a hole varied. . The evolution of thrust force and torque is explained in Section 3.5.1 and 3.5.2 in detail.

7.3. Drilling procedure and results

A study is necessary to assess the benefits of UAD compared to CD under the comparable drilling conditions. The average reduction in thrust-force and torque represents the immediate visible effect of ultrasonically-assisted drilling.

Based on the finite-element study of transducers in the previous chapter, new transducer systems are expected to reduce significantly the thrust-force and torque in UAD compared to CD. The heat generated during the UAD process was also expected to be higher than that of CD due to extra energy of ultrasonic vibration pumped into the drill bit in UAD application.

The experiments were conducted in three phases. In the first phase, the transducer System I was used with Ø3 mm drill. The levels of thrust-force and torque were determined at feed rate of 0.05, 0.1, 0.2, 0.3, 0.4 and 0.5 mm/rev with a constant spindle speed of 40 rpm.

In the second phase, System II was used with Ø6 mm drill bit. Both thrust-force and torque were recorded at the same feed rate and spindle speed. In the third phase, System III was used with Ø12 mm drill bit and the experiments were conducted on 4 mm-thick CFRP specimen. The feed rate was chosen as 0.05, 0.1, 0.2 mm/rev at the spindle speed of 40 rpm.

In all the experiments the conventional drilling was carried out first, for all the drilling parameters. After drilling CD holes the position of the workpiece was changed and UAD was conducted at the same machining parameters. Prior to UAD the transducers were tuned for the resonance frequency. Each run was carried out three times to ensure the repeatability and reasonable statistics. From preliminary experiments, it was concluded that three runs are sufficient to ensure the statistical significance of the data. After each run the workpiece and the drill bit was allowed a significant time of approximately 5 min to cool down to room temperature. This was done to ease the post drilling analysis such as hole roundness, surface roughness and micro-computed tomography for structural analysis. The phases of experiments are explained below.

7.3.1 First phase – transducer System I

In this phase, the experiments were conducted using a $\varnothing$ 3mm Jobber carbide two-flute twist drill bit. The optimised transducer system i.e. System I, was used. System I was composed of a pre-manufactured industrial transducer consisting of four piezoelectric rings, a conical adapter (optimised using FEA in the previous chapter) and the mentioned drill bit. The drill bit was firmly mounted in the conical adapter using grip screws to ensure minimum vibration losses. The composite material of 15 mm thickness was cut into 20 mm wide and 150 mm long specimens. This ensured the side-to-hole-centre distance of 10 mm and hole centre-to-centre distance of 15 mm. This was done to make sure that the damage caused by drilling on one hole would not interact with the damage caused by drilling on the other. Although a single drill bit can be used to produce 20 to 30 holes without any significant effect on the drilling quality (Wang et al., 2013; Faraz et al., 2009; Iliescu et al., 2010), however, the drill bit was replaced after drilling three holes to avoid any effect on the results. The transducer system and the schematic of workpiece are shown in Figure 7.3. The used experimental parameters are given in Table 7.3. The evaluation of thrust-force and torque for feed rate of 0.4 mm/rev are presented in Figure 7.4.

The main experimental results are given in Table 7.4. The magnitude of the averaged-peak thrust-force and torque, in case of CD, are found to increase linearly with the increase in the feed rate (see Figure 7.5). However, in case of UAD their magnitude was constant at each value of feed rates. The reduction (UAD vs. CD) in the averaged-peak thrust-force and torque was observed in an excess of 80% and 90% respectively, up to the feed rate of 0.4 mm/rev. The magnitude of drilling forces jumped suddenly up to the CD level when the feed rate was increased to 0.5 mm/rev. The increase in magnitude was found linear and equal to that of CD drilling forces beyond the feed rate of 0.5 mm/rev.

Figure 7.3. (a) Transducer System I and workpiece schematic and; (b) bench marking

Table 7.3. Drilling parameters

Feed rate (mm/rev)	0.05, 0.1, 0.2, 0.3, 0.4, 0.5
Spindle speed (rpm)	40
Vibration frequency (kHz)	30.2
Peak to peak vibration amplitude (μm)	18
Drill bit (D1)	$\varnothing 3$ mm Jobber carbide TiN coated two-flute
Adapter type	Conical
Workpiece material (WP1)	T700/M21 quasi-isotropic
Coolant	None

The reduction in averaged-peak thrust force and torque in case of UAD compared CD can be seen in Figure 7.4-5. It is clear from the figure that UAD provided an enormous extent of reduction in drilling forces. It was also noticed that the results were statistically significant. For further confirmations the experiments were repeated after one month time and the same results were observed. The performance of the transducer System-I showed the design and statistical significance of the system.

Table 7.4. Thrust force and torque with respective reduction for System I (at 40 rpm)

Feed rate (mm/min)	Averaged-peak thrust force (N)			Averaged-peak torque (N-cm)		
	CD	UAD	Percentage Reduction	CD	UAD	Percentage Reduction
2	230 ± 6.7	24 ± 4.2	89.5%	31 ± 5.2	1 ± 1.1	95.5%
4	254 ± 7.3	26 ± 3.8	89.9%	33 ± 6.3	2 ± 2.2	92.9%
8	303 ± 5.4	27 ± 3.5	91.1%	35 ± 7.2	2 ± 1.8	92.7%
12	356 ± 9.8	42 ± 5.2	88.1%	37 ± 6.1	2 ± 1.6	94.9%
16	403 ± 9.5	46 ± 4.9	88.5%	43 ± 4.9	3 ± 1.7	92.6%
20	511 ± 8.4	508 ± 9	0.5%	49 ± 5.7	48 ± 5	2%

7.3.2. Second phase – transducer System II

In this phase, the transducer System II was used. This system was capable of drilling with Ø 6 mm drill bits. The transducer system composed of the same transducer as used in the first-phase experiments, i.e. the pre-manufactured transducer with four piezoelectric rings. However, in this system a step adapter was used. It was studied in Chapter 6 that the same transducer could be effectively used for Ø6 mm drill bits with the step adapter. The transducer System II is shown in Figure 7.6. It should be noted that the experiments in this phase were conducted using two drill bits. One of them was

a $\varnothing 6$ mm Jobber carbide TiN-coated two-flute twist drill and the other was $\varnothing 6.35$ mm two-flute twist drill provided by AMRC

Figure 7.4. Thrust force and torque evolution at 0.4 mm/rev and 40 rpm for System I

Figure 7.5. Comparison of drilling forces between UAD and CD for System I: (a) averaged-peak thrust force; (b) averaged-peak torque

Depending on the requirements of AMRC the workpiece WP2 (10 mm) was used to study the effects of variable rotational speed at a constant feed rate. These experiments were conducted using a specially manufactured jig, which also acted as backing plate. The drill bit was guided through the jig into the workpiece. The distance between hole-centres was kept constant and three times the hole diameter. The experiments were

carried out at spindle speed of 40 , 85 and 260 rpm and constant feed rate of 8mm/min. Due to the machine limitations and the onset wobbling of the mounting tube at high spindle speed (i.e. safety reasons) it was not possible to conduct the experiments at high spindle speed.

Figure 7.6. Transducer System II for Ø6.35 mm drill bit

The CD experiments were conducted first followed by UAD ones with the same parameters except the provision of ultrasonic vibrations to the drill bit. For UAD the transducer was tuned at 37.8 kHz and the peak-to-peak amplitude was recorded as 12 μm . It is important to note that different types of drill bits vibrate at different resonant frequencies with different amplitudes. It was expected that different shapes of the drill bit would result in different magnitude of drilling forces. The experimental conditions for these experiments are given in Table 7.5. The average levels of thrust-force and torque are given in Table 7.6. It can be seen from Table 7.6 that the averaged-peak value of torque is near or below zero. However, it is clear from Figure 7.4 that the magnitude of torque fluctuates between 15 N.cm to -15 N.cm resulting in the average zero value. A possible reason for this is given in Section 7.4.

Table 7.5. Experimental conditions for variable-speed experiments for System II

Feed rate (mm/min)	8
Spindle speed (rpm)	40, 85 and 260
Vibration frequency (kHz)	37.8
Peak to peak vibration amplitude (μm)	12
Drill bit D2	$\varnothing 6.35$ mm two-flute provided by AMRC
Adapter type	Step
Workpiece material WP2	Woven type aerospace grade composite provided by AMRC
Coolant	None

The relationship of averaged-peak thrust-force and torque is shown in Figure 7.7. Figure 7.7-a demonstrates the increase in the rotational speed results in the decrease of the averaged-peak thrust-force in case of CD. However, in case of UAD it increases significantly. Figure 7.7-b shows that the averaged-peak torque in CD increases with an increase in the rotational speed; in case of UAD it was found almost constant close to zero for each rotational speed.

Table 7.6. Thrust force and torque at 8 mm/min for System II

Spindle speed (rpm)	Averaged-peak thrust force (N)			Averaged-peak torque (N-cm)		
	CD	UAD	Reduction	CD	UAD	Reduction
40	222 ± 1.6	32 ± 2.5	86%	27 ± 3.1	-0.4 ± 2.1	Nearly 100%
85	160 ± 6.3	42 ± 2.1	74%	31 ± 2.8	0.6 ± 1.8	Nearly 100%
260	130 ± 6.5	46 ± 2.6	65%	35 ± 4.2	-0.5 ± 2.4	Nearly 100%

Figure 7.7. Effect of spindle speed on drilling forces for System II: (a) averaged-peak thrust force; (b) averaged-peak torque

To compare the effect of the drill-bit size on drilling forces, the experiments were also conducted on workpiece WP1 using drill bit D3. That was geometrically similar to D1 except for its diameter. This was done to study also the effect of various feed rate at a

constant rotational speed. Workpiece WP1 was used for these experiments. The experiments were carried out without a backing plate. The same experimental conditions were used as those in the first phase of experiments. The tuned frequency of vibration for these experiments was recorded as 27.8 kHz with peak-to-peak amplitude of 6 μ m. The averaged-peak thrust-force and torque are given in Table 7.7 and the trend for them is shown in Figure 7.8.

Table 7.7. Thrust force and torque with respective reduction (at 40 rpm) for System II

Feed rate (mm/min)	Averaged-peak thrust force (N)			Averaged-peak torque (N-cm)		
	CD	UAD	Reduction	CD	UAD	Reduction
2	340 $\pm$ 6.8	31 $\pm$ 3.6	91%	65 $\pm$ 3.2	2 $\pm$ 1.2	97%
4	358 $\pm$ 9.3	48 $\pm$ 4.8	87%	72 $\pm$ 4.8	6 $\pm$ 1.4	92%
12	409 $\pm$ 7.4	58 $\pm$ 2.9	86%	88 $\pm$ 6.7	3 $\pm$ 1.8	96%
16	478 $\pm$ 6.7	63 $\pm$ 5.8	87%	102 $\pm$ 5.4	-1 $\pm$ 1.9	98%
20	528 $\pm$ 9.6	533 $\pm$ 7.4	0.9%	115 $\pm$ 6.4	113 $\pm$ 7	2%

The same trends for the thrust force and torque can be seen in Figure 7.8 as observed with the $\varnothing 3$ mm drill bit. The ultrasonic effect depleted at 20 mm/min or 0.5 mm/rev feed rate. The averaged-peak thrust force in case of UAD increased with the increase in the feed rate; however the increase was nonlinear. Averaged-peak torque was observed to be almost constant for the studied range of the feed rate for the UAD regime.

(a)

(b)

Figure 7.8. System II with D3 drill bit – Effect of feed rate on: (a) averaged-peak thrust force; (b) torque

7.3.3 Third phase – transducer System III

In this phase the transducer System III was used. This transducer had two $\varnothing 100$ mm piezoelectric rings, capable of drilling with a $\varnothing 12$ mm drill bit (see Figure 7.9). WP3 workpiece was used. The backing plate of resin was used because the thickness of WP3 was small (4 mm) compared to that of WP1 and WP2. The thickness of WP3 was sufficient to present the complete engagement of the drill bit with the workpiece for a noticeable period of time. This ensured that Stage II (refer Section 7.2) of the drilling process could be observed, and the averaged-peak drilling forces could be recorded. The transducer was tuned and peak-to-peak amplitude of $15\text{ }\mu\text{m}$ was recorded at 21.8 kHz resonant frequency. The experiments were conducted at 40 rpm and for a range of feed rates.

Figure 7.9. Transducer System III for $\varnothing 12$ mm drill bit

The tests conducted on WP1 using this transducer system showed that the ultrasonic effect depleted before the completion of the hole. This challenge could be solved by increasing the transducer's power. However, in order to achieve a higher power of a transducer, a proper and complete-redesign and manufacturing of the transducer are

necessary. As the objective of this phase of experiments were to study the effectiveness of ultrasonics using the Ø12 mm drill bit irrespective of the workpiece thickness, so WP3 (manufactured in Loughborough University) was used. This phase demonstrated that ultrasonics can be used to drill holes of larger diameters employing the suitable design and manufacturing considerations for the transducer. The results are presented in Table 7.8 and shown in Figure 7.10. It is clear that the ultrasonic effect disappeared at a feed rate of 8 mm/min. The reason for the depletion of ultrasonic effect was the high resistive force imposed on the drill bit face by workpiece. As this transducer was consisted of two piezoelectric rings therefore the transducer power was not high enough to resist the drilling load. However, this problem can easily be solved with the design improvements in the transducer System-III.

Table 7.8. Thrust force and torque reduction (at 40 rpm) with System III

Feed rate (mm/min)	Averaged-peak thrust force (N)			Averaged-peak torque (N-cm)		
	CD	UAD	Reduction	CD	UAD	Reduction
2	817 ± 7.2	367 ± 4.9	55%	107 ± 5.2	18 ± 2.5	83%
4	904 ± 8.4	458 ± 6.5	49%	123 ± 3.8	22 ± 4.2	82%
6	990 ± 9.4	564 ± 8.7	43%	146 ± 7.2	32 ± 3.8	78%
8	1095 ± 5.4	1102 ± 6.2	0.6%	170 ± 9.8	168 ± 9.1	1.2%

7.4 Discussion

In all three phases of the undertaken research similar trends for the thrust-force and torque were observed. It was found that they increased linearly in case of CD with the increase in feed rate. This finding is in line with previous experimental studies conducted with twist drills (Armarego, 1994; Wiriyacosol and Armarego, 1979). This

can be justified by the fact that a larger feed rate results in a larger instantaneous cutting area leading to higher cutting force and torque.

(a)

(b)

Figure 7.10: System III - effect of feed rate on averaged-peak: (a) thrust force; (b) torque

For UAD, it was observed that the ultrasonic effect resulted in the higher magnitude (more than 60%) of drilling forces reduction but it disappeared after a particular level of feed rate. After this level of feed rate the UAD process becomes effectively conventional and no reduction in the drilling forces could be observed. This depends on the ultrasonic power of the transducer, vibration frequency and amplitude. For example, in the second phase of experiments at variable spindle speed, it was observed that the ultrasonic forces increased with the increase in the spindle speed. This contrasts CD where the thrust forces decreased with such an increase. One possible reason for the increase in the thrust forces in case of UAD with the increase in the spindle speed could be due to a lower number of impacts experienced by uncut chip thickness per unit time. A reason for this was that the transducer vibrated at the same frequency but the drill bit rotated at a higher spindle speed. This could result in comparatively higher drilling forces at higher rotational speeds.

It was noticed that the ultrasonic effect completely disappeared at a feed rate of 20 mm/min in case of Ø3 mm and Ø6 mm drill bit. In our experiments it was revealed that the temperature in the case of UAD was higher than that of CD (refer Section 8.2). It was also observed that the temperature increased noticeably with an increase in the feed rate in case of CD. However, in UAD, the temperature is almost the same for each feed rate. It can be noticed from Chapter 8 that the magnitude of forces and temperature becomes the same for both cases (UAD and CD) at the feed rate of 20 mm/min. This demonstrates that the UAD effects diminished at this feed rate. The cause of force reduction could be due to the tool separation as explained by Astashev and Babitsky (2007) or could be due to increase in the temperature.

To investigate the contribution of temperature increase in drilling force reduction, hot CD experiments were conducted. In these experiments drill bit was heated to a temperature of 350 °C with band heater prior to drilling. The temperature measurements were taken using k-type thermocouples. During the preparation of experiments, it was observed that the time taken from removing of the band heated to the onset of drilling was 5 to 10 seconds and, it was ensured that the drill bit would be at 300°C at the onset of drilling. The experiments were conducted at 40 rpm spindle speed and 16 mm/min in

order to compare the results of CD, hot-CD and UAD. It was recorded that the decrease in thrust force (CD vs. hot-CD) was in the excess of 35%-55% (see Figure 7.11). The decrease in drilling forces varied from 35% 55% because it was difficult to control the temperature after the onset of drilling. Moreover, the higher temperature i.e. in the excess of 300°C led to the local burning of the matrix. The burning traces were observed on the hole wall at the hole entry and, when the drill bit penetrated further in the sample, these traces disappeared because of the decrease in the surface temperature of the drill bit.

Figure 7.11: CD vs. Hot-CD

To investigate the contribution of tool separation the results of finite element model developed by Phadnis (2013) are used here.

A solid continuum FE model of drilling in CFRP laminate (Figure 3) was developed which was based on the Lagrangian formulation [18] Figure 7.12. (A) Finite element model for simulating drilling process. (B) Details of stacking order in M21/T700 unidirectional CFRP laminate (first four layers). The FE model consists of eight layers of the CFRP laminate. A commercial finite element software ABAQUS/Explicit was

average forces for finite element model and experimental data are compared, they are found in a good correlation.

Hence, the reduction in drilling forces in UAD is a combined effect of temperature increase and tool separation. This combination can be achieved by the application of ultrasonic vibration. Hot-CD and, temperature control during the drilling process is invasive task. Moreover, it is difficult to control the temperature, once drilling process initiates therefor it is recommended to use UAD instead of hot-CD. Moreover, it is proven from the experiments that hot-CD contributes only

Figure 7.123. Finite element analysis for forces for one cycle of UAD

It can be concluded that the reduction in thrust forces in the excess of 90% was achieved in case of UAD compared to CD. Similarly, reduction in averaged-peak torque was observed in the excess of 100% in case of small diameter drill bits. However, in case of $\varnothing 12$ mm drill bit, the reduction in torque and thrust force was achieved in the excess of 50%.

The higher level of drilling force reduction, in case of $\varnothing 12$ mm drill bit could be achieved by improving the power of a transducers. The power can be increased with

help of extra piezoelectric rings and a new redesign. The reduction in UAD is a combined effect of tool separation and temperature increase during UAD.

CHAPTER8

THERMAL ANALYSIS AND CHIP FORMATION

It is essential to conduct the thermal analysis of drilling of carbon fibre-reinforced plastics (CFRP) because the structural integrity of CFRP is directly affected by temperature variations. Despite the fact that CFRPs are suitable for structural application they offer poor thermal conductivity and thermal resistance compared to metals. Due to this, the cutting-generated heat accumulates in the composite material during machining processes. Consequently, the materials temperature increases in the process zone. As discussed in Section 2.2 that CFRP are composed of carbon fibres and epoxy matrix. The latter offers lower heat resistance compared to of carbon fibres.

Moreover, most of the properties of epoxy resin such as Young's modulus and yield stress are functions of temperature (Foreman et. al., 2010). This could lead to degradation of the matrix (resin) and cause delamination during machining processes (Yashiro et. al., 2013). Different types of resin have different resistance to temperature, and most of the modern resins cannot withstand temperatures beyond 350° C (Richardson and Lokensgard, 2004).

As discussed in Section 3.6 that thermal imaging measure the surface temperature with a reasonable accuracy. Thermal imaging method was implemented using an infrared camera in our experiments due to its simplicity and since it avoids the inaccuracies that arise due to high-frequency vibration of the drill bit. The real-time thermal images were recorded and used to evaluate the difference in temperature between conventional drilling (CD) and UAD.

8.1 Thermal imaging experimentation

The thermal imaging experiments were conducted using the FLIR SC3000 thermal camera. This camera features Stirling-cooled quantum infrared photo detection. The camera is capable of measuring the temperature from -20°C to $+2000^{\circ}\text{C}$ with sensitivity of 10 mK at 30°C . The infrared detector offered a sensitivity of infrared radiations between 7 to 9 μm wavelength with an accuracy of $\pm 2^{\circ}\text{C}$ above 150°C . The image resolution was 320x240pixels in the used range of 14 bits radiometric IR digital image. The recorded images were proposed using the FLIR software provided with the camera.

The camera was calibrated for the emissivity of CFRP prior to the temperature measurements in the experiments. A set of measurements was taken for calibration to ensure the data accuracy. This was carried out by heating WP1 up to 200°C with the help of band heater. The temperature was measured with the help of K-type thermocouple. The four channel thermometer was used to record the temperature measurements. The distance between the workpiece and the camera was kept same as it was during the drilling-temperature-measurements. As per camera manufacturer, the

measured temperature is a function of distance and emissivity. Therefore, emissivity was calculated using the autocalculate option of the ThermoCam software. The default value of emissivity was 0.92, however, when the measured temperature (using thermocouples) was entered into the software, it evaluated the emissivity of the workpiece. Moreover, other calibration parameters such as room temperature, distance between the samples and the camera were also taken into account during the calibration process. These parameters were then used as an input for FLIR software. These experiments were repeated eight times and the average value of emissivity was evaluated as 0.29 by the software. Later, the temperature was recorded on the basis of this emissivity value of CFRP.

The temperature measuring experiments were conducted on workpiece WP1 using drill bit D1 (refer Table 8.1) with the transducer System I (Section 7.3.1). The camera was mounted on the tripod at a fixed distance from the workpiece. The thermal camera was focused on the point of contact of workpiece and drill bit. The schematic of the setup is shown in Figure 8.1. The surface temperature was recorded throughout the drilling process. The thermal distribution was captured in the process zone for both CD and UAD. The workpiece was cooled down by pressurized air near to the room temperature after each hole was produced to prevent the effect of pre-heating before starting the next hole-drilling. The drilling parameters and experimental conditions are given in Table 8.1.

Figure 8.1. Schematic of temperature-measurement setup

Table 8.1. Experimental parameters for temperature measurements

Feed rate (mm/min)	2, 4, 8, 12, 16, 20
Spindle speed (rpm)	40
Vibration frequency (kHz)	30.2
Peak to peak vibration amplitude (μm)	18
Drill bit (D1)	$\varnothing 3\text{ mm}$ two flute Jobber Carbide TiN coated
Adapter type	Conical
Workpiece material (WP1)	T700/M21 quasi-isotropic
Coolant	None

At the begin of a measurement, the camera was switched on and focused on the expected process zone. The workpiece was moved closer to the drill bit, and the lathe was turned on. The feed lever was engaged and, as the cutting began, the camera was focused on the process zone. The temperature range was selected. However, it should be noted that with the change in temperature range the camera adjusts its filter lens for precise measurement. Therefore, it was considered suitable to change the camera focus when the temperature range was changed. The software displayed the levels of temperature change in the form of colours. The contrast imaging pattern was selected such that the higher and lower temperature zones could easily be distinguished. This pattern represented the difference in temperature with respect to the room temperature. The name of the pallet selected for these experiments was Iron11. This pallet offers the best contrast for different temperatures in the desired range without mixing or blurring the image.

After satisfactory calibration, the drilling experiments were started. The camera acquired data for the tool and the workpiece at the same time throughout the drilling

process for one hole at one time. The software evaluated and displayed the maximum temperature together with the temperature-scale on one side of the image during the process. The emissivity of the drill bit was also evaluated; it was 0.27. As the emissivity of the drill bit tip was close to that of CFRP (0.29), the variation of the temperature on the drill bit surface was also visualised in the same image.

For all the drilled holes, the temperature was recorded on the surface near the drill bit penetration. It was observed that the surface temperature was almost equal to the chip temperature. The acquired images at the peak temperature for CD and UAD are shown in Figure 8.2. The data was first recorded just before the cutting started. The temperature signature was found almost similar to that of the thrust force signature. It followed the Stage-I and Stage-II (see Figure 8.3 a); however, when the drill bit exited the workpiece and was retrieved from it, the value of the temperature remained the same for 5 – 10 s depending on the feed rate. The temperature dropped gradually depending on the method of cooling, i.e. at room temperature or with pressurized air. The signature of thrust force and temperature at 40 rpm and 16 mm/min for CD and UAD are shown in Figure 8.3. The averaged-peak values of the temperature are reported in Table 8.2.

Figure 8.2. Thermal images at 40 rpm and 16 mm/min; (a) CD; (b) UAD

Table 8.2. Averaged-peak temperature

Feed rate (mm/min)	Temperature (°C)	
	CD	UAD
2	56.4 ± 2.6	260.4 ± 9.8
4	67.3 ± 5.4	265.6 ± 10.4
8	73.2 ± 6.1	262.5 ± 7.8
12	79.5 ± 9.6	263.7 ± 6.4
16	84.2 ± 3.9	265.6 ± 9.7
20	90.1 ± 4.5	92.3 ± 3.4

In ultrasonically-assisted machining the increased temperature was reported for machined metals. The extra energy pumped into the workpiece in form of vibration was considered as the cause of the increase in temperature during machining operations (Maurotto, 2012). Experiments conducted by Babistky et al. (2004) and Mitrofanov et al. (2005) revealed that the temperature in case ultrasonically-assisted machining increased. However, the reported difference in temperature was not significant. As the effects of ultrasonic vibration are material-dependent, it is challenging to predict the temperature rise for any type of material in case of ultrasonically-assisted machining. In our experiments it was observed that the temperature difference, in case of UAD, is considerably higher when compared to that for CD. It was observed that in case of CD the temperature increase was linear with increase in the feed rate, from 56° C to 90° C. However, in case of UAD after the rise, the temperature remained almost constant (265° C) at each feed rate (see Figure 8.4). The highest temperature difference (UAD vs. CD) 204° C was observed at the lowest feed rate.

This is because UAD temperature remained almost constant at each feed rate and the CD temperature was the lowest at this feed rate. It was observed that the temperature difference at the higher feed rate i.e. 16 mm/min was also significant. For example, the averaged-peak temperature at 2 mm/min (0.05 mm/rev) were recorded as 56.4° C and 260.4° C for CD and UAD, respectively. At 16 mm/min (0.4 mm/rev) the recorded

temperatures were 84.2°C and 265.6°C for CD and UAD respectively. However, at feed rate of 20 mm/min no difference in temperature was observed and the recorded temperature for UAD was same as in case of CD. This demonstrates that the ultrasonic effect disappeared at this feed rate for this type of the transducer system. It should be noted that all the experiments were conducted at 40 rpm .

Figure 8.3. Signatures of thrust force (a) and temperature (b) at 40 rpm and 16 mm/min

The findings, in case of CD, are in line with the research conducted previously for composites, i.e. the linear increase in temperature with the feed rate (Weinert and Kempmann, 2004; Rawat and Attia, 2009). As there is no research available for UAD on composites therefore, these findings were observed for the first time.

However, high temperature could affect the composite structure adversely. Therefore, another thermal study was conducted to assess possible decomposition of the composite with the increase in temperature. Thus, the studied composite T700/M21 was analysed using a thermogravimetric analyser.

Figure 8.4. Effect of feed rate on averaged-peak temperature

8.2 Thermogravimetric analysis

Thermogravimetric analysis (TGA) is extensively practiced in the industry and academia for the thermal analysis of materials. TGA measures the amount and rate of change in the weight of a material with respect to the increase in temperature or duration in a restrained experimental environment. This method is used to observe

thermal degradation of the subjected material. The material can be characterised on the basis of weight loss due to decomposition, oxidation, or dehydration. This method is also used to find the weight, mass or volume of each component in the material (Stuart, 2003; Lampman, 2003).

To study the thermal behaviour of the studied CFRP, TGA was conducted. The purpose of this analysis was to investigate the effect of the drilling-induced temperature on quality of the workpiece in terms of its thermal stability.

The experiments were conducted on a virgin material by exposing it to high temperature to observe the decomposition of the material with the increase in temperature. A TGA Q5000 – IR thermogravimetric analyser was used. The material was cut into 3mm x 3mm x 3mm samples using a diamond cutter. The samples were placed into the analyser's heating chamber; that heated the sample using four infrared heaters. The samples were heated at heating rate 10° C/min in air atmosphere with an air intake rate of 25 ml/min. These parameters were suggested by the machine manufacturer for carbon fibre-reinforce plastics.

Figure 8.5. TGA – decomposition of CFRP with temperature

The weight lost in the analysis is shown in Figure 8.5. It can be seen that the decomposition of this resin starts at a temperature of 360° C. The resin decomposes completely at the temperature of 700° C. The remaining weight represented the fibre fraction in the composite because the decomposition of the carbon fibre starts in the excess of 900° C (Wang et al., 2013). However, the resin or epoxy decomposition starts in a range of 350° C – 400° C (Wu et al., 2002). From this analysis it could be concluded that the epoxy did not burn during the drilling process. For further investigation the chip was analysed using scanning electron microscopy, which is presented in the next section.

8.3 Chip formation

A cutting process causes chip formation. A chip could be of different shapes and sizes depending on the machining conditions. Chip shapes and its characteristics could give valuable information about the machining/drilling process. Formation of the chip, in machining CFRP, is completely different from that in metal machining because of anisotropic and inhomogeneous character of the material. The chip formation process is governed by the type of fracture occurring during cutting. CFRP machining consisted of series of brittle fractures, which are dependent on the orientation of the fibres. This mechanism of chip formation is different from that for conventional metals because in metals the cutting happens mostly due to shear. Shear cutting increases the temperature of the cutting zone. Chip formation is also influenced by the temperature in the cutting zone. However, the material removal in the machining of CFRP is due to fracture; therefore, the temperature of CFRP cutting is lower than that of metal cutting (Wang et al., 2013). Hence, the formation of chip, in CFRP cutting is dependent on the type of cutting (shear or fracture), machining conditions and the temperature.

Various research groups proposed different ideas on the basis of their findings about the chip formation in CFRP. It was suggested that the chip formation in CFRP depends on the fibre orientation and occurs mainly due to the series of successive ruptures (Koplev, 1980). This was argued later and it was suggested that the chip formation in CFRP is

due to the brittle fracture and is not dependent on the orientation (Arola and Ramulu, 1997). However, all of them agreed that the material removal in case of drilling of CFRP is in the form of a powder, irrespective of the underlying dynamics of the chip-formation process.

In our CD experiments, the chip formation was found to agree with results reported in literature, i.e. in the form of powder. However, in case of UAD the chip formation was observed in the form of continuous chip as it happens in metals. This means that the material behaviour in UAD changed from brittle fracture or successive ruptures to ductile. For UAD of different brittle materials, the change in material behaviour, with regard to chip formation was also reported (Moriwakiet al., 1991; Suzuki et al., 2004). CFRP drilling is brittle in case of conventional machining operations. Conversely, in UAD, the material behaviour was similar to that of ductile materials. However, this change in material behaviour, in case of CFRP, for UAD was observed for the first time in our experiments.

In UAD, after the drill bit engagement, the material removal was in the form of powder for 2 – 5 s depending on the feed rate. This could be due to the time taken by ultrasonic vibration to consolidate in the process zone. After this time the material removal was in the form of continuous chip throughout the remaining cutting process. It was found that the length and the pitch of the chip varied depending on the feed rates. At lower feed rates long chip with a shorter pitch were observed whereas at higher feed rates the chip was shorter with a longer pitch. The optical microscopy of the chip was carried out and its results are shown in Figure 8.6.

Figure 8.6. Optical microscopy of chip at 40 rpm and variable feed rates: (a) CD at 2 mm/min; (b) UAD at 2 mm/min; (c) CD at 8 mm/min; (d) UAD at 8 mm/min; (e) CD at 16 mm/min ; (f) UAD at 16 mm/min

Another finding was that UAD chip was in the form of spirals and it whirled itself around the drill bit. This material removal behaviour was also similar to the drilling of ductile materials. In metal drilling, the chip is removed in the spiral form at an angle to the drill bit axis. Different types of drill bits have different number of flutes. The number of spirals of chip depends on the number of flutes. The Jobber carbide two-flute drill bit was used in the experiments; therefore, two successive chip spirals were observed in the UAD process. Just after removal from the material, the UAD chip was at high temperature (in excess of 280°C) which made it flexible. Hence, instead of removing at an angle to the drill bit axis the chip whirled itself along the body of drill bit (see Figure 8.7). After being separated from the material, the chip cooled down, became stiffer and retained its spiral shape.

After the UAD chip cooled it became fragile as compared to the metal chip. This could be because of lower internal structural forces present in the chip of CFRP as compared to those in the metal chips. In case of metals, the chip is composed of same homogeneous material, and the flow of chip is ductile and structure is uniform due to the similar composition throughout. Whereas, in case of CFRP, the chip flow was also continuous; however this chip was composed of cut fibres meshed in the matrix material. Owing to inhomogeneity, of the chip material, the UAD chip in case of CFRP was fragile.

To further investigate UAD chips, they were analysed using a scanning electron microscope (SEM) model *LEO – 440*. Sample of UAD chip were placed in the chamber and exposed to high voltage (5 kV) and current of $350\text{ }\mu\text{Amp}$ in the vacuum. The images were captured at magnifications of 150 and 400. It can be seen from Figure 8.8 that carbon fibres are bonded to the matrix material. The latter does not show any clear signs of burning in these images. It was also observed that cut fibres were embedded into the matrix.

Figure 8.7. UAD chip at 40 rpm and 8 mm/min

(a)

(b)

Figure 8.8. SEM of UAD chip at 40 rpm and 8 mm/min at magnifications of 150 (a) and 400 (b)

8.4. Discussion

As can be seen in Figure 8.2 the maximum temperature in drilling process was around the drill-bit tip. The temperature increased with the increase in the feed rate in case of CD. However, in case of UAD the temperature was observed at nearly the same value demonstrating that it is not dependent on the feed rate. It should be noted that these experiments were conducted at a low drilling speed. It was observed that benefits of ultrasonic drilling were lost beyond a certain feed rate and the process became similar to CD. When the ultrasonic effect disappeared at a particular feed rate, the temperature became equal to that of CD and the drilling forces become equal to CD.

To elucidate the rise in temperature FE simulations were carried out by Mr Vaibhav Phadnis and the increase in temperature was observed in case of UAD compared to CD. The FE simulated results presented almost the same degree of increase in the magnitude of temperature in case of UAD as compared to CD i.e. in UAD the temperature was 315° C and in case of CD 65° C for the same drilling conditions. The temperature in experiments was found around 5° C to 20° C lower than the simulations. As the temperature was measured on the surface with the help of thermal camera, the temperature in experiments could be lower than that of FEA due to convection taking place on the surface of the workpiece. A comparison of FEA and experimental data is shown in Figure 8.9.

The maximum temperature in case of UAD was observed as 290°C for a fraction of a second and then it dropped to the lower magnitude. This measured temperature was lower than the decomposition temperature of this CFRP. As all materials have different thermal resistance and subjected material needs to be exposed for a certain amount of time to heat before decomposition, this degree of measured temperature could be considered as safe. For decomposition of the studied aerospace-grade CFRP, it is necessary to expose the composite to high temperature for a significant period of time. Using TGA it was observed that degradation of the resin starts at 350°C while the maximum peak temperature in drilling was recorded as $290 \pm 2^\circ\text{C}$. It should be noted

that the temperature was recorded on the surface of the workpiece and not at the real cutting zone (where the actual cutting takes place).

(a)

(b)

Figure 8.9. Comparison of surface temperature FEA vs. Experimental: (a) CD; and (b) UAD

The higher level of temperature in UAD compared to CD could be due to several reasons. One of them could be the instantaneous friction. As the drill bit vibrates more than 20, 000 times in one second therefore the interaction between the workpiece and the drill bit takes place at the same frequency, which may increase the overall friction during the cutting time. Another reason could be the extra energy that is pumped into the system by ultrasonic transducer. Although the magnitude of energy is small (200 watts), it is very concentrated at the cutting zone which could be considered as a primary cause of increase in temperature.

To assess benefits and shortcomings of UAD, further investigations were made on surface roughness, hole-roundness and delamination of drilled holes. These results are discussed in the next chapter.

CHAPTER 9

POST-DRILLIGN ANALYSIS

Quality of drilled holes dependent on parameters of the drilling process such as feed rate and spindle speed. It is also strongly affected by the type of the drilling process such as conventional drilling (CD) and ultrasonically-assisted drilling (UAD). In case of composites, quality of a hole is determined by several factors such as hole-wall surface roughness, hole circularity, and delamination. Unlike metals, in carbon fibre-reinforced plastics (CFRP), these drilling defects can be classified into two categories: (i) geometric defects such as surface roughness, hole circularity and cylindricity; (ii) non-geometric defects, e.g. delamination. These defects have a detrimental effect on structures, and could adversely affect their survivability and reliability. In machining processes applied on CFRP, it is difficult to comprehend these defects because of material's anisotropy and complex drill-bit geometry. Moreover, orientation of fibres, a stacking sequence and interaction of a drill-bit cutting face with the composite makes the problem more cumbersome (Khan, 1991). Therefore, it is of prime importance to

evaluate the quality of drilled holes for any drilling technique performed with specific drilling parameters.

In this chapter, hole quality is analysed and reported. Studies of surface roughness, hole roundness and analysis of the drilled hole were carried out using a surface-roughness measuring machine, CMM (coordinate measuring machine) and micro computed tomography, respectively. A comparative study of these analyses, for UAD and CD, is presented below.

9.1 Hole circularity and diameter

For holes, circularity is defined as a sum of the distance from the least squares circle (LSC) to the highest peak and the distance from the LSC to the lowest valley (Smith , 2001). The LSC itself is defined as the circle fitted to the captured data points in such a way that the sum of the squares of the distance to the captured points is minimized. Circularity is an important parameter that determines the accuracy of the hole diameter. This parameter is also used to determine the tolerances for fit.

In this work, circularity of the holes, drilled with $\varnothing 3\text{ mm}$ and $\varnothing 6\text{ mm}$ drill bits was measured using Metris LK Ultra 627134 CMM with SP25 $\varnothing 1\text{ mm}$ and $\varnothing 3\text{ mm}$ stylus. The used setup is shown in Figure 9.1. The drilled workpiece WP1 (refer Table 7.1) was used in this study. The samples were positioned on the base-table of the CMM with the entrance face upwards. The specimens were levelled. The circularity was measured at the depth of 5 mm and 10 mm from the top surface for each hole. Then, the levels of circularity obtained for both depths were averaged. This procedure was carried out for three holes, drilled at the same drilling parameters for statistical significance. Finally, the circularity data for three holes, drilled at the same drilling parameters, was averaged again and reported. The same procedure was carried out to document the circularity for each drilling parameter mentioned in Tables 9.1 and 9.2.

Figure 9.1. Metris CMM

9.1.1 Hole circularity

The circularity, measured for both drilling techniques and corresponding improvements at each feed rate are shown Figure 9.2. It was observed that circularity of the holes was improved in case of UAD compared to CD for both sizes of the drill bit. At a lower feed rate, i.e. 0.1 mm/rev, the circularity was improved in the excess of 50%. With the increase in the feed rate, the improvement in circularity was decreased to 30%. It was found that the magnitude of circularity increased, almost linearly, with the increase in the feed rate in both cases, i.e. UAD and CD. However, the improvements in circularity remained considerable at each feed rate. Although, the drilling forces (in case of UAD and CD) had effectively the same magnitude beyond the feed rate of 0.4 mm/rev, considerable improvements in circularity were still found.

The magnitude of circularity, for a large diameter of the drill i.e. $\varnothing 6$ mm, was higher than that for the lower diameter drill bit. However, the improvements, with UAD, were also observed. Similarly, in case of the $\varnothing 6$ mm drill bit, the magnitude of circularity increased linearly (under CD) with the increase in the feed rate as for $\varnothing 3$ mm. In

contrast to UAD with $\varnothing 3$ mm drill bit, in case of with $\varnothing 6$ mm; the magnitude of circularity became almost constant beyond the feed rate of 0.2 mm/rev (see Figure 9.2).

(a)

(b)

Figure 9.2. Circularity CD vs. UAD for: (a) $\varnothing 3$ mm; (b) $\varnothing 6$ mm

The measured hole profiles for the $\varnothing 6 \text{ mm}$ holes drilled at 0.4 mm/rev , for both UAD and CD, are shown in Figure 9.3. Figure 9.4 shows the measured profile at 0.2 mm/rev and 0.4 mm/rev for $\varnothing 3 \text{ mm}$ drill bit. In case of CD, the profile demonstrates wide-spread spikes. Whereas, in UAD, the spikes are comparatively shorter and the hole profile is much smoother compared to CD-holes. This could be due the orientation of the fibres at those particular depths. It was investigated that the fibre orientation could affect the hole profiles (Chatelain et al., 2012).

Figure 9.3. Circularity profiles at 10 mm depth for $\varnothing 6 \text{ mm}$ drill bit at 0.4 mm/rev and 40 rpm

The smoother profile could be a result of the material removal in the form of chip, under the influence of vibrations in UAD (refer Section 8.3). Whereas, in CD, the removed material was in the form of a powder: Under optical microscope this powder was observed and it was found that it consisted of fragmented fibres and thick powder of resin in the form of micro-chunks (see Figure 8.6). When these micro-chunks were removed from the drilled composite, they left behind cavities in the materials at micro-

scale. These cavities resulted in deeper voids and spikes in case of CD compared to UAD.

Figure 9.4. Circularity profiles at 10 mm depth: CD vs. UAD with $\varnothing 3$ mm at 40 rpm:

(a) CD at 0.2 mm/rev; (b) UAD at 0.2 mm/rev; (c) CD at 0.4 mm/rev; (d) UAD at 0.4 mm/rev

9.1.2 Hole diameter

The hole diameter was measured for each hole following the same procedure as mentioned in Section 9.1.1. The measured diameter for holes, drilled with $\varnothing 3$ mm and $\varnothing 6$ mm drill bits are given in Tables 9.1 and 9.2 respectively. It was observed that the hole diameter, in case of CD, is slightly less than the nominal hole values. Whereas, in case of UAD, the measured diameter is slightly bigger than the nominal diameter value.

As mentioned in Chapter 6 the drill bit winds and unwinds during the ultrasonic process, this results in radial compression and expansion of a drill bit, which in turns increases the size of a hole. Explaining further, in FE model, that when the pre-twisted structure vibrates in longitudinal direction, the pre-twisted structure inherently vibrates in torsional direction along with the longitudinal one i.e. the longitudinal vibrations are overlapped by the torsional vibrations. The cycles of expansion and contraction are dependent on the vibration frequency of the drill bit. As the drill bit expands, the diameter of hole slightly increases from the nominal value. It can be seen from Tables 9.1 and 9.2 that, under UAD, although the hole's diameter is slightly bigger, it is more precise. However, in case of CD, the measured diameter values are less precise and less accurate. Moreover, the deviation of the measured values from mean value is higher in case of CD compared to UAD.

Table 9.1. Measured hole diameters for Ø3 mm drill bit

Drilling process	Nominal diameter(mm)	Feed rate (mm/rev)	Measured diameter (mm)
CD	3.00	0.1	2.9901 ± 0.018
	3.00	0.2	2.9885 ± 0.021
	3.00	0.3	2.9878 ± 0.026
	3.00	0.4	2.9926 ± 0.023
	3.00	0.5	2.9981 ± 0.025
UAD	3.00	0.1	3.0450 ± 0.011
	3.00	0.2	3.0429 ± 0.013
	3.00	0.3	3.0421 ± 0.015
	3.00	0.4	3.0493 ± 0.012
	3.00	0.5	3.0425 ± 0.016

Table 9.2. Hole measured-diameter for Ø6 mm drill bit

Drilling process	Nominal diameter(mm)	Feed rate (mm/rev)	Measured diameter (mm)
CD	6.00	0.1	5.9864 ± 0.015
	6.00	0.2	5.9802 ± 0.021
	6.00	0.3	5.9621 ± 0.019
	6.00	0.4	5.8722 ± 0.022
	6.00	0.5	5.9881 ± 0.017
UAD	6.00	0.1	6.0601 ± 0.018
	6.00	0.2	6.0692 ± 0.020
	6.00	0.3	6.0663 ± 0.014
	6.00	0.4	6.0698 ± 0.019
	6.00	0.5	6.0683 ± 0.023

To avoid the oversizing in UAD drill bits with diameter 50 µm less than the original size can be used so that the hole of accurate size could be drilled.

It is reported in Section 7.3 that the difference in the drilling forces (CD vs. UAD) diminishes at feed rate of 0.5 mm/rev for both sizes of drill bits. However, the accuracy and precision of the holes, drilled with UAD, remains unaffected, i.e. the diameter precision was improved.

Hole circularity and hole roundness are important parameters for the hole quality, however, for assembly fitting another parameter i.e. surface roughness is also of prime importance which is explained below;

9.2 Surface roughness

The quality of drilling process can be evaluated on the basis of surface roughness. Ultrasonically-assisted machining is known to improve the surface quality of machined surfaces. UAD also improved the surface quality of difficult-to-machine alloys as well as brittle materials. UAD renders the process of brittle materials machining more similar to that of ductile materials (see Section 8.4).

Generally, the surface geometry follows a repeated pattern. However, there are several deviations from the ideal surface due to different reasons such as tool chatter, material inhomogeneity and tool wear (Sheikh-Ahmad, 2009). These deviations are referred as waviness, lay, flaw and roughness (Groover, 2010), which are described below:

Waviness is reoccurring of large spacing deviation. Waviness is usually greater than 0.1 mm. This is a result of vibration and chatter of the tool.

Lay represents the predominant surface-texture direction. It is usually a microscopic contour.

Flaws are irregularities such as scratches and cracks.

Roughness is a regularly spaced deviation from the nominal surface which is determined by material properties and parameters of a manufacturing process. Roughness is a result of tool shape and feed rate.

These surface-texture parameters are shown in Figure 9.5.

Figure 9.5. Surface texture parameters (Sheikh-Ahmad, JY, 2009)

Surface roughness is, generally, measured by two methods: (i) contact method, in which stylus is used, (ii) a non-contact method. However, both methods are used to evaluate the same parameters. A number of surface-roughness parameters is used to evaluate the surface quality of machined parts. 1D surface roughness parameters such as R_a , R_z and R_q were used in literature to quantify the surface roughness. These parameters offer a reasonable statistical significance and information about the surface.

R_a is the arithmetic filtered roughness deviation with respect to the centre line along the evaluation length. This average value does not provide any information about the peaks and valleys present in a surface profile (see Figure 9.6) (Gadelmawla et al., 2002). A mathematical form of R_a is given by;

$$R_a = \frac{1}{L} \int_0^L |y(x)| dx, \quad (9.1)$$

where L is the measurement length and $y(x)$ is the position of the profile with respect to the centre line.

R_z is the difference in height between the average of the five heights (p_i) and five valleys (v_i) in the measured profile. This parameter is comparatively more sensitive than R_a . It is expressed as;

$$R_z = \frac{1}{n} \left(\sum_{i=1}^n p_i - \sum_{i=1}^n v_i \right), \quad (9.2)$$

where n is number of points.

R_q is also a root mean square, it is a standard deviation of the surface-heights distribution. It provides a higher weight to large deviations from the mean centre line; therefore, it is more sensitive than R_a .

$$R_q = \sqrt{\frac{1}{L} \int_0^L [y(x)]^2 dx} \quad (9.3)$$

Some other parameters such as R_{10} and S_{pd} are also used to evaluate surface roughness. Although the deviation of the mean average surface from the reference line is of high importance, the magnitude of peak height (R_p) and valley depth (R_v) from the reference line is also considered as vital in some cases.

In this research Taylor Hubson CLI 2000 machine was used to measure the values of surface-roughness parameters. R_a , R_z and R_q . The machine was capable of measuring the parameters using both contact and non-contact measurements; here, both methods were used to evaluate the significance of each method. After a series of experiments, it was observed that both methods measured the roughness with nearly the same accuracy. The non-contact method was chosen to measure the surface roughness, since the fibres could affect the path of the stylus hence, it was preferred to use non-contact method.

Holes drilled with the $\varnothing 3$ mm drill bit were examined with regards to surface roughness. The drilled holes, after circularity and roundness tests, were cut into half. It was done to project the light on the hole wall surface. It was made sure that all the measurements were taken along the same length of hole surface. Axial surface roughness was measured along two paths on each side of the cut hole. These two values were then averaged for one hole.

(a)

(b)

(c)

Figure 9.6. Surface roughness parameters (Sheikh-Ahmad, 2009) (a) R_a ; (b) R_z ; (c) R_q

All three drilled holes, at same parameters, were measured using same method. The roughness parameters for these three holes, at each drilling parameter, were then again averaged and reported here. The probe was travelled for the length of 12 mm, leaving 1.5 mm on each side for delamination not to influence the measurements. The measured values of surface roughness are given in Table 9.3. The extent of improvement of UAD with respect to CD, for each measure parameter, is shown in Figure 9.7 (a).

Table 9.3. Axial surface roughness for Ø3 mm drill bit at 40 rpm

Feed rate (mm/rev)	R_a (μm)		R_z (μm)		R_q (μm)	
	CD	UAD	CD	UAD	CD	UAD
0.1	1.57 ± 0.4	0.83 ± 0.3	12.34 ± 3.4	9.64 ± 2.9	1.94 ± 0.5	1.21 ± 0.4
0.2	1.75 ± 0.4	1.03 ± 0.4	15.35 ± 3.4	15.35 ± 3.2	2.54 ± 0.6	1.74 ± 0.5
0.3	2.02 ± 0.5	1.34 ± 0.5	17.24 ± 3.8	17.24 ± 2.8	2.77 ± 0.6	1.98 ± 0.4
0.4	2.36 ± 0.5	1.64 ± 0.4	19.24 ± 3.6	19.24 ± 3.1	2.96 ± 0.5	2.34 ± 0.3
0.5	2.48 ± 0.5	1.72 ± 0.3	20.54 ± 4.1	16.98 ± 3.5	3.14 ± 0.7	2.48 ± 0.4

It can be seen from Figure 9.7 (a) that improvement in R_a at lower feed rate was in the excess of 50%. With the increase in feed rate the percentage improvement decreased to 30%. Similar to hole circularity, the improvement in surface roughness was observed beyond the feed rate where no improvements in drilling forces were observed. The improvement in surface roughness (R_a) was evaluated as 30% even at higher feed rate. Surface roughness parameter, R_z , showed the minimum improvement compared to other parameters i.e. R_a and R_q . However, the improvement in R_z was almost consistent i.e. in the access of 17% , at each value of feed rate. Similar pattern in improvements

were observed with $\varnothing 6$ mm drill bit. A little variation was observed in R_z and R_q percentage improvement. However, the improvements in R_a were observed to be almost similar. The percentage improvements for $\varnothing 6$ mm are shown in Figure 9.7 (b).

(a)

(b)

Figure 9.7. Improvements in surface roughness due to UAD $\varnothing 3$ mm (a) $\varnothing 6$ mm and (b) drill bit

It was evaluated that the percentage improvements in R_q varied from 20% at higher feed rate to 40% at lower feed rate. The improvements in UAD-surface roughness showed that surface roughness under UAD is independent of thrust forces.

9.3 Delamination analysis

One of the major concerns in drilling of CFRP is delamination. Determination of the size of delamination zones after drilling is essential in assessing the effectiveness of UAD in comparison to CD. To measure delamination, micro-computed tomography (μ CT) was conducted for quantification of the damaged area in CFRP in the vicinity of the drilled hole. The X-tech System™ XTH-160 machine was used for this purpose. Each sample was exposed to X-ray radiation and rotated by 360° about a vertical axis to capture the images for 3-D re-construction. The X-ray voltage and current were set at 80 kV and 75 mA, respectively.

Delamination was measured at the hole entry and exit as a 1D delamination factor (F_D). A nominal diameter (D_{nom}) and a diameter (D_{max}) of the circle that enclosed the whole damage area are measured and reported here (see Figure 9.8). The delamination factor was evaluated using equation following equation:

$$F_D = \frac{D_{nom}}{D_{max}} \quad (\text{eq. 9.1})$$

Analysis of composite plies near the drill entry and exit demonstrate significantly reduced delamination zones after UAD when compared to those in CD (See Figure 9.9).

Delamination was measured for the $\varnothing 6$ mm drill bit hole and the results are reported in this section, whereas, the results of delamination for $\varnothing 3$ mm drill bit are reported and discussed in detail in Section 9.4.5. Delamination was measured for three holes at the

same drilling parameters and the average values of entry and exit delamination are reported here. The maximum delamination, in case of UAD, was observed at 0.4 mm/rev . This is shown in Figure 9.9. For visual display, the defect area is presented in red.

Figure 9.8. Delamination measurement (Khashaba, 2004)

A plot for the delamination factor at different feed rates is shown in Figure 9.10. A further comparison of delamination factors revealed that delamination increased with the increase in the feed rate. It was observed that the exit delamination was higher in both cases, i.e. CD and UAD, compared to the entry delamination. At feed rate of 0.5 mm/rev , unlike surface roughness and hole roundness and similar to the drilling forces, delamination almost became similar for both CD and UAD. This finding shows that the results reported here are in line with the previous research, i.e. delamination is a direct result of drilling forces (Pyo Jung, 2005; Kim and Lee, 2005; Tsao, 2012).

Figure 9.9. Delamination damage: (a) CD – entry delamination; (b) UAD – entry delamination; (c) CD – exit delamination; (d) UAD – exit delamination

Circularity, hole roughness and delamination are important to examine the quality of drilling. However, these parameters related to workpiece are also affected by quality of tool. Therefore the importance of tool quality cannot be neglected. As tool wears out with the time, hence, it is important to study the tool wear.

Figure 9.10. Delamination measurement factor: (a) entry delamination factor; (b) exit delamination factor

9.4 Tool wear

This part of the research was carried out together with Mr. Arth Mistry, undergraduate student at Loughborough University. The results, reported here, are a collective effort of the experimental work carried out, mentoring and supervision provided for the final-year of Mr Mistry.

Wear is the damage caused to the solid surface resulting in a progressive material loss due to relative motion of the surface and a contact substance. Wear, generally, leads to the change in dimensions and geometry of the subjected tool. This can even result in failure of the workpiece or the tool (Gwindon, 2005; Raymond, 2004). It was reported that the tool wear influenced directly the surface finish and integrity of components. When the tool is repetitively used for any machining operation, it loses its sharp edges. As discussed in Section 3.3.3, the tool life depends on several parameters such as workpiece material, tool material, tool geometry and speed of machining process. Different combinations of these parameters also influence the increase in a localized temperature gradient. This results in rapid tool wear, and the tool life is adversely affected (Raymond, 2004).

Tool failure occurs due to three main reasons: (i) fracture failure; (ii) temperature failure and (iii) gradual wear. Fracture and temperature failure occur due to high temperature and high stress concentration that accumulate at the workpiece and tool interaction surface. These types of failure result in brittle fracture or tool softening, whereas, gradual wear leads to loss of tool material and bluntness of the tool edges. As a result, the cutting efficiency decreases and cutting forces increase (Groover, 2010).

In the twist drill bit, cutting lips and a chisel edge are prone to wear. As these parts of a drill bit are responsible for cutting operation, therefore they experience high localized temperature and stress concentration. A rake face also suffers some tool wear due to friction between a chip and a rake face. The drill bit edges that are affected by wear are shown in Figure 9.11.

In our case, wear was measured on the front face (see Figure 9.12) as a volume of material lost during the drilling process (explained below). This was carried out using the Alicona InfinteFocus Standard system. This machine is a 3D light optical microscope, which uses focus-variation to obtain 3D images of a scanned object. The objective was adjusted to focus at the object. This objective collects the reflected light from the object and constructs a 3D image. The collected 3D data was processed using Alicona IFM 3.5.01 software.

Figure 9.11. Drill bit faces prone to wear (Thomas, 2007)

Different objectives were provided with the machine, offering resolution ranging from 10 nm to several hundreds of micrometres. However, for our experiments, the objective $5\times$ with a resolution of $23.48\text{ }\mu\text{m}$ was used. This objective was chosen after preliminary experimentation; the selection of objective was a compromise between the accuracy of wear measurements and noise reduction. As the machine scans the images, light is reflected in different ways from the drill-bit faces (see Figure 9.12). This

resulted in the noise and, as a result, artificial voids of the volume. The higher the resolution, the higher the noise.

A special fixture was manufactured to hold the drill bit in fixed position. The drill bit was marked on one side so that the scan can be started from the same reference point after a successive number of drillings; this fixture is shown in Figure 9.13. To minimise the noise, present in the scans, a polarizer and ring-light options were used.

Figure 9.12. Drill-bit face for measurements of volume

The measurement module “Difference Measurement” of the software was used after preliminary experiments. This allows the user to find a difference between two measured volumes. In this module, one scan is superimposed over another. The difference in volume is evaluated by the subtraction of a smaller volume from a bigger volume. A virgin drill bit was scanned first as a reference scan. The scan of a worn drill bit was then superimposed over the virgin one and the difference in volume was evaluated. This difference in volume, is reported here, as a wear parameter.

Figure 9.13. Fixture for scanning: tool wear of drill bits

For significance of results, a series of preliminary wear measurements were taken for a virgin drill bit. The purpose was to scan virgin drill bit several times and match the scans with a minimum possible error. Ideally, the two scans should have a zero difference. However, when the datasets of one scan were superimposed on the other scan, a difference in volume was recorded as $223204 \mu\text{m}^3$ (i.e. around 0.22 mm^3). This procedure was carried out for five times. It was observed that this difference, in the scans, cannot be minimised. The difference of these five values was averaged. The average value was $225907 \mu\text{m}^3$. This averaged value was subsequently subtracted from the measured values of tool-wear volume as a zero correction for misalignment. After selecting the objective lens and the software module, the drilling experiments were planned.

Four Jobber Carbide Guhring SL 5517 $\varnothing 3 \text{ mm}$ drill bits were used during these experiments together with workpiece WPI (see Table 7.1). The workpiece was cut into

10 mm strips. A specially designed fixture was employed to hold the workpiece on the force-measuring dynamometer (see Figure 9.14).

Figure 9.14. Setup and fixture for workpiece-drilling experiments

The measurements for thrust force, torque, axial surface roughness, hole circularity, delamination and tool wear were taken at six distinctive points. These points were at hole number 1, hole number 10, hole number 20, hole number 30, hole number 40 and hole number 50. All the experiments were conducted at 40 rpm . Two magnitudes of feed rate, i.e. 0.2 mm/rev and 0.4 mm/rev , were applied in the same manner as discussed in Section 7.2. For each feed rate, experiments were carried out for UAD and CD to compare tool wear and analyse its effect on surface roughness, circularity, delamination and drilling forces. The tuned frequency was observed at 33.03 kHz and the amplitude was recorded as $10.4 \mu\text{m}_{\text{peak-peak}}$. Two holes were drilled at each drilling parameter for reproducibility check; this was suggested based on the preliminary drilling experiments. It should be noted that preliminary drilling tests and

wear measurement experiments represent two distinctive sets of experiments. The experimental matrix is given in Table 9.4.

Table 9.4. Experimental matrix: spindle speed 40 rpm

Technique	Feed rate (<i>mm/rev</i>)	Hole numbers
CD	0.2	0, 10, 20, 30, 40, 50
UAD	0.2	0, 10, 20, 30, 40, 50
CD	0.4	0, 10, 20, 30, 40, 50
UAD	0.4	0, 10, 20, 30, 40, 50

1234567891011121314151617181920

Hole number

9.4.1 Volume lost: tool wear

As described, the tool wear was measured using the Alicona system. The results of tool wear at 0.2 *mm/rev*, in terms of volume lost, are shown in Figure 9.15. It can be seen that tool wear after 10 holes in case of UAD is higher than CD. From the hole number 30 to hole number 50, the wear is smaller in UAD as compared to CD. Finally, after 50 holes, the tool used for CD was worn out more compared to that was used in UAD. When the volume lost was evaluated at hole number 30, it appeared as if the tool has gained some volume. This could be due to the accumulation of CFRP dust on the drill bit or misalignment of the drill bit during scanning. It can be concluded that practically no volume was lost from hole number 20 to hole number 50 in case of UAD. This trend of tool wear at 0.2 *mm/rev* reveals that the tools used for CD are prone to more wear compared to UAD after a considerable number of holes.

It can be seen that the volume of the tool in CD, was lost between hole number 10 to hole number 30. It remained nearly constant from hole number 30 to hole number 50.

Figure 9.15. Drill bit volume lost at 40 rpm and 0.2 mm/rev

The results of drill-bit wear at 0.4 mm/rev are shown in Figure 9.16. Compared to the lower feed rate, a different trend in material loss was observed. It is obvious that as at a higher feed rate higher drilling forces are expected to be experienced by the drill bit; therefore a higher material loss was expected.

In case of CD compared to UAD, the loss of drill-bit material was higher from hole number 20, and no loss in material was observed up to hole number 40. When the volume of drill bit face was measured again after 50 holes, the significant loss in material was observed. However, it can be considered that the smooth curve from hole number 20 to hole number 40 at this feed rate followed the same trend as observed for 0.2 mm/rev from hole number 30 to hole number 50 in case of CD (refer Figure 9.15). Both in Figure 9.15 and Figure 9.16, for CD it can be seen that after losing material

volume in the excess of $5 \times 10^6 \mu m^3$, the drill bit did not experience any material loss for next 20 to 30 holes.

Figure 9.16. Drill bit volume lost at 40 rpm and 0.4 mm/rev

In case of UAD for feed rate of 0.4 mm/rev, no material loss was observed from hole number 10 to hole number 30. The material loss after 10 holes was higher, in UAD compared to CD. The magnitude of volume lost under UAD, after which the drill bit experiences no material loss i.e. 0.0044 mm^3 , is nearly the same at both values of feed rates. This level was achieved for hole number 20 for 0.2 mm/rev and for hole number 10 at 0.4 mm/rev. This indicated that once the drill bit lost a specific amount of material from the drill-bit surface, the drill bit experienced no loss in material volume for approximately next 30 holes in both CD and UAD.

It can be summarised that, overall volume lost in case of CD is higher compared to UAD at both rates. In both cases i.e. UAD and CD at each values of feed rate, there is a magnitude of volume lost after which no loss in material volume was experienced for next 30 holes.

9.4.2 Drilling forces vs. tool wear

Thrust force and torque were measured with respect to tool wear in the same manner as explained in Section 7.2 and reported here. Unlike the volume lost by the drill bit, the thrust force and torque were measured for each hole. The thrust force in case of CD and UAD at both mentioned feed rates is shown in Figure 9.17. It was observed that the thrust force increased linearly with the number of holes at both values of feed rate, in case of CD. Although, for UAD, the thrust force increased with the increase in the number of holes, the increase was not as steep as in case of CD. For UAD, it can also be seen that the value of thrust force remain almost at the same magnitude as for feed rate of 0.2 mm/rev. The increase in thrust force was observed with increase in the hole number at 0.4 mm/rev. However, the slope of thrust force increase in case of UAD is negligible as compared to the slope of CD at both feed rates

A similar trend was observed for the torque. The gradual increase in the thrust force and torque, with the increase in the feed rate, was found at both feed rates, in case of CD. Compared to the thrust force, for UAD, the torque value increased with the increase in the hole number. However, the slopes of CD-torque are steeper than those of UAD-torque at both feed rates.

From Figure 9.17 (a) and Figure 9.17 (b) it can be observed that the CD-thrust force and CD-torque increased with the increase in tool wear. Similarly, UAD-thrust force and torque increased with the increase in tool wear. However, the effect of volume lost of the drill bit on UAD-forces was not as significant as it was for CD-forces.

(a)

(b)

Figure 9.17. Evolution of thrust force (a) and torque (b) with number of drilled holes

9.4.3 Hole circularity vs. tool wear

Circularity of the holes was measured following the same procedure as explained in Section 9.1.1. However, it was measured at the depths of 2, 4 and 6 mm from the top surface. The average value of circularity, at the mentioned values of depths, is reported here.

Circularity, at feed rate of 0.2 mm/rev is shown in Figure 9.18 (a). It can be seen that it increased with the increase in the number of holes for both CD and UAD. It was also observed that circularity increases with the increase in the depth for CD. For example, after 20 holes, the circularity at 2, 4 and 6 mm depths was measured as 0.0215, 0.0573 and 0.0974 μm , respectively. Similarly, after 40 holes at the same value of depths the following data were recorded for circularity: 0.0238, 0.0881 and 0.1606 μm in both CD and UAD.

The levels of circularity, at 0.4 mm/rev are shown in Figure 9.18 (b). It can be seen that circularity, in case of CD, increased highly after 30 holes. This was caused by higher delamination at entry. Due to delamination, the stylus measured the values of circularity with considerable error. This effect of delamination on circularity is shown in Figure 9.19. The measured circularity for CD and UAD at 0.4 mm/rev at 6 mm depth from top surface for 50 numbers of holes is given in Table 9.5.

Table 9.5. Circularity at 0.4 mm/rev and 6 mm depth from top surface

Hole number		1	10	20	30	40	50
Circularity(μm)	CD	0.0234	0.1099	0.1233	0.2021	0.2208	0.3862
	UAD	0.033	0.037	0.1201	0.1249	0.1316	0.1859

Figure 9.18. Evolution of circularity with number of drilled holes at 0.2 mm/rev (a) and 0.4 mm/rev (b)

Figure 9.19. Circularity measurement error due to delamination

9.4.4 Hole roughness vs. tool wear

Following the same methodology, as in Section 9.2., surface roughness was measured for holes number 1, 10, 20, 30, 40 and 50 at both values of feed rate. The measured values of surface roughness R_a are reported here.

Surface-roughness plots with respect to the number holes, at both feed rates, are shown in Figure 9.20 (a) and Figure 9.20 (b). Surface roughness increased with the increase in the hole number at both feed rates. For feed rate of 0.2 mm/rev , the difference in surface roughness between UAD and CD was higher compared to that for 0.4 mm/rev . The maximum improvement, for surface roughness (i.e. UAD vs. CD), was observed at 0.2 mm/rev from hole number 20 to hole number 30. The maximum improvement in roughness, in case of UAD was observed in the excess of 40%.

The measured values of surface roughness and value to volume lost (tool wear) showed that the surface roughness increases with the increase in the hole number at both feed rates.

(a)

(b)

Figure 9.20. Evolution of axial hole roughness with number of drilled holes at 0.2 mm/rev(a) and 0.4 mm/rev (b)

9.4.5 Delamination vs. tool wear

For the study of tool wear related-delamination, the latter delamination was measured using Alicona, using its module “2D-Image Measurement”. This module enables the user to capture a 2D image and take the measurements i.e. length, width and diameter. Delamination was measured at hole’s entry and exit as a 1D parameter delamination factor (F_D) in the way as discussed in Section 9.3. Delamination reported here was measured for hole number 1, 10, 20, 30, 40 and 50, both at entry and exit, for UAD and CD at both values of feed rate.

At feed rate of 0.2 mm/rev

It was observed that the entry delamination factor was lower than that for exit at both values of feed rate and for both drilling techniques; the comparison is shown in Figure 9.21. The entry and exit delamination, in case of CD, became almost equal after 50 holes. The value of delamination factor for entry and exit, after 50 holes with $F_d = 2.76$.

The difference in entry delamination for CD and UAD was not high up to 30 holes. As the drill bit was used for more holes the entry delamination increased. The difference in entry delamination factor for CD and UAD, up to 30 holes, was evaluated as 0.22; however, it increased to 1.17, when it was measured for hole number 50. Still, in case of UAD, the entry delamination was higher in the beginning. After 30 holes, delamination was almost the same, and it increased at exit in the end. This could be due to the reason that the drilling forces, in case of CD, crossed the threshold value of forces which resulted into increased delamination; whereas, in UAD the forces almost remained same for test matrix therefore the value of delamination almost stayed at same level. The threshold drilling forces and delamination was also addressed by Karnik et al. (2008), Tsao and Chiu (2011) and Qi et al. (2013).

Comparing entry and exit delamination for CD and UAD, it was observed that they were lower for UAD compared to CD at each measurement interval. For example, the hole-entry delamination factor, for CD, varied from 1.38 to 2.76 from hole number 1 to

50. In case of UAD, it varied from 1.23 to 1.57. Similarly, the hole-exit delamination factor, for CD was measured as 2.36 and 2.76 for hole number 1 and 50, respectively. For UAD, for the same number of holes, the respective values of delamination factor were evaluated as 1.13 and 2.06. From this it can be concluded that UAD is by 10% to 45% safer at this feed rate, for any hole number, compared to CD.

Figure 9.21. Evolution of hole entry delamination with number of drilled holes

At feed rate of 0.4 mm/rev

The delamination factor, at hole entry and exit, relative to the hole number was plotted and is presented in Figure 9.22. It can be seen that the hole-entry delamination factor, in both CD and UAD, did not change much compared to the one for hole exit. It was observed for UAD this factor did not exceed the value for hole entry in CD. This shows that delamination, in case for UAD, was lower at each measurement interval. After 50 holes, the hole exit delamination factor in UAD was much lower than that in CD. The

corresponding exit values for UAD and CD were calculated as 3.13 and 5.54. From these values of, it can be considered that UAD was 36 to 76% safer than that of CD at 0.4 mm/rev.

Figure 9.22. Evolution of hole entry delamination with number of drilled holes

Generally, it can be concluded that UAD is a safer process, in case of delamination. From lower to higher feed rate i.e. from 0.2 mm/rev to 0.4 mm/rev, the improvement in delamination thanks to UAD changed from 10 to 76%, for both exit and entry delamination. The minimum improvement was at hole entry for hole number 1; the maximum improvement was observed for exit delamination after 50 holes. The experiments also revealed that at the higher feed rate, delamination increased adversely in case of CD with respect to the increase in the hole number. The maximum change in the delamination factor, from hole number 1 to hole number 50 was observed for CD at

hole exit at feed rate of 0.4 mm/rev, i.e. from 2.18 to 5.74. However, the change in delamination for UAD at the same parameters was observed from 1.25 to 3.14.

It can be also concluded that UAD reduces delamination and improves surface roughness and hole circularity. The hole diameter was observed slightly higher than that of CD; however, it was more precise. The exact dimensions of a hole could be achieved by selection of a slightly undersize drill bit in order to compensate the margin.

The study on of tool wear suggested that the drilling forces significantly increased with the increase in number of holes in case of CD. However, in UAD, the increase in drilling forces was lower compared to CD. Delamination was found to be decreased in case of UAD with increase in drilled hole number; whereas in CD, the increase in delamination was significantly higher than that of in UAD.

9.5 Discussion

In the first of this chapter, the quality of holes, drilled with UAD and CD, was analysed by measuring the circularity, roughness and delamination. It was observed that the circularity and surface roughness of the holes drilled with UAD was improved compared to the ones drilled with CD. The improvements in circularity and surface roughness were observed beyond the feed rate of 20 mm/min where the ultrasonic vibration seemingly disappeared and drilling process mimics CD. However, in case of delamination, the improvements disappear at 20 mm/min feed rate and the same level of delamination were observed for both CD and UAD. This is because the drilling forces became equal in both cases i.e. CD and UAD, and there is threshold of drilling forces for delamination to initiate (mentioned in Chapter 3).

In the second half of this chapter, tool wear caused by UAD was measured for UAD and compared with CD. This was done by measuring the volume lost of the drill bit after 50 holes for both CD and UAD. Although, the volume lost was measured with caution, it could not be measured with an accuracy because of the shiny surfaces of the drill bit. However, after drilling 50 holes, it was observed that the volume lost in CD was higher

than the one measured for UAD. Alternatively, indirect methods of estimating the tool wear, was used in which surface roughness, circularity, delamination and drilling forces were measured and recorded for both UAD and CD for 50 number of holes. The delamination, surface roughness and circularity was measured after 10 number of holes in each case, whereas, the drilling forces were recorded for each hole. Similar to volume lost, the wear in case of Cd was observed higher with this indirect method. The drilling forces recorded for UAD were considerably low compared to CD. This implies that the damage sustained in UAD after 50 holes was less. This lower damage was observed in the form of improved surface roughness, circularity and delamination after 50 holes.

To compare the mechanical perforce of the holes, drilled with CD and UAD, was attempted to measure using both nano and micro indentation tests. However, this was not successful because the indenter could not make any impression on the surface. Several attempts were made; however, the hardness was difficult to be measured. One of the images after indentation is presented in Figure 9.23. It can be seen that there is no impression on the surface. This could be due to the softness of the polymer matrix which failed to record any impression. However, from the overall study, the quality of holes drilled with UAD was improved compared to CD.

Figure 9.23: Hole wall surface: unable to record any indent.

CHAPTER 10

CONCLUSIONS AND FUTURE WORK

10.1 Conclusions

In this study, UAD was used to drill CFRP and the obtained results were compared with those for CD. A substantial reduction (in excess of 90%) was observed compared to CD. This was achieved by improving a drilling transducer design. Three new transducer systems were manufactured to accommodate Ø3 mm, Ø6 mm and Ø12 mm drill bits. The experiments were conducted at 40 rpm and up to 20 mm/min feed rate. Reduction for drilling forces, in excess of 90%, was observed in UAD compared to CD for Ø3 mm and Ø6 mm drill bits; whereas, reduction for Ø12 mm drill bit was in excess of 50%. To investigate the cause of forces reduction, hot-CD was carried out and, FEA results of UAD and CD produced by Mr Vaibhav Phadnis were compared with the experiments, and it was found that in case of UAD the tool is in contact with the workpiece for some 10% of the drilling time. Therefore, the tool does not experience any forces for the rest of time in UAD compared to CD where the tool is in a permanent contact. Hot-CD and FEA revealed that the increased temperature in UAD reduces the drilling forces in the

excess of 35% to 45% and the tool separation reduces the drilling forces in the excess of 45% to 55%. These two types of reduction result into collective decrease of drilling forces in the excess of 90% in UAD compared to CD.

The change in chip morphology was observed at the onset of drilling process. In UAD, the drilled material material (CFRP) undergoes a complete behavioural change resulting in a transition from powder-like chips in CD to a metal-like ductile continuous chip. The cause of the material behaviour could be partially attributed to the increase in temperature in UAD.

High temperature was recorded in case of UAD as compared to that in CD. Averaged-peak temperature in case of UAD was observed as 265°C and 90°C in case of CD. The linear increase in temperature with respect to feed rate was experienced in CD; whereas, in UAD almost the same temperature was found for each level of feed rate. To elucidate the effect of high temperature in UAD, TGA of a virgin piece of CFRP was carried out. It was found that this material starts to deteriorate after 350°C. Therefore, the level of temperature rise in UAD could be considered as safe. In order to study the effect of vibration on CFRP hole quality analysis was conducted.

Chip formed during UAD and CD was analysed using optical and scanning electron microscope. Under optical microscope, continuous quasi-metal-like chip was observed in case of UAD, whereas, in CD the chip was in the form of fragments of different size. The difference in chip formation was the first visible sign noticed for UAD. The chip produced during UAD changed in thickness and pitch with the change in drilling parameters (federate and spindle speed). At the lower level of feed rate, the chip was thin and the pitch was larger, whereas, at higher feed rate, thicker chip with lower pitch was observed. However, in CD, the fragmented chip remained almost remained same in size at the drilling parameters studied in this research. Scanning electron microscopy revealed that the chips produced in UAD process were composed of broken fibres meshed (embedded) into the matrix (epoxy) material.

In hole quality analysis, the surface roughness, hole diameter, hole circularity and delamination were studied. It was found that UAD improved surface roughness and hole

quality in excess of 50%. This could be due to the fact that vibration may polish the surface as the chip removes at high temperature. In terms of the hole size, it was established that the holes drilled with CD were little undersize with regard to the nominal dimensions, and were also not precise. However, in UAD the hole size was several microns higher than the nominal size more precise. This could be explained by the fact that when the vibration is applied in the longitudinal direction to the drill bit, its face expands laterally due to inherent characteristics of the pre-twisted drill bit. In UAD delamination was found to decrease from 40% to 75% compared to that in CD. This decrease in delamination was due the lower level of drilling forces in UAD, since it is well known that delamination is directly related to drilling forces (Davim, 2003; Hocheng and Tsao, 2006). After observing the beneficial effects of vibration on the drilled workpiece, it was considered to analyse effect of drilling with UAD on the tool quality and compare it with that for CD.

Tool wear was studied for 50 drilled holes, and it was found that tool wear, in terms of volume loss of the drill-bit face, was less in UAD. However, measurements were affected by light reflections on a drill bit face. To analyse the effect of tool wear with the number of holes, drilling forces, surface roughness, circularity and delamination were studied for different stages of wear. It was observed that drilling forces increase linearly with number of hole in case of CD. However, in case of UAD drilling forces were almost the same. The increase in the thrust force and torque from approximately 300 N to 550 N and 105 N-cm to 170 N-cm, respectively, was observed for feed rate of 0.4 mm/rev in case of CD. These increased forces adversely affected the value of delamination factor; that increased from 1.94 to 3.12 at entry and 2.1 to 5.54 at exit, at the same level of feed rate; whereas in UAD the corresponding values were calculated as changing from 1.24 to 1.94 at entry and from 1.25 to 3.13 at exit. This means that the maximum value of delamination factor for UAD at the hole exit was almost equal to the maximum value of delamination factor at hole entry in CD. This effect is a direct result of a low level of drilling forces in UAD. Surface roughness and circularity also improved considerably improved with the increased number of holes in case of UAD compared to CD.

10.2 Research outcomes

FE-model was developed for the eigenfrequency analysis of ultrasonic transducer together with the drill bit.

New transducer systems were designed, optimised and manufactured for drilling of CFRP using Ø3 mm, Ø6 mm and Ø12 mm drill bits. A method was suggested to optimise a transducer for a specific application and performance.

Developed transducers were studied for the drilling performance in CFRP. Drilling parameters, for the manufactured transducers, were studied to achieve the higher level of drilling forces reduction and minimum damage. The drilling performance was compared with CD at the same parameters.

Chip formation, during UAD, was studied and compared with CD. The change in chip formation, during UAD of CFRP, was observed for the first time.

Thermal analysis was conducted to evaluate the level of temperature in both drilling process (UAD and CD) and, was compared. The increased temperature, during UAD was recorded and reported for the first time.

Tool wear was studied with both direct and indirect methods. Tool wear was quantified for the first time for UAD. This was achieved by measuring the volume lost during 50 numbers of holes and, it was compared with CD.

10.3 Future work

During this course of study several challenges related to drilling of CFRP were successfully treated, yet there are further research areas that could be addressed in order to expand the current research work. The research can be expanded:

- To develop a mathematical model for UAD on CFRP to predict the material behaviour and chip formation at different drilling parameters;
- To develop a method and equipment measuring the actual output power of transducer. the capability of the equipment could be stretched to measure the ultrasonic power at the tip of a drill bit ;
- To develop a force measurement system to record the data at the frequency higher than 40 kHz as it is important to record the impulsive response of drilled material and drill bit at ultrasonic vibration;
- To develop a dedicated tool for UAD, as standard twist drill bits are usually used during the drilling process. These drill bits are prone to failure as they cannot withstand the stresses and strains developed during ultrasonic vibration.

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