Analyzing objects in images for estimating the delamination influence on load carrying capacity of composite laminates

L. M. Durão & A. G. Magalhães
ISEP – Porto, Portugal

J. M. R. S. Tavares, A. T. Marques
FEUP – Porto, Portugal

ABSTRACT: The use of fiber reinforced plastics has increased in the last decades due to their unique properties. Advantages of their use are related with low weight, high strength and stiffness. Drilling of composite plates can be carried out in conventional machinery with some adaptations. However, the presence of typical defects like delamination can affect mechanical properties of produced parts. In this paper delamination influence in bearing stress of drilled hybrid carbon+glass/epoxy quasi-isotropic plates is studied by analyzing objects in images. Conclusions show that damage minimization is an important mean to improve mechanical properties of the joint area of the plate and the appropriateness of the image processing techniques used.

1 INTRODUCTION

1.1 *Composites drilling*

The use of composite laminates in structures has enabled a considerable weight reduction and, consequently, an improvement in their dynamic characteristics. Although the early development of these materials has been related with aeronautical and aerospace usage, recent years have seen the spread of their application in many other industries like automotive, railway, naval, sporting goods and many others.

Their widespread use is yet limited by the cost and by the difficulties found during machining and joining of parts. Although composites components are produced to near-net shape, machining is often needed, as it turns out to fulfill requirements related with tolerances or assembly needs. As these parts need to be connected to others, drilling is often used for producing holes for bolts, rivets or screws.

Drilling is a machining operation that can be characterized by the existence of two effects: an extrusion or indentation caused the drill chisel edge that has null or very small linear speed and orthogonal cut exerted by the rotating cutting edges at a certain linear speed that is the result of tool diameter and rotational rate. In fact, the cutting action is more efficient at the outer regions of the cutting lips than near drill centre, Langella et al (2005).

As composites are neither homogeneous nor isotropic this operation raises specific problems that can be related with subsequent damage in the region around the hole. The most frequent defects caused by drilling are delamination, fiber pull-out, interlaminar cracking or thermal damages. Rapid tool wear, as a result of material abrasiveness, can also be an important factor in damage occurrence. These damages cannot be disregarded as they can result in a loss of static or fatigue strength of the part, Persson et al (1997). However, delamination has been considered as the most severe problem as it reduces the load carrying capacity of composite parts and so it needs to be avoided, Abrate, (1997).

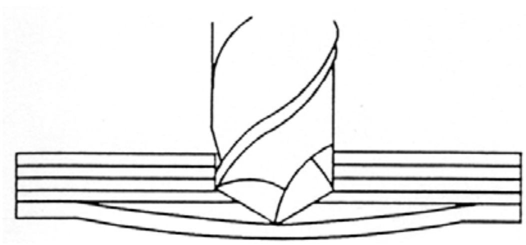

Figure 1 . Delamination mechanism (Hocheng & Dharan, 1990)

Delamination is a damage characterized by the separation of adjacent plies caused by an external action. It depends not only on fibre nature but also on resin type and respective adjacent properties. In drilling operations, delamination is a consequence of the indentation force exerted by the drill chisel edge stationary centre that acts more as a pierce than as a drill. The laminate under the drill tends to be drawn away from the upper plies, breaking the interlaminar bond in the region around the hole. As the drill approaches the end of the laminate, the uncut thickness becomes smaller and the resistance to deformation decreases. At some point, the loading exceeds the interlaminar bond strength and delamination occurs – figure 1.

Push-out delamination caused by this piercing action can be reduced if thrust force during drilling is minimized, Hocheng & Dharan (1990). The reduction of force can be accomplished by different ways and so several studies had been published with the aim to suggest alternative drilling methods to avoid delamination onset. Piquet et al (2000) listed some basic rules to be observed in drill geometry design. Tungsten carbide should be used as material, a rake angle of 6º will reduce peel-up delamination, a great number of cutting edges, up to six, will facilitate heat removal by increasing tool/part contact length. Park et al. (1995) applied the helical-feed method to avoid fuzzing and delamination. Dharan & Won (2000) proposed an intelligent machining scheme to avoid delamination. Stone & Krishnamurthy (1996) studied the implementation of a neural thrust force controller that updates feed rate every three spindle revolutions. Tsao & Hocheng (2004) compared three different drills with varying parameters and concluded for the major importance of feed rate and drill diameter on delamination. The importance of feed rate was also established by Davim et al. (2003). A comprehensive summary of the steps towards free-delamination holes can be found in Hocheng & Tsao (2005).

Another possible approach is the execution of a pilot hole in order to reduce thrust force during drilling. The pilot hole reduces the chisel edge effect on the drill thrust force and, consequently, delamination hazard. Reduction of thrust force can reach 50%, according to the work of Won & Dharan (2002). Recently, Tsao & Hocheng (2003) also studied the effect of chisel length and pilot hole on delamination. According to these authors the pilot hole diameter should be around 15 to 20% of final drill diameter to minimize delamination risk.

Finally, the use of a sacrificial backup plate, if possible, can reduce delamination by providing a support for the uncut plies of a laminate.

1.2 *Damage criteria*

After hole completion it is necessary to define delamination criteria that allow the comparison of the damage caused by different drilling parameters. Remind that, due to the unique nature of composites, such comparison is only valid to plates fabricated according to identical stacking sequence, same type of reinforcement fibre and identical fibre fraction. Two ratios were established for damage evaluation.

The first is *Delamination Factor* (F_d), Chen (1997), proposed as a quotient between the maximum delaminated diameter (D_{max}) and hole nominal diameter (D),

$$F_d = D_{max} / D \quad (1).$$

The second is *Damage Ratio* (D_{RAT}), Mehta et al (1992). It was defined as the ratio of hole peripheral damage area (D_{MAR}) to nominal drilled hole area (A_{AVG}),

$$D_{RAT} = D_{MAR} / A_{AVG} \quad (2).$$

Both criteria are based on the existence of digitized damage images obtained by radiography, ultrasound inspection or computerized tomography that must be analyzed using suitable image processing techniques, Tsao & Hocheng (2005). Those techniques can be pixel counting of digitized areas or direct measurement on the images or even on the part, if material is not opaque.

1.3 *Bearing test*

The main purpose of hole making in a plate is the possibility to assemble it to different parts in a structure. As parts will be subjected to efforts during service that will cause stress at the hole surrounding area, it is important for design engineers to know the load carrying capacity of the connection. That can be analyzed by a bearing test according to *ASTM D5961-01, procedure A*, which determines the load bearing response of multidirectional polymer composite laminates reinforced by high-modulus fibers. The results from this test, whose are believed to be affected by machined hole quality, will enable to compare different drilling options and determine the relative influence of delamination.

1.4 *Hybrid laminates*

The term hybrid refers to a composite that has more than one type of fibre or matrix in its construction. One of the main attractive when using hybrids is their synergy effect or 'hybrid effect'. A certain property, like tensile strength, will have a final value higher than the one predicted by the rule of mixtures. Hybrids present unique features that can be used to meet design requirements in a cost-effective way. Some of these advantages are balanced strength and stiffness, reduced weight or cost, improved fatigue or impact resistance and others, Schwartz (1988). Sometimes, a negative effect may also occur, Bader (1994).

Among the several type of hybrid composites, this work will deal with interply hybrids (figure 2), that consist of plies from two or more different unidirectional composites (carbon/epoxy, glass/epoxy) stacked in a specific sequence. This combination of carbon and glass fibres is referred as a good mix, as price and mechanical properties can be balanced according to designer needs.

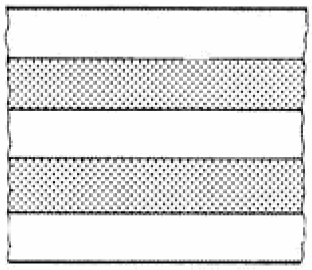

Figure 2 . Interply hybrid (Bader, 1994)

2 EXPERIMENTAL WORK

2.1 *Materials and tools*

In order to perform the experimental work, a batch of hybrid composite plates using carbon/epoxy and glass/epoxy pre-preg materials was made. The stacking sequence - $[(0/-45/90/45)_C/(0/-45/90/45)_{3V}]_s$ - has the purpose of obtaining quasi-isotropic properties in the plates to be drilled and an optimization of characteristics combining glass fiber reinforced plies with carbon fiber reinforced plies. In fact, when comparing properties of plain glass/epoxy plates with these hybrid plates – table 1 – it is possible to observe that a percentage of 25% of carbon/epoxy plies has enabled an analogous increase of tensile strength and modulus and a great increment of flexural modulus, which is the most interesting feature. In order to have this increase in flexural modulus it is important that the material with higher flexural strength, carbon/epoxy in this case, is located at the outer plies of the laminate. The opposite option, that is to say with carbon/epoxy plies in the middle of the laminate, will be better for delamination reduction, keeping the same tensile properties but the increase of flexural modulus will be merely 10%.

Table 1. Properties of quasi-isotropic plates.

Material	R_m MPa	E GPa	ν	E_{fl} GPa
Gl/Ep	394	21.8	0.53	25.7
Hybrid	454	27.8	0.49	43.2
Carbon/Ep	771	49.9	0.51	130

All the plates used for comparison had a stacking sequence with the purpose of obtaining quasi-isotropic properties, so identical as the one described above but using one only type of reinforcement fibre. The laminates were cured under a pressure of 3 kPa and a temperature of 140ºC for one hour in a hot plate press and air cooled. The final thickness of all plates was 4 mm.

Drilling experiments were executed in a vertical machining centre with 6 mm diameter drills. Initial cutting parameters were selected according to tools manufacturer advice and later confirmed or changed according to experimental results. Finally a ‘best set’ was selected for each tool used. Five types of drills and two tool materials were experimented for comparison: twist drill in HSS and tungsten carbide, brad, dagger and special step drill all in tungsten carbide only. Machining parameters are shown in table 2.

Table 2 – Machining parameters

Tool	Cutting speed m/min	Feed rate mm/rev
HSS twist	20	0.09
Carbide twist	100	0.025
Carbide Brad	80	0.025
Carbide Dagger	38	0.05
Carbide special step	53	0.025

Twist drill is a standard geometry tool. Associated with the use of the twist drill, a pilot hole of 1.1 mm diameter was performed. The intention of pilot hole was to reduce the maximum thrust force achieved and decrease delamination around the hole by cancelling the chisel edge effect of the drill. The use of HSS has the purpose of confirming the general idea that this material is not adequate for fibre reinforced composites drilling. Brad drill is a special edged drill firstly designed for cutting wood, with edges in scythe shape, that causes the tensioning of the fibres prior to cut, thus enabling a ‘clean cut’ and a smooth machined surface. Dagger drills are designed for fibre reinforced laminates and had a very sharp tip – 30º – in order to reduce the indentation effect. Due to its particular geometry it needs to have enough space at the exit side of the plate, which sometimes is not possible, limiting its application in field work. The special step drill follows a suggestion from Dharan (2000) and was developed in the aim of a dissertation, Durão (2005). This special tool has two drilling diameters – 1.25 and 6 mm - dividing the drilling operation, and consequently the thrust force, in two stages. This division of the drilling operation also cancels the chisel edge effect for the final hole diameter drilling. The diameter transition has a conical shape, for a soft transition. The reduction of delamination risk by reducing the maximum thrust force is also looked for. Another advantage of this tool is the possibility of executing the hole in one operation only.

Axial thrust force (F_z) and torque (M_t) during drilling were monitored with a *Kistler 4782* dynamometer associated to a multichannel amplifier and a personal computer for data collection. All the plates were drilled without the use of a sacrificial plate.

2.2 *Delamination measurement*

Delamination extension is not possible to be measured by a visual inspection as carbon/epoxy plates are opaque. So, the plates need to be inspected by enhanced radiography. Delamination can be detected using a contrasting fluid, like di-iodomethane. For that it is necessary to immerse the plate in the contrasting fluid for one and a half hour in a dark chamber. After time elapsed, plates are cleaned and radiographed. The final result of a developed film can be seen at figure 3.

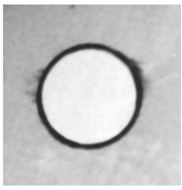

Figure 3 . A radiography of a drilled part

The resulting images were then processed using a previously developed image analysis and processing platform, with the help of Computational Vision techniques. The use of Computational Vision has the purpose to reckon from the images obtained by radiography, information regarding damaged area or diameter. This process has the advantage of reducing operator dependence to measure the dimensions wanted, thus increasing results reliability. An existing processing and image analysis platform was used, Tavares (2000), Tavares (2002). This platform turned possible the use of some standard Computational Vision techniques, Awcock (1995), Jain, (1995), Schalkoff (1989) of image processing like filtering, segmentation and region analysis.

For radiographic images, the first step is the manual selection of the interest zone, in order to reduce computer processing time. Then it is necessary to pre-process the sub image by using smoothing filters to reduce sudden changes of intensity, thus noise. Then, the smoothed image is segmented in interest areas. As this step can result in a large number of segmented areas it is followed by the elimination of those who are nor relevant. Noise areas are eliminated by the application of erosion and dilation morphologic filters. After this step, each image is composed of the damaged area and its background. The final step is the use of a region processing and analysis algorithm to distinguish the several regions of each image. For each region the required measurements are made.

In the end it was possible to obtain the dimensions judged as necessary in order to have a damage evaluation according to equations (1) or (2). Results considering the two criteria mentioned were determined using the results given by this technique. In figure 4 some steps of the processing of a radiographic image are presented.

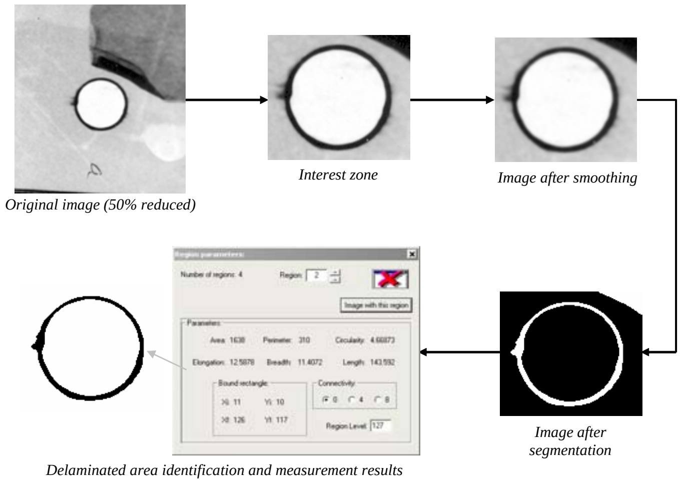

Figure 4 . Example of the determination of damage measurements in an radiography image

2.3 *Bearing test*

The last phase of experimental work was the execution of the bearing test. The main purpose of hole making in a plate is to assemble it to other parts in a structure. It is important to know what is the load carrying capacity of a plate. This test is designed to determine the bearing response of multidirectional polymer matrix reinforced composite laminates and it follows the orientations determined in *ASTM D5961-01* standard test method. This procedure provides data for compare the effect of several machining methods used in this work. The tests were carried out at an *INSTRON 4208* with a speed of 2 mm/min. Deformation data was collected by two independent systems: one connected to the test machine and other from two LVDT installed at the to test jig and connected to the plate. In order to have a valid test, a maximum load followed by a 30% decrease should be noticed, before shear out of the plate. Valid test results were then plotted against data regarding delamination by the two criteria referred.

3 RESULTS

The results considered in this work were the maximum thrust force and torque during drilling, evaluation of delamination based on the criteria referred as *Delamination Factor*, equations (1), and *Damage Ratio*, equation (2) and finally by the bearing stress test values.

Thrust force and torque data obtained during drilling are presented in table 3. In the same table the results of the bearing stress for each tool are shown. These values are the average of five tests under identical experimental conditions for each tool geometry involved in this study.

Table 3. Drill geometry comparison results.

Tool	Maximum thrust force N	Maximum torque Nm	Bearing stress MPa
HSS twist	104	0.22	709
Carbide twist	28	0.34	748
Carbide Brad	42	0.16	733
Carbide Dagger	52	0.31	728
Special step	43	0.49	764

From the results presented it is possible to observe that there is a substantial difference when changing from HSS to carbide twist drills. The thrust force has a strong reduction and the bearing stress of the plate notably increases. Although some of these effects can be explained by the use of different cutting parameters, it must be reminded that those were optimized for each drill geometry and material prior to the experimental work here described. Comparing the results of thrust force with bearing stress, it can be said that a reduction of thrust force during drilling, reducing the risk of delamination onset, has resulted in higher values of bearing stress. Clearly, drill geometry has a definitive influence on machined hole quality, affecting properties of plates to assemble in a structure. It was evident that the higher values of bearing stress correspond to the plates with lower delamination. A 14% difference was found when comparing the better individual value of bearing stress with the lower one. When considering average values, this difference comes to 7% between special step and HSS twist drill, that has always the worst results.

Torque values are always low for all drills considered and no influence on delamination or other damage was identified as relevant.

After drilling, the plates were radiographed and the images processed as described in 2.2. The results from the application of Computational Vision techniques are presented in figure 5, considering *Delamination Factor* criteria and a nominal hole diameter of 6 mm.

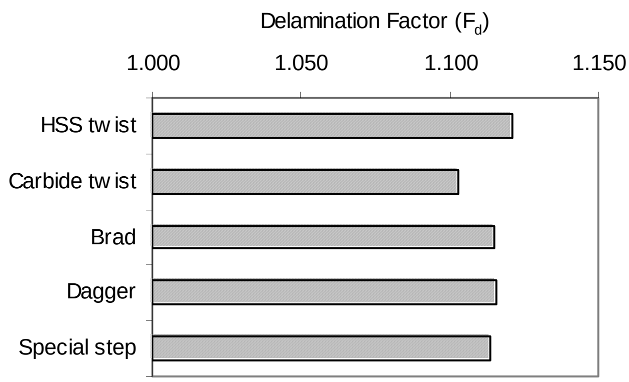

Figure 5 . Comparison of delamination factor for several tools

A relation connecting damage ratio and bearing stress was established from the data collected during experimental work. This relation can be seen in figure 6, with a correlation factor higher than 0.8. A second relation linking delamination factor to bearing stress was also set up, although the correlation factor was lower (around 0.5). In both cases a linear correlation was tried, returning a line with negative slope. This slope confirms that delamination is an important factor in load carrying capacity of a laminate plate with assembly by screws, rivets or bolts.

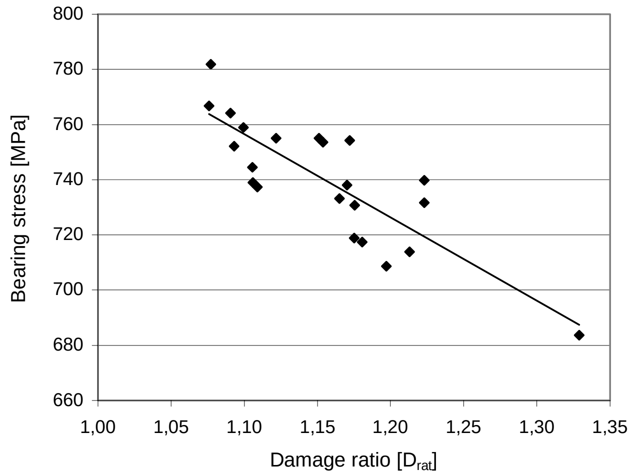

Figure 6 . Bearing stress to damage ratio correlation.

From the data in figure 6, and the results of table 3, it is possible to say that higher thrust forces during drilling lead to higher delamination around the hole and, consequently, a decrease in plate mechanical strength, given by bearing stress test results.

4 CONCLUSIONS

Five different tools for drilling hybrid laminates were compared, one of them in HSS and the others in tungsten carbide. These four carbide drills had different geometries: twist, brad, dagger and a special step design. With such purpose a laminate with two types of reinforcement – carbon and glass – fibres in an epoxy matrix was drilled using the tools mentioned. Each drill was used at the cutting parameters considered as ‘best set’. Forces were monitored during drilling, delamination evaluated through radiography associated with an analysis and processing platform. Finally, drilled laminate strength was measured by a bearing test.

Based on the experimental work presented it is possible to draw some conclusions.

A correct choice of cutting speed and feed rate will reduce delamination. This damage can be evaluated by a non-destructive test like enhanced radiography.

From the drills experimented, HSS twist drill had the lower results, showing the inadequacy of the use of this material in drilling tools for fiber reinforced plastics.

Carbide twist drill had the best results for thrust force and *Delamination Factor*, but bearing stress test results were lower by about 2% from the best.

Special step drilled plates had the higher results of bearing stress, although these plates do not have the lower delamination factor value.

The image processing techniques used showed to be adequate to analyze the image objects involved. Their use can be easily extended to other materials that are suitable to be radiographed, C-scanned or examined by any other imaging technique.

Delamination extension can be correlated with bearing stress showing that higher delamination has a correspondence with lower bearing stresses.

The relationships vary if a different composite laminate - material or stacking sequence - is used. This has to be present when designing a structure using fibre reinforced laminates.

5 REFERENCES

Abrate, S., 1997, Machining of Composite Materials, *Composites Engineering Handbook*, Ed. P. K. Mallick, Marcel Dekker, New York, pp. 777-809.

Awcock, G. W., Thomas, R., 1995, *Applied image processing*, McGRAW-HILL International Editions, New York.

Bader, M.G., 1994, Hybrid effect, *Handbook of Polymer-fibre Composites*, Longman Scientific Technical, 225-230.

Chen, W. C., 1997, Some experimental investigations in the drilling of carbon fibre-reinforced plastic (CFRP) composite laminates, *Int. J. of Machine Tools and Manufacture*, 37, 1097-1108.

Davim, J. P., Reis, P., 2003, Furação de laminados epóxidos reforçados a fibras de carbono (CFRP): relação entre as forças de corte e o factor de delaminagem, *VI Congr. Ibero-Americano de Engenharia Mecânica*, Coimbra, pp. 1079-1084.

Dharan, C. K. H., 2000, *Conference on composites machining*, INEGI-PORTO.

Dharan, C. H. K., Won, M. S., 2000, Machining parameters for an intelligent machining system for composite laminates, *Int. J. of Machine Tools and Manufacture*, 39, pp. 415-426.

Durão, L. M. P., 2005, *Machining of Hybrid Composites*, PhD. thesis, FEUP, Porto.

Hocheng, H., Dharan, C. K. H., 1990, Delamination during drilling in composite laminates, *J. of Engineering for Industry*, 112, 236-239.

Hocheng, H., Tsao, C.C., 2005, The path towards delamination-free drilling of composite materials, *J. of Materials Processing Technology*, 167, p. 251-264.

Jain, R., Kasturi, R., Schunck, B. G., 1995, *Machine Vision*, McGRAW-HILL International Editions, New York.

Langella, A., Nele, L., Maio, A., 2005, A torque and thrust prediction model for drilling of composite materials, *Composites A*, 36, p. 83-93.

Mehta, M. ,Reinhart, T. J., Soni, A. H.,1992, Effect of fastener hole drilling anomalies on structural integrity of PMR-15/Gr composite laminates, *Proc. of the Machining Composite Materials Symposium, ASM Materials Week*, 113-126.

Park, K. Y., Choi, J. H., Lee, D. G., 1995, Delamination-free and high efficiency drilling of carbon fiber reinforced plastics, *J. of Composite Materials*, 29, pp. 1988-2002.

Persson, E., Eriksson, I., Zackrisson, L., 1997 Effects of hole machining defects on strength and fatigue life of composite laminates, *Composites A*, 28, 141-151.

Piquet, R., Ferret, B., Lachaud, F., Swider, P., 2000, Experimental analysis of drilling damage in thin carbon/epoxy plate using special drills, *Composites A*, 31, p. 1107-1115.

Schalkoff, R. J., 1989, *Digital image processing and computer vision*, John Willey & Sons, Inc..

Schwartz, M. M., 1988, *Composite Materials Handbook*, McGraw Hill.

Stone, R., Krishnamurthy, K., 1996, A Neural Network Thrust Force Controller to Minimize Delamination During Drilling of Graphite-Epoxy Composites, *Int. J. Machine Tools and Manufacture*, 36,pp. 985-1003.

Tavares, J. M. R. S., 2000, Tese de Doutoramento: "*Análise de Movimento de Corpos Deformáveis usando Visão Computacional*", FEUP.

Tavares, J. M. R. S., Barbosa, J. G., Padilha, A. J., 2002, Apresentação de um Banco de Desenvolvimento e Ensaio para Objectos Deformáveis, *RESI - Revista Electrónica de Sistemas de Informação*, vol. 1.

Tsao, C. C., Hocheng, H., 2003, The effect of chisel length and associated pilot hole on delamination when drilling composite materials, *Int. J. of Machine Tools and Manufacture* 43, pp. 1087-1092.

Tsao, C. C., Hocheng, H., 2004, Taguchi analysis of delamination associated with various drill bits in drilling of composite material, *Int. J. of Machine Tools and Manufacture*, 44, 1085-1090.

Tsao, C. C., Hocheng, H., 2005, Computerized tomography and C-Scan for measuring delamination in the drilling of composite materials using various drills, *Int. J. of Machine Tools and Manufacture*, 45, 1282-1287.

Won, M. S., Dharan, C. H. K., 2002, Chisel edge and pilot hole effects in drilling composite laminates, *Trans. of ASME J. of Manufacturing Science and Engineering*, 124, pp. 242-247.