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ORIGINAL ARTICLE

Evaluation of a novel approach to a delamination factor after drilling composite laminates using a core–saw drill

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Abstract Drilling is the most commonly applied method for hole making of fiber-reinforced materials owing to the need for structure joining. Delamination is the most common defect during drilling because of the heterogeneity of both the fibers and the matrix. The delamination, in general, is an irregular shape and size, containing long and fine breaks and cracks at the exit of the drilled hole, especially in the drilling of carbon-fiber-reinforced plastic (CFRP). On the other hand, a core–saw drill is designed to reduce the threat of chip removal in drilling composite materials. Since the thrust force of core–saw drill is distributed toward the periphery, the core–saw drill allows a larger critical thrust force than the twist drill at the onset of delamination when drilling composite materials. The aim of this paper is to present a novel approach of the equivalent delamination factor (F_{ed}) to characterize drilling-induced delamination using a core–saw drill and compare it with the adjusted delamination factor (F_{da}) and the conventional delamination factor (F_a). The experimental results indicated that the F_{ed} obtained is considered suitable for characterizing delamination at the exit of a hole after drilling CFRP.

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1 Introduction

Carbon-fiber-reinforced composites have gained much attention for their superior mechanical properties and are attractive for use in aerospace, defense, and transportation applications. However, these materials possess peculiar characteristics governing their behavior during machining. The mechanism of machining composite materials fundamentally differs from that of homogeneous metal removal [1]. Based on experimental observations, little plastic deformation of composite materials occurs during machining, and the fracture resistance is ten to 100 times lower than that of common steels. In conventional machining, drilling is the most commonly applied method for as much as 40% of all material removal processes [2]. Various cutting tools are available for making the hole, but the twist drill with two cutting edges on its working end is by far the most common. The efficiency of the cutting action varies, being the most efficient at the outer diameter of the twist drill. However, the quality of the hole is a curb aspect for all hole-making processes used on composite materials. This can affect the in-service life under fatigue loads. Delamination is the most common defect during drilling because of the heterogeneity of both the fibers and the matrix. It is also a critical factor in assessing the machinability of composites. Figure 1 depicts the delamination mechanism of drilling with a twist drill in composite materials. In drilling, the twist drill always exerts a compressive thrust force on the workpiece. In the case of composites, the laminate under the twist drill is subjected to bending

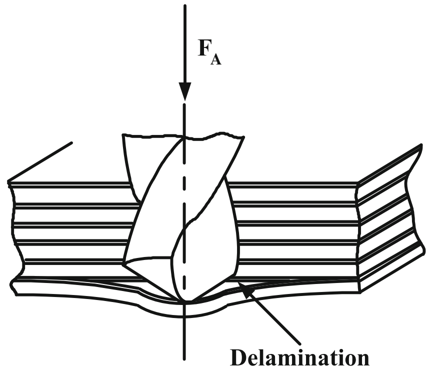


Fig. 1 Delamination mechanism of drilling with a twist drill in composite materials

deformation and tend to be pushed away from the interlaminar bond around the machined hole. At some point, the loading exceeds the interlaminar bond strength and delamination occurs.

Hocheng and Dharan first presented the critical thrust model at the onset of delamination using linear elastic fracture mechanics and classic plate bending theory [3]. The critical thrust force of the twist drill (F_A) at the onset of delamination can be expressed as follows:

$$\begin{aligned} F_A &= \pi\left[\frac{8G_{IC}Eh^3}{3(1-v^2)}\right]^{1/2} \\ &= \pi\sqrt{32G_{IC}M} \end{aligned} \quad (1)$$

where G_{IC} is the critical crack propagation energy per unit area in mode *I*, $M = Eh^3/12(1-v^2)$ is the stiffness per unit width of the fiber-reinforced material, E is Young's modulus, h is the uncut thickness under tool, and v is Poisson's ratio for the material. From Eq. 1, the delamination is correlated to thrust force during the approach and exit of the drill. To avoid delamination, the applied thrust force should not exceed this value, which is a function of the material properties and the uncut thickness. Numerous studies on the drilling of fiber-reinforced plastics state that the delamination (or thrust force) strongly depends on the tool geometry and drilling parameters [1, 4–7]. Nevertheless, conventional drilling continues to be widely used for practical purposes. The core–saw drill is a compound special drill bit designed to reduce the threat of chip removal in drilling composite materials [8]. The total thrust force of the core–saw drill (F_{CS}), in fact, is composed of the periphery circular load (inner) and the annular area load (outer), as shown in Fig. 2. Tsao and Hocheng found that the thrust of the core–saw drill allows the obtaining of a larger critical thrust force than the twist drill at the onset of delamination when drilling composite materials [8, 9].

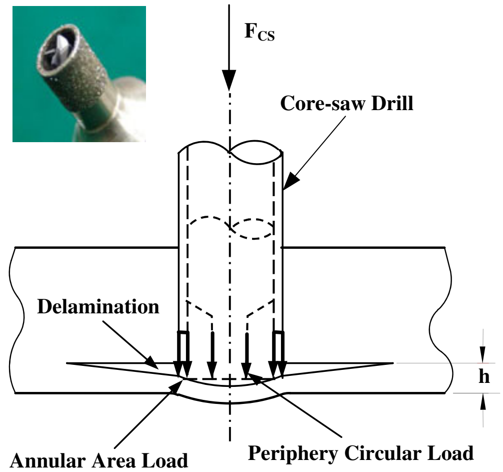


Fig. 2 Total thrust force of the core–saw drill at the onset of delamination

Delamination commonly occurs at both the entrance and the exit planes of the workpiece after drilling composites. The experimental results indicate that the delamination at the entry side is much smaller with respect to that at the exit side, as shown in Fig. 3. Several studies have shown the assessment and measurement of delamination around a drilled hole [1, 10, 11]. However, the quality control and evaluation of drilling-induced delamination during the drilling of fiber-reinforced composite materials is rather difficult. Many investigators reported that the X-ray [12, 13], optical microscope [14, 15], ultrasonic C-scan [16, 17], and digital photograph [17–19] have been used to acquire the size, shape, and location of delamination on the composite laminates. Tsao and Hocheng presented a comparative study on computerized tomography and ultrasonic C-scan evaluation techniques for characterizing the drilled damage in carbon-fiber-reinforced composites [17]. They concluded that visual inspection is demonstrated as a feasible and effective tool for evaluating drilling-induced delamination. Chen first proposed the concept of the delamination factor (i.e., the ratio of the maximum diameter D_{max} in the damage zone to the hole diameter D), namely the conventional delamination factor (F_a), to easily

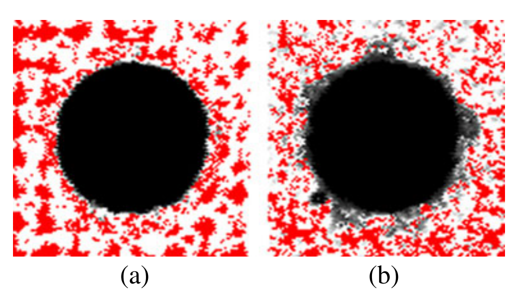


Fig. 3 Delamination at **a** entrance side and **b** exit side

analyze and compare the degree of delamination in drilling CFRP composite laminates [12]. The equation of the conventional delamination factor can be expressed as follows:

$$F_a = \frac{D_{max}}{D} \quad (2)$$

Advanced digital image processing technology to measure drilling-induced delamination has been widely used because it emphasizes the improvement in process efficiency, stability of image quality, and cost-saving. The delamination, however, is an irregular shape and size, containing long and fine breaks and cracks at the exit of the drilled hole, especially in the drilling of CFRP. A combination of measuring the crack and damaged area in the delamination factor is suitable for obtaining a better visualization of the variations in the damage extension after drilling the composite materials. Therefore, Davim et al. proposed the idea of an adjusted delamination factor (F_{da}) to evaluate the delamination zone by digital image processing [20]. The advantage of the measurement technology is it incorporates a novel approach to area function. The F_{da} gave better measurement results compared to the F_a for the different drilling damages, in which D_{max} was identical. So, the F_{da} can provide a more effective and actual measurement for hole defects that can then be analyzed using suitable techniques for image processing. The equation of the adjusted delamination factor can be expressed as follows:

$$F_{da} = F_a + \frac{A_d}{A_{max} - A_o}\left(F_a^2 - F_a\right) \quad (3)$$

where A_{max} is the delamination area related to the D_{max}, A_o is the drilled area of the D, and A_d is the delamination area in the vicinity of the drilled hole. The first part of Eq. 3 represents the size of the crack contribution, and the second part represents the damage area contribution [20]. From Eq. 3, the higher the damage on A_d, the higher the effect on F_{da}.

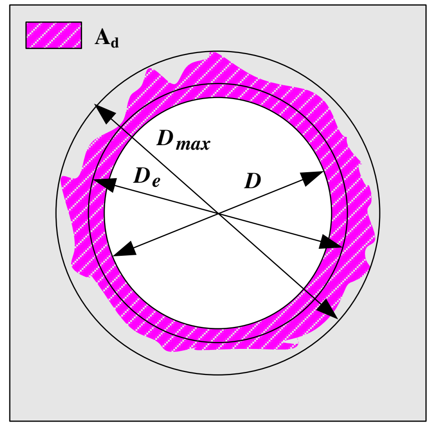


Fig. 5 Scheme of the F_{ed} in drilling composite laminate for drill bit

2 Proposed delamination factor

Due to the damage geometry and the brittle behavior of CFRP, drilling CFRP creates some irregular forms, which are not expected from the damaged regions. In this case, practical experience proves the advantage of using the adjusted delamination factor. However, whether the delamination area is minimal or maximal, F_{da} does not equal F_a. The scheme of two critical cases in the drilling composite laminate for the drill bit is shown in Fig. 4. Therefore, a novel approach was proposed to characterize the delamination factor in this study, namely the equivalent delamination factor (F_{ed}) calculated through Eq. 4. The scheme of F_{ed} in drilling the composite laminate for the drill bit is shown in Fig. 5.

$$F_{ed} = \frac{D_e}{D} \quad (4)$$

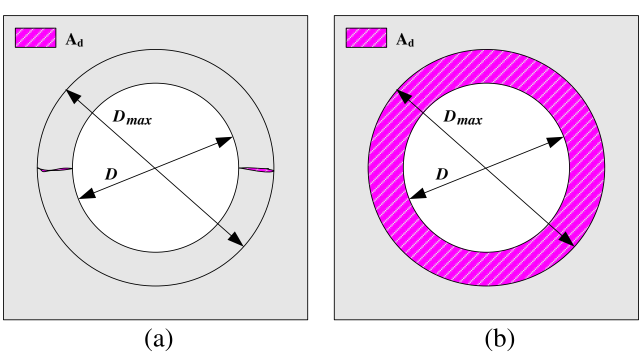


Fig. 4 Critical cases in drilling composite laminate **a** minimal delamination area and **b** maximal delamination area

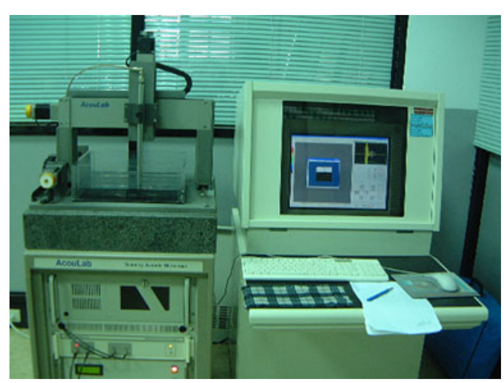


Fig. 6 Photograph of ultrasonic C-scan to measure the delamination

Table 1 Effect of delamination parameters on various delamination factor models

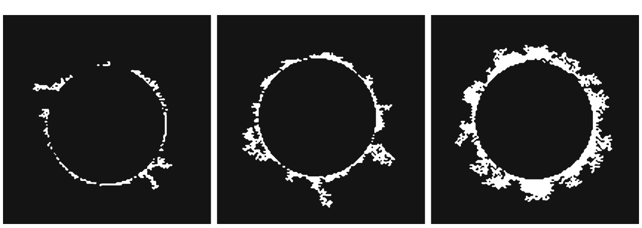
Test	Delamination parameter				Delamination factor models		
	D (mm)	D_{max} (mm)	A_d (mm^2)	D_e (mm)	F_a	F_{da}	F_{ed}
1	10	10.000	0	10.000	1.0000	1.4375	1.0000
2	10	14.375	6.099	10.381	1.4375	1.4839	1.0381
3	10	14.375	14.977	10.911	1.4375	1.5513	1.0911
4	10	14.375	31.102	11.815	1.4375	1.6739	1.1815
5	10	14.375	83.756	14.375	1.4375	2.0664	1.4375

where D_e is the equivalent delamination diameter and can be expressed as follows:

$$D_e = \left[\frac{4(A_d + A_o)}{\pi}\right]^{0.5} \quad (5)$$

3 Experimental procedure

The carbon/epoxy composite material is drilled in this investigation. The laminates were fabricated from the toughened, woven carbon/epoxy of Amoco T300 fibers in 934 epoxy matrix using autoclave molding. The stacking sequence of the laminates was $[0/90]_{12S}$. Specimens of size 60×60 mm were cut on a water-cooled diamond table saw. Twenty-four laminae make the plate thickness 6.0 mm. The fiber volume fraction is 0.63. The drill diameter and core tool thickness of the core–saw drill were 10 and 1 mm, respectively, with the end of the core tool coated with # 60 diamond grits and having a length of 12 mm. The internal part of the core–saw drill was a saw drill. Saw drills of 5.5 mm diameter with tungsten carbide were used to obtain the entire induced delamination. Drilling tests were carried out on a 5.5-kW LEADWELL MCV-610AP vertical machining center. All tests were run without coolant at spindle speeds of 800, 1,000, and 1,200 rpm and feed rates of 8, 12, and 16 mm/min, respectively. Digital images of the drilling delamination area were produced from the carbon-fiber-reinforced composite material sections obtained by ultrasonic C-scan. The ultrasonic C-scan equipment was an AIT-5112 unit (Automated Inspection Technologies Inc.), as shown in Fig. 6. The specimen was placed between the sender and receiver and scanned at normal incidence in through-transmission mode by a focused broadband transducer (9.5 mm in diameter) with a center frequency of 5 MHz. The testing device consisted of a 0.025-mm resolution scanning bridge, an AIT-2230 ultrasonic pulser/receiver, and a digital oscilloscope used for radio frequency echo signal acquisition. Commercial software (PhotoImpact 8.0) was used to extract the ultrasonic C-scan image data during scanning for measuring the delamination. A large number of high-contrast images, each consisting of 200×200 resolution (pixels), were obtained from each scanning.



(a) Test 2 (b) Test 3 (c) Test 4

Fig. 7 Ultrasonic C-scan shows the identical F_a with various tests

4 Experimental results and discussion

To evaluate the delamination damage at the exit edge of the drilled hole using a core–saw drill, we comprehensively analyzed delamination with various delamination factor models. In this analysis, the equivalent delamination factor is compared with the adjusted delamination factor and the conventional delamination factor. Table 1 shows the effect of the delamination parameters on various delamination factor models. Table 1 shows that F_{da} and F_{ed} had better delamination damage discrimination than F_a, which had the same delamination factor for tests 2 to 4. In addition, Table 1 shows that the trend for F_{da} and F_{ed} is almost the same for tests 2 to 4. Increasing A_d causes a higher delamination factor for F_{da} and F_{ed}. However, F_{da} is clearly larger than F_{ed}. The ultrasonic C-scan shows an identical F_a with various tests (nos. 2 to 4), as shown in Fig. 7. Figure 7 shows that the delamination area in test 4 possesses a regular distribution near the drilled hole. However, the delamination area presents an irregular form, containing long and fine breaks and cracks at the hole exit for tests 2 and 3. When there was a larger delamination

Table 2 Experimental results of various delamination factor models obtained under selected drilling conditions

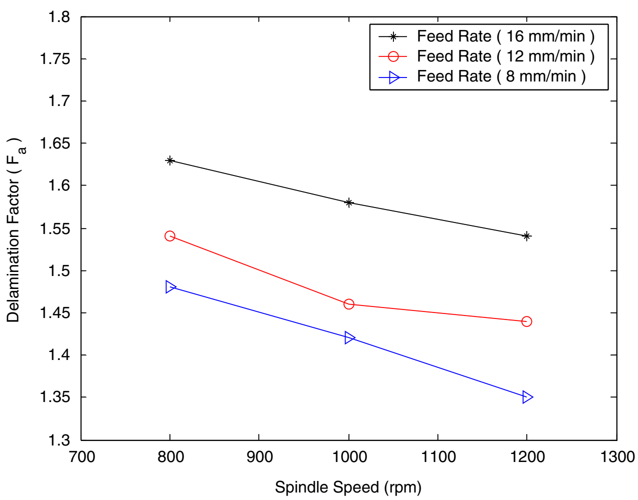
Drilling conditions		Delamination parameter				Delamination factor models		
Feed rate (mm/min)	Spindle speed (rpm)	D (mm)	D_{max} (mm)	A_d (mm^2)	D_e (mm)	F_a	F_{da}	F_{ed}
8	800	10	14.8	15.8	11.0	1.48	1.60	1.10
8	1,000	10	14.2	10.9	10.7	1.42	1.50	1.07
8	1,200	10	13.5	8.6	10.5	1.35	1.41	1.05
12	800	10	15.4	25.9	11.5	1.54	1.74	1.15
12	1,000	10	14.6	18.8	11.1	1.46	1.60	1.11
12	1,200	10	14.4	13.5	10.8	1.44	1.54	1.08
16	800	10	16.3	41.8	12.4	1.63	1.96	1.24
16	1,000	10	15.8	34.8	12.0	1.58	1.85	1.20
16	1,200	10	15.4	30.5	11.8	1.54	1.78	1.18

area occurring at the hole exit, then the variance of delamination factor measuring F_{da} would be clearer. Additionally, the delamination factor between F_{da} and F_{ed} for test 1 (delamination-free) and test 5 (full uniform delamination area) in Table 1 was compared. However, F_{da} is null for two critical cases (minimal or maximal delamination area). In other words, F_{da} is comparatively suitable for a regular delamination area. Table 1 shows that F_{ed} is the same as F_a for two critical cases. However, the difference between F_{ed} and F_a increases with the delamination area.

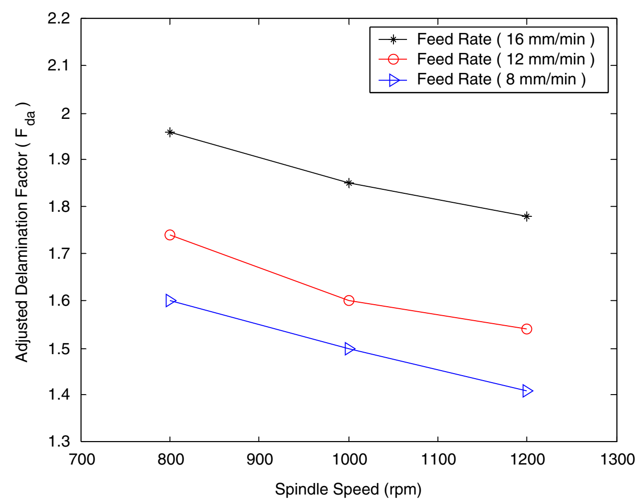
Table 2 shows the experimental results of various delamination factor models obtained under selected drilling conditions using the core–saw drill. The various delamination factor models result in different levels of delamination after drilling the composites. Note that the adjusted delamination factor in the selected drilling condition is the highest followed by the conventional delamination factor, while the equivalent delamination factor is the lowest. Figure 8 shows the correlation between various delamination factors and spindle speeds at feed rates of 8, 12, and 16 mm/min, respectively. Figure 8 shows that the delamination is highly sensitive to feed rate variations, especially a feed rate over 12 mm/min. A rapid increase in the feed rate at the end of drilling will cause significant delamination around the exit edge of the drilled hole. The occurrence of delamination is mainly governed by the thrust force acting on the cutting edge of the core–saw drill. In addition, the delamination has a tendency to decrease with increasing spindle speed. This result can be explained by the cutting speed being increased. The cutting edge action is reduced at the number of passes across the same region, and the friction between cutting edges and composite laminate will cause temperature elevation and a softening of the matrix phase, thus reducing damage.

5 Conclusion

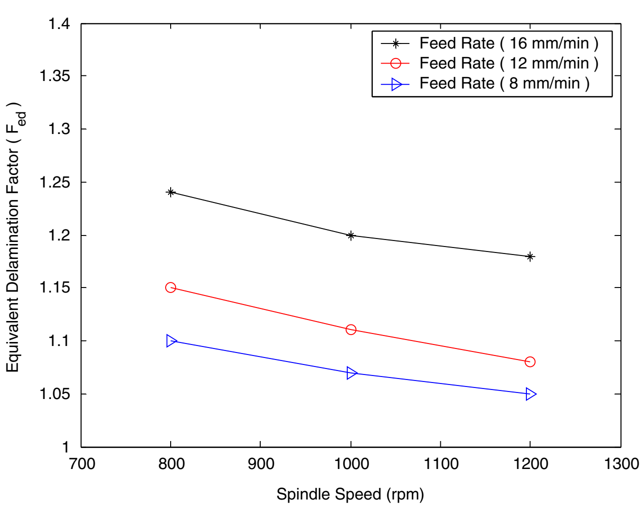
Delamination is a critical factor in discussing the quality of the drilled hole in drilling composites. Due to the damage geometry and the brittle behavior of CFRP, drilling CFRP causes some irregular forms, which is not expected from the damaged regions. Therefore, using a reasonable and efficient mathematical approach to characterize the drilled damage is very beneficial as the drilling parameters are altered. A comparative analysis of various delamination factor models after drilling CFRP using core–saw drill is presented in this paper. In this study, F_{da} and F_{ed} had better discrimination of delamination damage compared to F_a, which was identical at the hole exit. Additionally, the trend is almost similar to that of F_{da} and F_{ed}. F_{da} is clearly larger than F_{ed}. However, F_{da} is null for the minimal and maximal delamination area at the exit of the drilled hole. On the other hand, image digitalization and processing is also an essential method to acquire and evaluate the delamination area after drilling a hole on the composite laminates due to the development of computers, as well as in the algorithms and software used. In addition, the experimental results indicated that the F_{ed} obtained through digital image processing is considered suitable for characterizing delamination at the exit of the drilled hole. The delamination is highly sensitive to feed rate variations, especially a feed rate over 12 mm/min. A rapid increase in the feed rate at the end of drilling with the core–saw drill will cause significant delamination around the exit edge of the drilled hole. The occurrence of delamination is mainly governed by the thrust force acting on the cutting edge of the core–saw drill.



(a) Conventional delamination factor (F_a)



(b) Adjusted delamination factor (F_{da})



(c) Equivalent delamination factor (F_{ed})

Fig. 8 The correlation between various delamination factor and spindle speed at feed rates of 8, 12, and 16 mm/min

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References

1. König W, Wulf C, Grass P, Willerscheid H (1985) Machining of fiber reinforced plastics. Ann CIRP 34(2):536–548
2. Brinksmeier E (1990) Prediction of tool fracture in drilling. Ann CIRP 39:97–100
3. Hocheng H, Dharan CKH (1990) Delamination during drilling in composite laminates. ASME J Eng Ind 112:236–239
4. Hocheng H, Tsao CC (2006) Effects of special drill bits on drilling-induced delamination of composite materials. Int J Mach Tools Manuf 46:1403–1416
5. Tsao CC (2007) Taguchi analysis of drilling quality associated with core drill in drilling of composite material. Int J Adv Manuf Technol 32:877–884
6. Tsao CC (2008) Comparison between response surface methodology and radial basis function network for core-center drill in drilling composite materials. Int J Adv Manuf Technol 37:1061–1068
7. Abrão AM, Rubio JC, Faria PE, Davim JP (2008) The effect of cutting tool geometry on thrust force and delamination when drilling glass fibre reinforced plastic composite. Mater Des 29(2):508–513
8. Tsao CC (2008) Thrust force and delamination of core–saw drill during drilling carbon fiber reinforced plastics (CFRP). Int J Adv Manuf Technol 37:23–28
9. Tsao CC, Hocheng H (2008) Analysis of delamination in drilling of composite materials by core–saw drill. Int J Mater Prod Technol 32:188–201
10. Tagliaferri V, Caprino G, Diterlizzi A (1990) Effect of drilling parameters on the finish and mechanical properties of GFRP composites. Int J Mach Tools Manuf 30(1):77–84
11. König W, Graß P (1989) Quality definition and assessment in drilling of fibre reinforced thermosets. Ann CIRP 38:119–124
12. Chen WC (1997) Some experimental investigations in the drilling of carbon fiber-reinforced plastic (CFRP) composite laminates. Int J Mach Tools Manuf 37(8):1097–1108
13. De Albuquerque VHC, Tavares JMRS, Durão LMP (2010) Evaluation of delamination damage on composite plates using an artificial neural network for the radiographic image analysis. J Compos Mater 44(9):1139–1159
14. Davim JP, Reis P (2003) Study of delamination in drilling carbon fiber reinforced plastics (CFRP) using design experiments. Compos Struc 59:481–487
15. Gaitonde VN, Karnik SR, Davim JP (2008) Prediction and minimization of delamination in drilling of medium-density fiberboard (MDF) using response surface methodology and Taguchi design. Mater Manuf Process 23(4):377–384
16. Durão LMP, Tavares JMRS, De Albuquerque VHC, Marques AT, Magalhães AG, Vieira AA (2010) Tool effects on hybrid laminates drilling. Mater Manuf Process 25(6):476–481
17. Tsao CC, Hocheng H (2005) Computerized tomography and C-scan for measuring delamination in drilling of composite material using various drills. Int J Mach Tools Manuf 45(11):1282–1287
18. Piquet R, Ferret B, Lachaud F, Swider P (2000) Experimental analysis of drilling damage in thin carbon/epoxy plate using special drills. Compos Part A 31(10):1107–1115
19. Bhatnagar N, Singh I, Nayak D (2004) Damage investigation in drilling of glass fiber reinforced plastic composite laminates. Mater Manuf Process 19(6):995–1007
20. Davim JP, Rubio JC, Abrão AM (2007) A novel approach based on digital image analysis to evaluate the delamination factor after drilling composite laminates. Compos Sci Technol 67(9):1939–1945