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Authors	Shi, Yu;Wang, Xiaonan;Wang, Fuji;Gu, Tianyu;Xie, Pengheng;Jia, Yu
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Effects of inkjet printed toughener on delamination suppression in drilling of carbon fibre reinforced plastics (CFRPs)

Yu Shi [a], Xiaonan Wang [a, b, *], Fuji Wang [b, **], Tianyu Gu [b], Pengheng Xie [a], Yu Jia [c]

[a] Department of Mechanical Engineering, University of Chester, Chester, CH2 4NU, UK

[b] Key Laboratory for Precision and Non-traditional Machining Technology of Ministry of Education, School of Mechanical Engineering, Dalian University of Technology, Dalian, 116024, China

[c] School of Engineering and Applied Science, Aston University, Birmingham B4 7ET, UK

Corresponding author: Xiaonan Wang, 18842660282@mail.dlut.edu.cn; Fuji Wang, wfjsll@dlut.edu.cn

Abstract

Delamination has been recognised as the predominant damage induced during the drilling of carbon fibre reinforced plastics (CFRPs). It could significantly reduce the bearing capacity and shorten the service life of the designed component. To enhance the delamination resistance of CFRPs for different applications, great affords have been done to improve their interlaminar fracture toughness. However, due to the difficulty in accurately controlling the amount of the toughener applied in the interface, effect of the toughener content on the toughening efficiency is rarely studied. In this work, an experimental research was developed to investigate the performance of the toughener on the improvement of delamination resistance in the drilling of CFRPs and parametrically optimise the toughener content with the consideration of different feed rates. Specifically, poly(methyl methacrylate) (PMMA) solutions with various concentrations were selected to add on the CFRP prepreg, and co-cured together with layups. The inkjet printing technology was adopted to deposit the PMMA solutions for precisely controlled toughener contents. Through drilling experiments on the toughened CFRPs, it was found that the optimal content of the PMMA solution was 10 wt. % to offer the least delamination, in particular, for the situation under the highest feed rate condition. The toughing mechanisms were also concluded by analysing the histories of the thrust force and torque in the drilling process. The results of this study is significantly contribute to the locally toughening of the composite interfaces and the improvement of the drilling quality, which is specifically helpful to strengthen the joint property for the structural design stage for the aircraft.

Keywords: CFRP; Delamination; Toughen; Inkjet printing; PMMA content; Feed rate

1. Introduction

Lightweight and excellent mechanical strength of the components are always the priority during the design and processing and manufacturing stage of the aerospace, transportation, and energy fields. Carbon fibre reinforced plastics (CFRPs) that consist of carbon fibres and epoxy resin matrix system have been the ideal candidate to meet such criteria with high specific strength and modulus, abrasion and damage resistances etc. therefore, widely used as the primary structures with remarkable benefits offered [1-5]. However, it was also identified that a challenge to constrain the expansion of CFRPs application could be their relatively high cost of machining, in particular, drilling process which is highly demanded for assembly purpose by bolts. For instance, there are approximately three million holes required to be drilled for fastening in a large transport aircraft [6-8]. These holes are under strict quality control to ensure the safe and reliable performance due to any potential damages resulted from drilling process might significantly affect their service time and safety.

The different mechanical properties of the individual phases in CFRPs often result in difficulties to achieve a balanced cutting performance with ideal quality. This could be specifically reflected that the fibre with higher strength is always more difficult to cut than the matrix where the angled layups of CFRPs could have been subjected to a high risk with delamination around the hole due to the anisotropic features and the mismatch of the neighboured plies with different fibre orientations [3, 9, 10]. In addition, with the development of fibre manufacturing technology, the strength of carbon fibre has been greatly improved, thus more loads are applied on the intralaminar interfaces during processing like drilling. Therefore, serious damages, especially the delamination are frequently induced during the drilling of CFRP components [2, 11, 12]. The delamination could not only degrade the structural integrity, but also seriously reduce their bearing capacity to fail the joining. It would also decrease the surface quality of the processed workpieces so that cause the assembly error, resulting in the composite wastes [13-15]. Optimisation of the drilling process for CFRPs have been hence become one of the research hotspots in recent years.

A number of researches were reported to improve the drilling quality on composite by the optimised design of the tooling such as drill bit. Alternatively, processing parametric studies on the drilling operational conditions were investigated by experiments. For instance, Hocheng and Tsao et al. [16-18] developed the analytical model for delamination analysis during the CFRP drilling by the various designs of twist drill, candle stick drill, saw drill and core drill bits. It was indicated that the drill bits could play a determinant factor on the onset of delamination based on the different thrust force applied. Isbilir et al. [19, 20] studied the effect of stage ratios of step drill on delamination via the finite element (FE) simulation, and they calculated the delamination factor from the ratio of the maximum diameter of the delamination region to the nominal hole diameter for the quantitative assessment of the delamination. The step drill has demonstrated an obvious suppression of the delamination form and growth compared to the general twist drilling, and the delamination factor decreased with the increasing of the stage ratio. Based on a comprehensive analysis of the effects of action point and cutting direction on material removal at the hole exit, Jia et al. [21] proposed a novel intermittent-sawtooth drill design on the one-shot drill. With the help of this specific drill bit, the cutting conditions at the hole exit were totally improved with a significant control on the reduction of the delamination after drilling. For the processing parameters, Davim et al. [22] revealed the influences of cutting velocity and feed rate on delamination factors at the hole entrance and exit by Taguchi optimisation where the correlations between drilling parameters and delamination factors by multiple linear regression was explored. Tsao et al. [23] evaluated the cutting velocity ratio and feed rates on delamination by compound core-special drills through proposing a mathematical model with response surface methodology. The results indicated that the feed rate had demonstrated to be dominant to decide the delamination occurred under the drilling process. However, either way above had to experience a high number of manufacturing and experimental consumables, which also strongly depended on the material systems used.

Therefore, some researchers focused on the improvement through the material design. As reported, the thermoplastic resin particles [24-27], inorganic whiskers [28] or carbon nanofibers/nanotubes [29-33] applied at the interfaces of laminate have significantly improved the interlaminar fracture toughness. Odagiri et al. [24] developed a kind of high-toughness prepreg based on the particulate interlayer toughening technology, aiming for an enhanced delamination resistance. Sato et al. [27] confirmed that the fracture toughness of CFRPs could be toughened by polyamide-12 (PA12) particles with more than twice higher than that of non-toughened CFRPs. Wang et al. [28] dispersed SiC whiskers along the interfaces of composite to improve the interlaminar fracture toughness of laminates, which both G_{IC} and G_{IIC} exhibited a nearly 50% and 25% increasing compared with those without whiskers. In addition, Hamer et al. [30] found a toughening effect by the electrospun Nylon 66 nanofibrilmat on the fracture toughness of the composite under pure Mode I test and concluded a three-fold improvement in G_{IC} values compared to a non-interleaved carbon/epoxy laminate. Magniez et al. [31] upgraded the G_{IC} and G_{IIC} of CFRPs up to 150% and 300% of their original values by incorporating electrospun poly(hydroxyether of bisphenol A) (phenoxy) nanofibrous. Liu [32] and White [33] et al. proposed both PA micro particles and carbon nanotubes together to toughen CFRP laminates where a remarkable increase of the G_{IC} and G_{IIC} values was obtained with 1.3 and 2.5 times higher. However, the modification of material interfacial behaviour was mostly focused by the static mechanical tests with individual damage mode assessed where the severity of improvement on a dynamic machining process with mixed-mode effects was rarely studied. In addition, traditional interlayer toughening technologies were unable to adding a constant amount of toughener in the interface of the CFRPs, which makes it difficult to research the effect of the toughener content on the toughening efficiency. Furthermore, the toughening mechanism in the drilling process of the toughened CFRPs is also need to be figured out.

In this work, the main objective is to study the improvement of delamination resistance during the dynamic drilling process for the CFRP laminates, with consideration of suppressing mixed-mode damages. To avoid any change of the material design with a higher manufacturing efficiency, the thermoplastic resin particles poly(methyl methacrylate) (PMMA) as the toughener were deposited on the surface of the original prepregs prior to lay-up and curing stage. Wherein, the inkjet printing technology was used to evenly print the PMMA solutions therefore accurately control the PMMA amount in the CFRP interface. Then, drilling experiments were carried out on the CFRP laminates toughened by various PMMA contents under different feed rates and the induced delamination was assessed to parametrically optimise the toughener content. The histories of the thrust force and torque in the drilling process were also analysed and the toughing mechanisms were concluded to guide the higher drilling quality for holes on the composite plate.

2. Materials preparation and Experiments

2.1 Materials preparation

2.1.1 Strategies for toughening composite with improved damage resistance

Based on the theory of Ho-Cheng et al.[34], delamination has been recognised as the predominant damage mode to affect the quality of drilled hole. That is because the delamination was always remained around the hole after drilling which is serious to the bearing capacity of the workpiece. The formation of delamination was strongly dependent on the loads applied by the drill bits, as well as the inherent interfacial properties of the composites, which the interfacial strengths determined the initiation and the fracture toughness then decided the propagation of delamination. Since the beginning of the drilling, the delamination was usually initiated at the first interface neighboured to the top ply for the relatively thick laminate, but occurred at the interface between last layers at the bottom when the thickness is thin. With the further feed of the drill bit, the initiated delamination kept propagating at the same interface, but also delamination at other interfaces were driven to form simultaneously. Due to the initial delamination has degraded their mechanical properties, the drilling loads would accelerate the propagation of delamination along other interfaces of the rest laminates. That is why at the end of the drilling delamination was always difficult to control and appearing around the drilled hole as the unexpected failure.

Currently, adding thermoplastic particles in the interface of the composites has become the main method to block the propagation of delamination, which had been widely used in the manufacturing of the primary structures of aircraft and already well evaluated [35]. Therefore, this research attempted to toughen the interfacial properties (strengths and fracture toughness) of laminate by thermoplastic resin particles so that improve the delamination resistance during drilling. Compared to the traditional deposition with the drawback of the uneven distribution of additives, the inkjet printing technology was adopted for a better quality of deposition and accurate control of the micro-particles contents distributed onto the raw prepregs. It is thus helpful to perform a parametric study to pursue the optimised interfacial toughening by the optimal deposition contents with personalised droplet patterns printed.

2.1.2 Material selection

The unidirectional carbon fibre prepreg (XPREG® XC130) used in this work was produced by Easy Composites Ltd, UK. The prepreg is approximately 0.25 mm thick and 300 mm wide, which is designed to be oven cured with typical curing cycle suggests offered by manufacturer [36].

In addition, PMMA (Sigma Aldrich, UK) was selected as the toughening material for inkjet printing. The reason to print PMMA is it has been proven to be an effective functional micro-particles for toughening the interfacial properties of laminate. In particular, it was an ideal candidate to be co-cured with prepregs at the oven curing cycles [37]. In order to achieve a high printing quality, the PMMA dispersed within the organic solvent N,N-Dimethylformamide (DMF) has been identified to enable an optimal viscosity for inkjet printing. Moreover, the DMF offers a perfect evaporation rate matches with the printing process, which avoids excessive solvent on the prepreg or the print head clogging [37]. To find out the optimal concentration of PMMA solution on delamination resistance during drilling, the 5 wt. % (The fraction of the weight of PMMA to the weight of solution), 10 wt. % and 20 wt. % PMMA solutions were formulated, respectively.

2.2 Fabrication of toughened composite by inkjet printing

The carbon fibre composite was laid up with the stacking sequences of $[(0/90)_2]_S$, which is 90 mm long, 70 mm in width and 2 mm thick (See Fig. 1a). This dimension of laminate was selected to fit in the fixture of drilling operations as shown in Fig. 2b.

The Dimatix DMP-2850 (Fujifilm Ltd, US) in Chester Smart Composite Group (CSCG) was used for inkjet printing PMMA particles. An embedded online inkjet observation system can real time monitor the printing process so that helps to calibrate and adjust the proper printing parameters at the pre-print phase. The nozzles consist of the piezoelectric ceramic crystals to ensure the linearity of the ink and guarantee a reliable accuracy when the printing is repeatedly operated. The vacuum supplied by the platform of the printer helps to strictly fix the substrate during printing.

As the purpose to improve the local interfacial properties for drilling, there were only three circular areas selected for printing with a diameter of 12 mm where the composite workpiece was supposed to be drilled (See Fig. 1b). Such proposed toughened areas were printed onto individual prepreg plies prior to layup, as shown by Fig. 1c.

The printed prepreg was then laid up as the designed layup and cured within the OV301 oven with reference of the advised curing cycles (Table 1). The laminates with three various PMMA contents as well as neat CFRP without any printed particles were manufactured for drilling tests.

2.3 Drilling experiment setups

Drilling experiments for the toughened CFRP laminates were carried out by the Micron 3-axis machining centre, which was powered with maximum 13 kW. A schematic of drilling setups can be illustrated by Fig. 2a where the Kistler 9253B dynamometer is responsible to measure the thrust force during drilling. To meet a standard drilling request, a fixture with a number of holes with diameter of 14 mm was used to clamp the composite workpiece to ensure a satisfied quality of the drilling. The Kistler 5080 amplifier and 5697A data acquisition play the important roles to record the force data, which a sampling frequency of 24 kHz was used for the whole drilling tests in this work. A KEYENCE VH-Z50L microscope helped to observe and record the induced delamination around the hole after drilling.

In order to offer a comparable data used for analysis of the inkjet printed particles, a uniform design of the twist drill bit was used in this work. The drilling tool is made from YG8 cemented carbide with polycrystalline diamond coatings externally to improve the wear resistance of the bit during drilling. Based on previous literature reviews, the feed rate has been a critical factor to determine the delamination produced by drilling composite, therefore, three most widely used feed rates were performed in this work to find out the proposed micro-particles toughening effects onto different drilling operational conditions. Details of the twist drill and drilling conditions are listed in Table 2.

3. Results and discussions

CFRP laminates toughened by several weight contents of PMMA solutions were manufactured and experimentally drilled at the different feed rates. The thrust force, torque and drilling induced damages by evaluating the laminates with and without micro-particles printed were discussed, respectively, for demonstrating the toughening effects and the mechanisms of improving the damage resistance by the proposed method in this work.

3.1 Drilling damages assessment

As the primary damage modes could be visually observed around the hole after drilling, the KEYENCE microscope was used to assess and analyse the damage resistance resulted from the printed PMMA micro-particles. Although slight damage was seen at the entrance, the exit was where the delamination were mostly found, therefore, the hole exit was focused in the analyses of damages.

Figure 3 shows the typical damages formed at a drilled hole exit of the laminate with 5 wt. % of PMMA printed for toughening. In order to quantitatively assess the effect of the tougheners in different concentrations with the feed rates, a damage factor was defined:

$$F_{DAM} = \frac{A_{DAM}}{A_{HOL}} \tag{1}$$

Where, A_{DAM} is the area of the damage at the hole exit, and A_{HOL} is the area of the hole. To accurately identify the damaged area, A_{DAM}, an algorithm was employed in this work [19, 20, 38, 39] to extract the damaged areas to compute the damage factor. The Matlab programme was developed to post-process the digital image analysis under three steps: 1) filtering the dynamic noise for improved quality; 2) identifying the individual damage areas by the edge detection; 3) extracting the total damaged area, as listed in Table 3. Therefore, the damaged area could be accurately obtained based on the N_{DAM}, N_{SCA} and L_{SCA}, by Eq. 2. Where, N_{DAM} is the number of the black pixels, and N_{SCA} is the number of pixels in the longitudinal direction of the scale bar, and L_{SCA} that equals to 2 mm is the actual length of the scale bar defined for the images in Table 3.

$$A_{DAM} = N_{DAM}\left(\frac{L_{SCA}}{N_{SCA}}\right)^2 \tag{2}$$

Furthermore, damage factors could be calculated by substituting Eq. 2 into Eq. 1:

$$F_{DAM} = \frac{A_{DAM}}{A_{HOL}} = \frac{N_{DAM}\left(\frac{L_{SCA}}{N_{SCA}}\right)^2}{A_{HOL}} \tag{3}$$

The damage factors measured under the various feed rates for laminates with and without toughening were compared in Fig. 4a. It can be seen that the whole toughened laminates exhibited a smaller damage factor than neat CFRP which indicated the inkjet printed PMMA at interfaces have significantly contributed towards an enhancement on damage resistance. However, three individual contents of toughened laminates by PMMA demonstrated the different tendency on the damage resistance under the various feed rates.

For drilling by a low feed rate of 150 mm/min, the different toughener contents seems not to be a key factor to improve the damage resistance (see Fig. 4a). This gave the confidence that the proposed method by inkjet printing PMMA could improve the drilling quality with obvious reduction of damages, however, there is no need to print a high concentration of toughener at such less intensive drilling, avoiding an unnecessary cost and time consuming resulted.

As expected, the damage areas were obviously enlarged with the increased feed rates, as shown by Fig. 4b. For the drilling when the feed rate reached 350 mm/min, the toughening effect tended to be stable since 5 wt. % while the optimal damage resistance was achieved at 10 wt. % of PMMA toughener printed at the highest feed rate of 550 mm/min. It indicated that a 10 wt. % concentration of PMMA toughener was advised to be optimal with fewest damages formed for the intensive drillings (feed rate >350mm/min).

The damage areas above were analysed through a straightforward approach to measure the delamination at the exit of hole. Considering the potential overall damaged areas where were failed to observed or ignored, a different strategy by defining the area of the minimum circumscribed circle of the delamination region [40], A_{DEL}, was performed to further find out the toughening effect by the proposed method, as shown by Fig. 3. The delamination factors were then defined and calculated by Eq. 4:

$$F_{DEL} = \frac{A_{DEL} - A_{HOL}}{A_{HOL}} \tag{4}$$

The calculated delamination factors and delamination area are shown in Fig. 5. The delamination factors shown in Fig. 5a has demonstrated an agreement with what was shown in Fig. 4, which the damage resistance of the laminates with toughening have been significantly improved. For lower feed rate of 150 mm/min, almost same delamination areas (See Fig. 5b) were created for both 5 and 20 wt. % toughened laminate whereas a larger damage area was resulted by the 10 wt. % toughener printed. The difference of the damaged areas might be due to the assumption of the calculation from the circular areas captured. But the result helped to further prove the earlier finding that a low weight content of toughener would be recommended during drilling when feed rate was low.

For the higher feed rates scenarios, an optimal weight content of 10 wt. % of the PMMA toughener was found to decelerate the most delamination propagations during drilling where showed the smallest damage area and factor (See Table 4), in particular, at a more intensive feed rate level. Compared to the results in Fig. 4, a good agreement has been met that both prediction approaches led to the same optimal content value of 10 wt. % for the best toughening effect. It makes sense that with a higher PMMA content printed than 5 wt. %, the interfacial properties were further toughened and therefore the delamination were kept decreasing. However, once the content value was beyond 10 wt. %, there might be excessive micro-particles deposited along the individual interface, which induced the local stress concentration and accelerated to initiate the delamination.

Therefore, for high feed rate drilling request, content value of 10 wt. % was suggested to be optimal according to the minimisation of the delamination.

3.2 Toughening mechanism analyses

According to the conclusions assessed in the section above, the least delamination was recorded when the toughener concentration was 10 wt. %. Therefore, this typical case was selected to analyse the thrust forces and torques under different feed rates and compared with CFRP without printed PMMA, aiming to reveal the toughening mechanism on how to minimise the delamination formed during drilling.

3.2.1 Thrust force

Figure 6 illustrates the thrust force histories by comparing both toughened and untoughened CFRPs at different feed rates of drilling. To get rid of the noise confusion from the measured data, a post-processing was conducted by developing a programme to filter the high frequency vibrations of those above 10 Hz.

It is hardly seen with an obvious difference at the initial drilling phase between laminates with and without toughening for all feed rates, however, with the drill bit further penetrated the laminates, the toughening was shown with a higher thrust force until complete drilling exit, especially at the highest feed rate condition. Therefore, in order to figure out the toughening mechanisms during the whole drilling process, three stages were categorised as A, B and C (shown in Fig. 7) to help clarify how the toughening affected delamination and reflected by the thrust forces in Fig. 6. In Stage A, it showed the moment that the chisel edge initially contacted the top surface and drilled laminate. Stage B was the occasion that the chisel edge was at a critical status of the perforation. Following that, in Stage C, it was the scenario when drill bit has completely perforated the laminates.

In stage A, the thrust force intensively increased since the feed of the drill bit started. The peak-to-peak oscillations could be observed afterwards because of the damage propagation with the drilling process. The thrust force obtained of the toughened laminate was smaller than that of the untoughened one at this phase. The reason might be due to the chisel edge was the only contributor to the initiation of penetrating laminate. A toughened laminate offered a stronger bending resistance so that the penetration was initiated by in-plane damages of the top surfaces where the local stress was concentrated contacted with the drill bit.

At stage B, due to the drill bit has critically perforated the laminate, the chisel edge was less able to result a high reaction force from the contact of laminate like stage A, the thrust force was hence significantly dropped. It has to be noted that the thrust force measured in the toughened laminates kept a larger value than that in the untoughened case. That could be attributed to the predominant role of the primary cutting edge, which determined the thrust force instead of the chisel edge. The toughened interfaces resulted in a higher reaction force for the primary cutting edges of the drill bit.

Afterwards, the primary cutting edges played the most important role to completely perforate the laminate, and the thrust force became relatively stable across stage C. Similarly, based on the analysis for the stage B, the experimentally measured thrust force of the toughened laminates was higher again due to the predominance of the primary cutting edges.

In addition, the comparison of thrust forces in Fig. 6 could help to validate the previous assessment in section 3.1 that the toughening effect was maximised for a relatively intensive feed rate condition. In Fig. 6c, the greatest errors at both stages B and C between toughened and untoughened laminates could be always obtained, which indicated a better resistance to the primary cutting edges when the drill bit tended to perforate the laminate.

3.2.2 Torque

The torque-time histories for comparison of untoughened and toughened with 10 wt. % of PMMA laminates were experimentally measured in Fig. 8, at different feed rate conditions. The torque-time histories were still analysed based on the three phases defined by A, B and C. For stages A and B, it can be seen that a greater torque was always shown for toughened laminates, however, for stage C, it was reverse that the torque value of toughened laminates became smaller than those without toughening. Following the analysis in 3.2.1, due to the higher bending resistance of the toughened laminates, there was a larger contact area between the top surface of laminate and drill bit, and therefore resulting in a higher torque. However, for the untoughened laminate, the thrust force predominantly contributed the deformation of laminate through the thickness, which the torque effect was thus weakened. Once the drill bit penetrated the laminates, the improved toughening behaviour by PMMA was more obvious to resist the form and propagation of delamination and prevent the further penetration, therefore a higher torque was required to overcome it. That is why the higher torque was always observed for the toughened laminates until stage B.

When it came to the stage C, the torque value of toughened laminate drilled under feed rate of 150 mm/min was remarkably lower than that of untoughened laminate. That might be due to the untoughened laminate was more bent than toughened one and at the exit of the hole the drill bit had to cut off the excessive deformed material and therefore required a stronger torque. It can be also seen that when the feed rates were higher, for instance, 550 mm/min, there was only a slight difference of torque between toughened and untoughened laminates at this stage. This phenomenon could be due to the thrust load has primarily contributed the perforation at such intensive feed rate. At the exit of the hole, consequently, there were more damages formed instead of the deformation due to bending by the feed rate of 150 mm/min. Therefore, for either type of laminate, a far difference of torque was rarely found. This hypothesis could be further validated by the previous damage assessment images at the exit of hole in Table 3.

4. Conclusion

In this paper, a novel approach by inkjet printing the micro-scaled toughener was developed to study the delamination resistance for the composite drilling. PMMA was printed onto the prepregs to improve the interlaminar fracture toughness of the CFRP laminates. The effects of toughener weight contents and feed rates were experimentally measured to assess the induced delamination resistance through drilling. The delamination images were discussed combing with the predicted damage areas and factors. To further figure out the mechanisms of the toughening effect on drilling process, the thrust forces and torques were analysed in details, respectively, which the 10 wt. % of toughening content was selected as a typical example to be compared with untoughened laminates under the various feed rates. Some key conclusions can be drawn as follows:

1. In general, the delamination induced at the hole exit was increased with an increasing of the feed rate, however, due to the toughening effect, both damage areas and damage index factor were significantly reduced. The less damages were visually found by the damage images captured.
2. The optimal content of the PMMA toughener was suggested to be 10 wt. %, which was more obvious for the relatively high feed rate. For the low feed rate condition (≤150 mm/min) a content of 5 wt. % was advised to use by considering the fabrication efficiency.
3. The printed tougheners have affected both thrust force and torque during drilling. This was because the toughened laminates generally exhibited a better bending resistance and therefore there were less damages produced at the exit of the hole once the drilling was completed, which was particularly obvious to the relatively higher feed rate operation.

This study is helpful to find out how the additive inkjet printing technology helped to toughen the whole laminate with improvement of damage resistance during drilling. It will be aimed to offer a useful guidance on optimisation of composite drilling, especially suitable to the cases which request high feed rate processing, for both enhanced drilling quality and efficiency.

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