

Minimizing the Drilling-Induced Damage in Fiber Reinforced Polymeric Composites

S. D. El Wakil, M. Pladsen

Abstract—Fiber reinforced polymeric (FRP) composites are finding wide-spread industrial applications because of their exceptionally high specific strength and specific modulus of elasticity. Nevertheless, it is very seldom to get ready-for-use components or products made of FRP composites. Secondary processing by machining, particularly drilling, is almost always required to make holes for fastening components together to produce assemblies. That creates problems since the FRP composites are neither homogeneous nor isotropic. Some of the problems that are encountered include the subsequent damage in the region around the drilled hole and the drilling – induced delamination of the layer of ply, that occurs both at the entrance and the exit planes of the work piece. Evidently, the functionality of the work piece would be detrimentally affected. The current work was carried out with the aim of eliminating or at least minimizing the work piece damage associated with drilling of FRP composites. Each test specimen involves a woven reinforced graphite fiber/epoxy composite having a thickness of 12.5 mm (0.5 inch). A large number of test specimens were subjected to drilling operations with different combinations of feed rates and cutting speeds. The drilling induced damage was taken as the absolute value of the difference between the drilled hole diameter and the nominal one taken as a percentage of the nominal diameter. The later was determined for each combination of feed rate and cutting speed, and a matrix comprising those values was established, where the columns indicate varying feed rate while and rows indicate varying cutting speeds. Next, the analysis of variance (ANOVA) approach was employed using Minitab software, in order to obtain the combination that would improve the drilling induced damage. Experimental results show that low feed rates coupled with low cutting speeds yielded the best results.

Keywords—Drilling of Composites, dimensional accuracy of holes drilled in composites, delamination and charring, graphite-epoxy composites.

I. INTRODUCTION

FRP composites have recently gained widespread industrial applications. This is due to their excellent mechanical properties such as the specific strength and the specific modulus of elasticity compared with those of metals. An additional advantage is the ability of the designer to tailor the composite properties to meet specific needs by the selection of appropriate reinforcement materials, their ratio, and the orientation of the reinforcing fibers in each ply in laminates. Near-net-shape parts and panels can conveniently be produced to meet specific needs. Nonetheless, further secondary processing such as machining (or adhesive bonding) is almost

always indispensable for the production and assembly of components. In this respect, drilling is the most commonly used machining process for composites, because of the need for holes for fastening mechanical components and subassemblies. It has to be born in mind, however, that machining of FRP composites, and particularly, drilling, is different from that of conventional engineering materials because of the anisotropic nature of composites.

Composites, as the name suggests, are composed of two constituent materials, namely matrix and fiber reinforcement. Consequently, the properties of each of them, as well as its ratio and orientation have significant effect on the drilling operation. The process parameters such as feeds and cutting speeds should be carefully chosen in order to avoid defects such as splintering, delamination, and burning of the composite material around the hole. Those drilling-induced flaws would result in poor assembly tolerance, structural performance deterioration, shorter service life, and eventually catastrophic failure of the product or assembly.

In recent years, there has been greater emphasis on development of alternative hole-making operations. Several non-traditional hole-making processes have been reported. Those included laser-beam, water jet, and ultrasonic drilling as well as electrical discharge machining (EDM). Nevertheless, conventional drilling using twist drills is still the most economic and convenient hole-making operation for FRP composites. Therefore, numerous studies were carried out to examine the effects of process parameters on the quality of drilled holes [1], [2]. It was found that, generally speaking, drilling-induced damage occurs at both the entrance and the exit planes of the workpiece. It was also found that the damage correlated to the thrust force, which in turn depends on several factors such as the geometry and material of the tool and the workpiece, the drilling process parameters, and the cooling conditions. The obtained equations are, however, very complicated and cannot easily be applied. Therefore, the objective of the current study is providing simply applicable guidelines and recommendations for minimizing the drilling-induced damage. It involves employing the multivariable analysis in order to optimize the drilling process parameters and thus minimize the drilling-induced damage of the FRP composites.

II. EXPERIMENTAL

A. Materials

While several polymers are used as matrix material in composites, epoxy resin is the most commonly used one particularly for structural composites. On the other hand,

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carbon, glass, graphite, aramid, silicon carbide, and born fibers, are used as reinforcement, but graphite is definitely favored for reinforcing epoxy. Graphite-epoxy composite is, therefore, commonly used in marine, aerospace, and light-weight structural applications because of its non-volatility, good thermal and dimensional stability, and very strong bond between the fibers and the matrix. Consequently, it was decided to use graphite-epoxy composite throughout the experiments in this study. Each specimen was a strip of graphite-epoxy, which was 38.1 mm (1.5 inch) in width, 12.7 mm (0.5 inch) in thickness, and 101.6 mm (4.0 inch) in length, allowing three drilling experiments to be performed. The composite had quasi isometric woven fabric reinforcement, a fiber ratio of 0.7, and was produced by the lay up method. Clear Carbon & Components of Bristol, Rhode Island, U.S.A, supplied the composite material used throughout the current research.

B. Drilling Operation

All drilling operations were carried out using a CNC Bridgeport milling machine fitted with a Heidenhein controller. Thus, the drilling feed rate and the cutting speed could precisely be controlled and determined. The feed rate varied between 0.212 mm/s (0.5 inch/minute) and 1.06 mm/s (2.5 inch/minute), in increments of 0.212 mm/s (0.5 inch/minute). For each of the above-mentioned feed rates, the cutting speed was varied between 0.254 m/s (50 ft./minute) and 1.27 m/s (250 ft./minute) in increments of 0.254 m/s (50 ft./minute), thus yielding 25 combinations of feed rate and cutting speed.

During the drilling operation, the specimen was held firmly by a vise and rested on two parallels. The distance between each two successive holes was at least 12.7 mm (0.5 inch). The tool used throughout the study was a conventional twist drill having a diameter of 12.7 mm (0.5 inch) and a tool point angle of 118 degrees. Flood cooling of the specimen was not used, but the twist drill was subjected to cold airflow with mist coolant to reduce its temperature thus avoiding burning of the composite.

C. Measurements

For each combination of feed rate and cutting speed, three experiments were performed and the maximum diameter of the drilled hole on the inlet plane was determined in each case. The average of those three measurements was taken to represent the maximum diameter corresponding to that specific combination of feed rate and cutting speed. Also, an identification code was marked in the vicinity of each drilled hole, for possible use later. Finally, the maximum diameter of each drilled hole was accurately measured using an optical comparator Deltronic MPC-1 with an accuracy of 0.0025 mm (0.0001 inch). Fig. 1 shows the projection of a drilled hole as it appeared on the screen of the optical comparator.

The process of determining the hole diameter involved selecting three points on the perimeter of the circle. The machine would then indicate the radius of the circle with that high precision.



Fig. 1 The projection of a drilled hole as it appeared on the screen of the optical comparator

III. RESULTS

The maximum drilled-hole diameters for the various combinations of feed rate and cutting speed are given in Table I. As can be seen from the above-mentioned table, all of the maximum drilled-hole diameters are less than the nominal diameter of the twist drill that was used to produce them, and which actually was 12.7 mm (0.5 inch). Furthermore, smoke arose and charring odor developed during the drilling operation, and they increased with increasing feed rate and /or cutting speed. In fact, the 12.7 mm (0.5 inch) twist drill that was used to produce those holes could not fit into any of them because they were noticeably smaller, as was mentioned in previous literature [3], [4]. Accordingly, it was decided to use an appropriate expression for the drilling –induced damage factor (DF), which involved the absolute value of the difference between the drilled hole diameter and the nominal one taken as a percentage of the nominal diameter.

TABLE I
DRILLED – HOLE DIAMETERS FOR VARIOUS RATES AND CUTTING SPEEDS

Feed rate (mm/s)	Cutting speed (m/s)				
	0.254	0.508	0.762	1.016	12.7
0.212	12.352	12.113	12.113	12.108	11.895
0.424	11.298	11.374	11.646	10.968	11.488
0.636	11.941	11.542	11.524	10.65	11.306
0.848	11.618	11.626	11.534	11.069	11.504
1.06	11.758	11.641	11.3	11.389	11.397

The calculated values of the drilling – induced damage factor (DF) for the various combinations of feed rate and

cutting speed are given in Table II. That matrix was then subjected to interpretation and analysis in order to obtain the optimal conditions for the drilling operations.

TABLE II
THE DAMAGE FACTOR FOR VARIOUS FEED RATES AND CUTTING SPEEDS

Feed rate (mm/s)	Cutting speed (m/s)				
	0.254	0.508	0.762	1.016	12.7
0.212	2.74	4.62	4.62	4.66	6.34
0.424	11.04	10.44	8.3	13.64	9.54
0.636	5.98	9.12	9.26	16.14	10.98
0.848	8.52	8.46	9.18	12.84	9.42
1.06	7.42	8.34	11.02	10.32	10.26

IV. DISCUSSION

The phenomena observed during the drilling experiments can be explained if we bear in mind that the energy consumed in removing the material reappears as thermal energy. The later is retained in a narrow zone surrounding the drilled hole because of the low coefficient of thermal conductivity of the composite. The final outcome would, therefore, be a noticeable increase in the temperature localized around the hole that is undergoing machining. The higher the feed rate and/or the cutting speed, the higher the temperature of the machined surface would be. In some extreme cases, the resulting temperature was high enough to cause charring of the epoxy matrix of the composite material. Another detrimental effect of the high temperature generated, is the deviation of the diameter of the drilled hole from the nominal diameter of the twist drill used in producing it. The diameter of any drilled hole is definitely identical to that of the drilling tool, but only at the high temperature generated during the drilling operation. After the later is completed and the drilling tool is withdrawn, the temperature of the localized zone surrounding the hole would then drop resulting in shrinking of the diameter of the drilled hole. Consequently, it should be expected that the higher the generated temperature during drilling, the smaller the diameter of the resulting hole would be, when compared to the nominal diameter of the drilling tool. The extent of the deviation of a drilled hole diameter from the desired nominal value of the tool, is referred to as the drilling –induced damage factor (DF), and is usually taken as a percentage of the nominal value of the diameter.

Fig. 2 indicates the variation of the drilling –induced damage factor versus the cutting speed for different values of feed rate. It can be seen in the figure that the drilling-induced damage factor is the lowest and has a value of 2.74 per cent when a combination of the lowest feed rate and lowest cutting speed was used in drilling. This was actually expected. It is also clear from that figure that the value of the drilling –induced damage factor increases with increasing cutting speed for the same value of the feed rate (0.212 mm/s, 0.5 inch/min.) and attains a value of 6.34 percent. For the other values of feed rate, the values of the drilling –induced damage factor are much higher and the trend of the curves is different. The values of the drilling-induced damage factor increase with increasing cutting speed, but attain a maximum value at a

cutting speed of about 1.0 m/s, then drops again. That trend can be explained if we bear in mind that each of the thrust force, the drilling torque, and the thermal energy generated is a function of the feed (i.e. mm/rev. or in/rev.) and not of the feed rate (mm/s or in/s). Each of them increases with increasing feed, and of course decreases with decreasing feed. Consequently, increasing the cutting speed (or in the other words the rpm), while keeping the feed rate constant, would equate to reducing the feed and therefore the thermal energy released. The final outcome would evidently be less thermal damage and lower values of drilling –induced damage factor

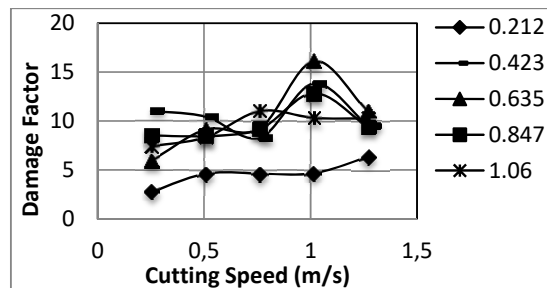


Fig. 2 Variation of the drilling-induced damage factor versus the cutting speed

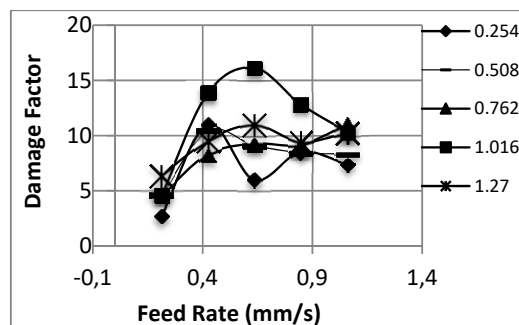


Fig. 3 Variation of the drilling-induced damage factor versus the feed rate

The variation of the drilling-induced damage factor with the feed rate, for different values of cutting speed is shown in Fig. 3. As can be seen in that figure, the drilling –induced damage factor increases with increasing feed rate (i.e. with increasing feed for the same cutting speed/rpm), as was reported in previously published literature [3]. It then almost flattens at a value of 10% damage factor DF. Nevertheless, that trend did not hold true when the cutting speed was 1.016 m/s. The reason is not clear and could not be explained because of the complexity of the problem of heat dissipation and heat generation, which result in the thermal damage. Again, the lowest value for the drilling-induced damage factor, which translates to the highest quality, is obtained when the combination of the lowest feed rate and cutting speed is employed. This is in general agreement with previously published work [5]. In fact, those are the optimal process parameters as confirmed by the outcome of the Minitab software. In addition, flooding the work piece with a coolant

during the drilling process would flush the generated heat away and would further decrease or even eliminate the drilling-induced damage factor when the process parameters are optimal. On the other hand, lower feed rates translate to longer machining times. Accordingly, the above-mentioned combination of feed rate and cutting speed is optimal when the quality of the hole is the only consideration, and when productivity is not included as a factor. Again, for the combination of lower values of feed rate and cutting speed, coupled with flood cooling, it might be possible to eliminate the drilling-induced damage completely, thus be able to use the drilled hole. This is evidently not the case when high feed rates and cutting speeds are used. While drilling time would be shorter, further secondary machining would almost be a must, something that translates to longer production time. In addition, higher values of feed rate or cutting speed would result in the increase in tool wear, with the need for frequent tool changes, thus detrimentally affecting the production economies.

It is important to emphasize that the scope of the current work was limited to investigate the deviation of the diameter of the drilled hole from the nominal one due to the thermal damage at the inlet plane. There is also, however, a different type of damage at the exit plane which is usually referred to as the thrust-induced damage. It can be explained by considering the action of the twist drill on the composite plate similar to that of a pin exerting pressure on a shell, thus creating thrust force and bending moment. In the case of composite drilling and when the tool penetrates and reaches the lowest ply, the thrust coupled with the bending moment would result in delamination and fracture. Reducing the feed rate when the tool reaches that ply before exiting the work piece can eliminate that problem.

V.CONCLUSION

1. The drilling-induced damage factor (DF) has been determined for various combinations of feed rates and cutting speeds, when drilling a 12.7 mm (0.5 inch) slab of graphite-epoxy composite without using a coolant.
2. It has been found that the minimum drilling-induced damage factor is obtained when using a feed rate of 0.212 mm/s (0.5 inch/min.) together with a cutting speed of 0.254 m/s (50 ft./min).
3. While it is expected that the drilling –induced damage factor would further decrease or even be eliminated if a coolant is used to flood the work piece during drilling, further research is needed to confirm that and to expand the scope of the current work.

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