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# Effects of tool geometry and process parameters on delamination in CFRP drilling: An overview

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**Abstract**

Fiber reinforced polymers (FRPs) show advantageous physical-mechanical, thermal, and dielectric characteristics, making them promising candidates for weight reduction in structural applications. However, machinability is often difficult because of the specificity of their structure. This paper highlights the latest advances in CFRP drilling. Key papers are analyzed with respect to workpiece materials, geometrical tool features, and input variables (such as variation in process parameters). The influence of tool geometry and process parameters on workpiece delamination and hole quality/integrity represents the primary focus of this review. In addition, some new data are presented and discussed.

*Keywords:* Carbon fiber reinforced plastics; Drilling; Tool geometry; Delamination; Surface integrity.

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## 1. Introduction

Fiber reinforced polymers (FRPs) are increasingly applied in aerospace and automotive structural components, mainly due to their high strength-to-weight ratio and stiffness. FRPs are made of a thermoset or thermoplastic polymer matrix that binds carbon (CFRP) or glass (GFRP) fibers [1]. The machinability of such composite materials is related to the anisotropy/heterogeneity of their structure, together with the high abrasiveness caused by the fiber reinforcements [2-4]. Drilling is a common machining process for components made of composite laminates. The hole quality is affected negatively by matrix cratering, thermal damage, spalling, surface delamination, and material degradation (e.g., fiber pullout). Delamination, in particular, is defined as the interlaminar crack propagation in laminated fiber reinforced plies [3]. This phenomenon is due to the combined action of thrust force and torque. The presence of delamination significantly reduces the fatigue resistance as well as the hole quality in terms of dimensional and geometrical tolerances [5]. The design of drilling processes through the choice of suitable tools, process parameters, and cutting conditions appears to be a key task for reducing the hole delamination. In this context, focusing on CFRP drilling, the present paper reviews and discusses the main outcomes achieved with different cutting tool geometries at the varying of process parameters. In addition, some new results obtained by the authors are included in the discussion.

## 2. Drilling-induced delamination

The delamination factor ($F_d$) is the most commonly applied index for evaluating the delamination of a drilled hole. $F_d$ is typically defined as the ratio between the maximum diameter of the delaminated zone ($D_{max}$) and the hole nominal diameter ($d$), as shown in Figure 1. The delamination factor can be assessed either at the hole entrance (where fibers are peeled up), or at the hole exit (where fibers are pushed down). At the hole entrance, adjacent plies could be separated by a peeling force due to the slope of the drill bit flutes. At the hole exit, the uncut plies below the drill could be affected by deformation owing to their reduced thickness. Push-out delamination is observed more frequently than peel-up delamination, particularly when the thrust force exerted by the drill is greater than the inter-ply bonding strength [1].

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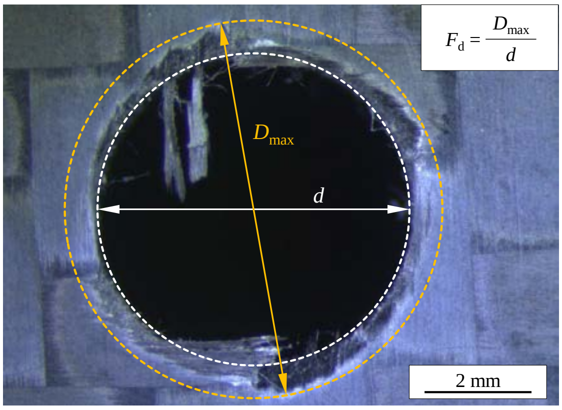

Fig. 1. Assessment of delamination factor ($F_d$) at hole exit.

## 3. Effects of tool geometry on hole delamination

Many authors have focused on the drilling of composite materials with a variety of tool geometries. Besides standard twist drills [2-21], twist drills with double point angle [18], ‘one shot’ drills [13, 18], ‘brad & spur’ (or candle stick) drills [2, 4, 6-9, 12, 14, 17, 20, 22], drills with multiple flutes [3, 12, 13, 20], step drills [6, 8, 9, 14, 15, 17, 21], dagger drills [8, 14, 17], saw drills [4, 6, 7, 9], core drills [6, 9-11, 16], step-core- [23-25] and core-special drills [6, 25] were also applied. The main difference among drill geometries is the different distribution of cutting forces exchanged with the workpiece.

### *3.1. Conventional twist drills*

The comparison conducted by Faraz et al. [13] between conventional twist drills, two types of three-flute drills with a helix angle, and straight-four-flute drills revealed that the conventional drill type led to a lower delamination (up to 50% with respect to the $F_d$ of straight-four-flute drills), especially at the hole exit. This can be traced back to the lower thrust force level, especially compared to that of four-flute drills with a zero rake angle at the cutting edge. The authors highlighted that delamination, especially at the hole exit, was very sensitive to the rake angle of the drill cutting edge. Davim and Reis [3] showed that carbide twist drills achieved better performance than High Speed Steel (HSS) twist drills and carbide four-flute drills, allowing a lower delamination factor. In addition, carbide drills were a better choice for CFRP drilling also due to their lower tool wear progression. When using a pilot hole, drilling with twist drills represented the best solution as evaluated by Marques et al. [14] during the comparison of twist, brad, dagger, and special step drills. When drilling reinforced laminates it is preferable to use a drill bit geometry that reduces the indentation effect of the chisel edge. Entry delamination factor was found by Shyha et al. [15] to be (5%) lower with conventional drills compared to stepped drills. This result was in contrast with the results presented by the same authors in terms of thrust force, tool life, and drilling torque. To minimise delamination Durão et al. [17] suggested twist drills with a higher point angle (120° instead of 85°) with respect to brad drills, dagger drills, or step drills. It is known that peel-up and push-down delamination are affected in contrasting ways by the point angle. Gaitonde et al. [5] highlighted that thrust force and delamination at the hole exit were reduced up to 45% by using a lower point angle (85°) that enables a cutting edge angle reduction. Regarding entry delamination, Shyha et al. [15] achieved better performance with the point angle of 140° with respect to the point angle of 118°. Within the same study, this result was in contrast to that in term of thrust force where the smaller point angle led to a lower force level.

### *3.2. Other tool geometries*

Compared to twist drills, ‘brad & spur’ drills reduce the delamination factor [2, 4, 7, 8, 12, 20], even if power and specific cutting pressure are higher [2]. Moreover, the thrust force depends on the chisel edge geometry: a shorter chisel edge length can imply a lower contribution on thrust force. Candle stick drills and saw drills have a smaller center with respect to twist drills. This entails a smaller extent of the last laminate that is subjected to bending force. It has been found that delamination occurs only over a critical thrust force level. Above that level, delamination is due to matrix cracks generated by the growth of crack tips [4]. Tsao and Hocheng [7] highlighted a lower delamination extent (of 55%) when drilling with candle stick drills rather than with twist or saw drills. Candle stick drills (C-shape) used by Durão et al. [8] achieved the best results in terms of delamination compared to twist drills (either with or without the pilot hole), dagger drills, and step drills. During drilling of GFRP laminates Abrão et al. [12] found lower damage on both sides of the holes when using ‘brad & spur’ drills with respect to two different twist drills (made of HSS or tungsten carbide) and three-flute drills. This was also due to the lower thrust force values allowed by this type of geometry that is similar to a trepanning tool. Spur drills used by Grilo et al. [20] performed holes with no or only slight delamination (below 1.3 for the lowest feed rate) for all cutting conditions tested, either at the hole entrance or at the hole exit. Twist drills and four-flute drills gave worse results with respect to spur drills.

According to Hocheng and Tsao [9] core drills showed better results in terms of delamination compared to those of twist drills, saw drills, candle stick drills, and step drills. Core drills were advantageous because they allowed a higher critical thrust force level, which causes the onset of delamination. Core drills caused a lower delamination in comparison to twist drills due to the distribution of the thrust force toward the drill periphery [10]. Tsao [11] showed that the surface of holes drilled with core drills was smoother than that obtained with twist drills. It was shown that cemented or plated diamond core drills are suitable to improve hole quality compared to conventional drills [16]. Plated diamond core drills show better self-dressing capability and more chip pockets than cemented diamond core drills. In addition, plated diamond core drills are not easily clogged or smeared out.

Step drills with optimized geometry were developed by Isbilir and Ghassemieh [21] using a 3D FE model minimizing delamination and other hole defects. FE simulations indicated that step drills presented advantages in comparison to twist