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Milling angular references and process parameters on fiber reinforced plastics

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Abstract: Machining of fiber-reinforced composites produces delamination in the workpiece. In bidirectional long fiber fabric reinforced composites, delamination depends on different parameters. In this work, two parameters are studied: fiber orientation angle respect to machining direction and the distance of the warp yarn from the trimmed edge until the next dip below the crossing fill. This work defines angles relating fiber orientation with cutting and feed movements and their relations in a robust way, being applied to edge trimming and grooving operations. On the other hand, for Type II delamination, three different kinds of delamination (constant, uniform pattern variation and random) are studied taking into account fiber orientation, wick size and the fiber orientation angle respect to machining direction.

Keywords: Edge trimming, Delamination, Fiber cutting angle.

1. Introduction

Delamination is one of the main problems that appears when machining fiber-reinforced composites, and affects to dimensional precision and posterior joining between parts. Delamination consists of a separation of the fabric layers from the composite material due to the force exerted by the cutting tool during machining process. Cutting tool bends fibers instead of cutting them, producing a non-uniform cutting in the part. In trimming edge, delamination appears in the upper and lower layers, if there is not enough resin to hold the fiber fabric. Delamination can be classified into three types: I, II and III, and Type II appears when there are fibers that protrude from the machined edge.

The most studied factors to evaluate delamination in machining are cutting conditions (cutting speed, feed per tooth and depth of cut), fiber orientation angle respect to machining direction and material and geometry of the cutting tool [1]. In order to study delamination in angular regions with different fiber orientations, the following angles have been defined: fiber orientation angle, fiber cutting angle and cutter engagement angle [2]. Although different authors have worked with these angles, there is no accord about nomenclature, definitions and relationship between them to explain delamination. For instance, some of them define fiber orientation angle measured counterclockwise from the feed movement to the fiber direction [3-5], and some of them define it clockwise [6]. Fiber cutting angle is defined in different ways as well. On the other hand, when these angles have been defined to the grooving operation, references about fiber orientation angle is not maintained.

In bi-directional long fiber fabric reinforced composites, composed by warp and fill yarns, delamination depends on the distance of the warp yarn from the trimmed edge until the next dip below



the crossing fill. This distance is called X_d [3] and depends on the fiber direction, wick size and the fiber orientation angle respect to machining direction [7].

Firstly, this work proposes a complete and robust definition of angles that characterize milling process of fiber reinforced composites, applied to edge trimming and grooving operations. Secondly, fiber orientation angle respect to machining direction and the distance of the warp yarn from the trimmed edge until the next dip below the crossing fill are studied and related to type II of delamination. Three different kinds of delamination can be observed: constant, uniform variation and random.

2. Definition of reference angles on fiber composite milling

Fiber orientation angle respect to machining direction affects delamination. To study this effect, different angles are defined between fiber direction and fundamental movements of machining process. In this way, the orientation of the fabric with respect to the cutting path of the tool is fixed. Firstly, these angles will be particularized for the trimming edge (down milling), where the cutting movement (M_c) is carried by the cutting tool and the feed movement (M_a) is carried by the part. Secondly, angles definition will be applied to the grooving operation, in order to check their consistency. Defined angles are:

- Engagement angle (φ)
- Fiber orientation angle (ϕ)
- Fiber cutting angle (χ)

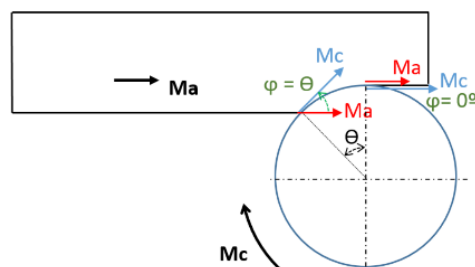


Figure 1. Engagement angle (φ).

Engagement angle (φ) is the angle between fundamental movements (figure 1). It is defined from the feed movement to the cutting movement, in a counterclockwise direction. At the start of the cut, when the tooth enters to cut the workpiece, the engagement angle coincides with the milling angle (Θ) and its value decreases with the rotation of the milling tool until the directions of the fundamental movements coincide. Cutting speed changes direction at every instant, so that the engagement angle changes continuously with the rotation of the milling tool.

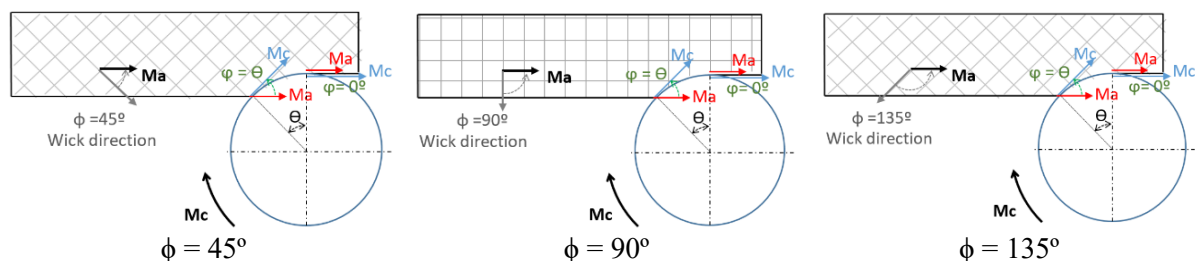


Figure 2. Fiber orientation angle (ϕ).

Fiber orientation angle (ϕ) relates the fiber orientation with respect to feed movement. It is defined from the direction of fiber orientation to the feed movement in a counterclockwise direction. In order to define fiber orientation angle ϕ , positive direction was chosen to be the outward direction of the

machining edge in down milling. Fixed values of 45°, 90° and 135° are chosen, although it could vary if the cutting machining path varies with respect to the fiber orientation of the fabric (figure 2).

Cutting angle (χ) is the angle formed from the fiber orientation to the cutting movement, in a counter-clockwise direction. This angle allows to know how the tool starts cutting the fiber and, consequently, the direction in which the main cutting force is applied. Since the cutting speed changes direction with milling tool rotation at each instant, cutting angle also varies continuously with milling tool rotation (figure 3).

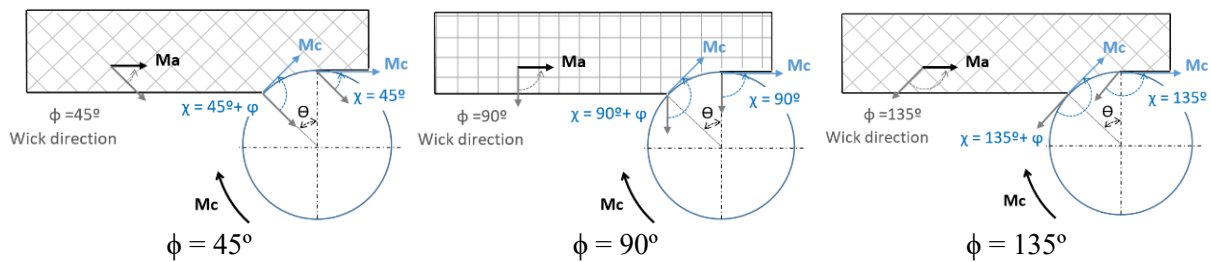


Figure 3. Fiber cutting angle (χ).

Angles defined above are related to each other (Equation 1). Figure 4 summarizes different configurations for down milling trimming edge operation. Engagement angle (φ) at the beginning of the cut always coincides with the milling angle (Θ), being zero at the end of the cut. Cutting angle (χ), which represents the fiber orientation with the cutting movement, is always the result of the sum of the fiber orientation angle (ϕ) plus the engagement angle (φ).

$$\chi = \phi + \varphi \tag{1}$$

In down milling of edge trimming, it can be concluded that at the end of cutting, the cutting angle (χ) coincides with the fiber orientation angle (ϕ), because at that point of machining the engagement angle (φ) is always equal to zero.

		Fiber orientation angle (ϕ)		
		$\phi = 45^\circ$	$\phi = 90^\circ$	$\phi = 135^\circ$
Cutting start		$\chi = 45^\circ + \varphi$ $\varphi = \Theta$ $\phi = 45^\circ$	$\chi = 90^\circ + \varphi$ $\varphi = \Theta$ $\phi = 90^\circ$	$\chi = 135^\circ + \varphi$ $\varphi = \Theta$ $\phi = 135^\circ$
Cutting end		$\varphi = 0^\circ$ $\phi = 45^\circ$ $\chi = 45^\circ + \varphi$	$\varphi = 0^\circ$ $\phi = 90^\circ$ $\chi = 90^\circ + \varphi$	$\varphi = 0^\circ$ $\phi = 135^\circ$ $\chi = 135^\circ + \varphi$

Figure 4. Different angles at cutting start and cutting end for edge trimming (down milling).

These relationships have been deduced when the cutting movement (Mc) is carried by the cutting tool and the feed movement (Ma) is carried by the part. However, if the feed movement is carried by the cutting tool instead of the workpiece, the direction of the feed movement differs by 180° from the above, and other relationships between the different angles are maintained.

In grooving operation, both milling modes are presented: down milling and upper milling. Figure 5 shows engagement angle (φ) variation, fiber orientation angle (ϕ) and cutting angle (χ), maintaining the

previous equation relationship (1), for all fiber orientation angles.

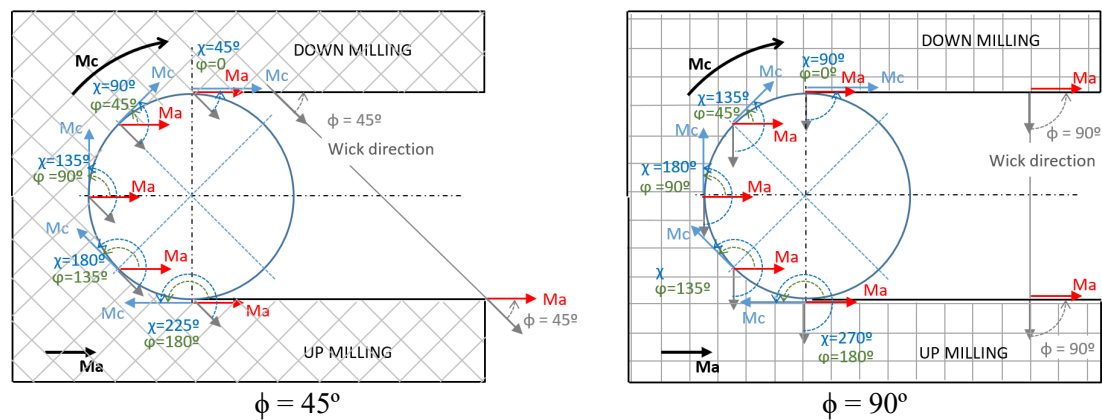


Figure 5. Reference angles in grooving operation.

3. Type II delamination in edge trimming

Type II delamination is the most important delamination produced when milling fibre reinforced composites. It can be classified in three ways, attending to its appearance:

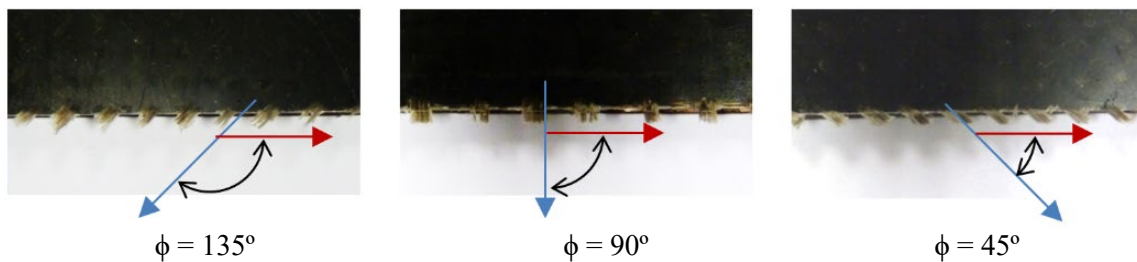


Figure 6. Uniform delamination.

- Uniform delamination (figure 6). It is produced when fiber orientation angle (ϕ) coincides with fiber angle of the fabric (45° , 90° or 135°).
- Wave effect delamination. It is produced in fiber orientation angle 90° , when cutting path is slightly inclined respect to the main direction of the fabric.
- Random delamination. Delamination presents an irregular appearance, varying between light and dense. It appears when fabric is slightly inclined respect to 45° and 135° fiber orientation angle, or when fabric present deformations and fiber orientation vary continuously respect to cutting path.

4. Relation between Xd parameter and Type II delamination

Type II delamination defect depends on Xd parameter. Xd parameter is defined as the distance of the warp yarn from the trimmed edge until the next dip below the crossing fill. Values of this parameter will depend on the fiber orientation, wick size and the fiber orientation angle respect to machining direction.

Xd can take a constant value, it can follow a uniformly varying pattern, or it can be completely random.

4.1. Constant value of Xd

If fiber orientation angle has a value of $\phi = 90^\circ$, feed movement coincides with the weft/ warp orientation of the fabric. In this situation, the value of Xd is constant and coincides with the distance of the warp

yarn from the trimmed edge until the next dip below the crossing fill (figure 7). Therefore, maximum value of X_d can be theoretically the wick size.

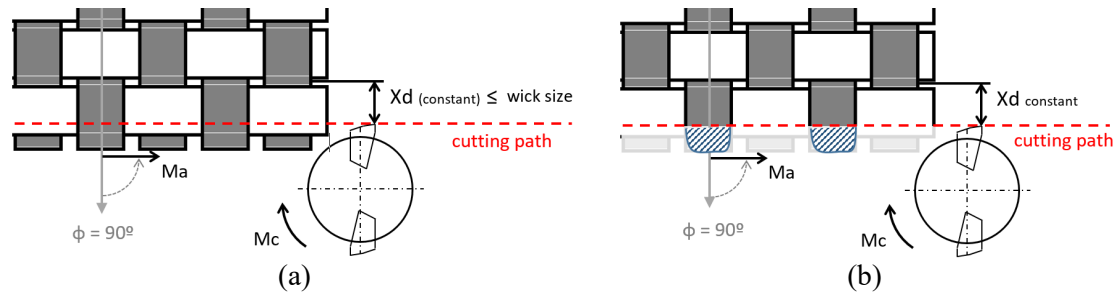


Figure 7. (a) X_d constant with $\phi=90^\circ$; (b) uniform Type II delamination observed.

4.2. Uniform variation pattern of X_d

In certain cases, parameter X_d does not have a constant value, but follows a uniform and predictable pattern of variation. These cases are:

- Fiber orientation angle $\phi = 45^\circ$ or 135° .
- There is a slight path angle of inclination (ρ) of the fabric at 90° fiber orientation with the cutting path.

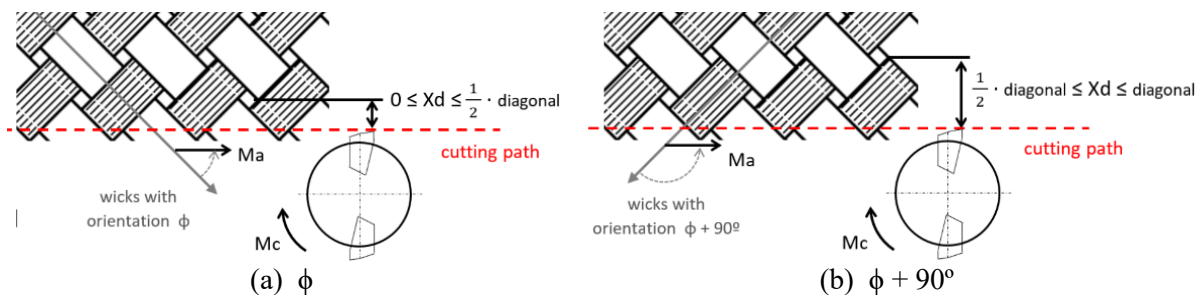


Figure 8. X_d variation with fiber orientation.

In the first case, figure 8 shows variation of X_d between two adjacent yarns at 90° (bidirectional fabric), over the main yarn directions of 45° - 135° . In these cases, X_d parameter varies from zero, to the value of the half diagonal or to the value of the entire yarn diagonal, depending on the point where the tool path crosses the fabric yarn.

Figure 9 shows a schematic of the value that X_d takes at each point. When cutting path passes through the gap between two adjacent yarns, parameter X_d has a value of zero, which increases or decreases as it moves away from or towards the next crossing of fabric yarns.

In the second case, cutting path is slightly inclined with respect to the weft of the fabric. This inclination usually appears, causing a non-uniform delamination at the edge, with an increasing trend until it reaches a maximum at the center of the yarn and decreasing until it reaches a minimum at the crossing between two yarns. Both, X_d and observed delamination have a uniform variation pattern. To study this effect, an angle of inclination of the yarn (ρ) respect to the cutting path is defined and measured from the cutting speed to the weft direction in a counter-clockwise direction. In figure10, it can be observed uniform variation of parameter X_d for a fabric with a main fiber orientation of 90° , but slightly inclined with respect to the cutting path.

Trimming edge presents zones with and without Type II delamination along its length. Delamination is reduced to zero when cutting tool passes through the empty space of fabric between two yarns, because these areas have enough resin to support the reinforcement fabric of the part. Delamination reaches its

maximum value when the tool path crosses the center of a fabric yarn, where the fibers are closer to the surface. Figure 11 shows X_d variation and delamination produced along the trimming edge of the part.

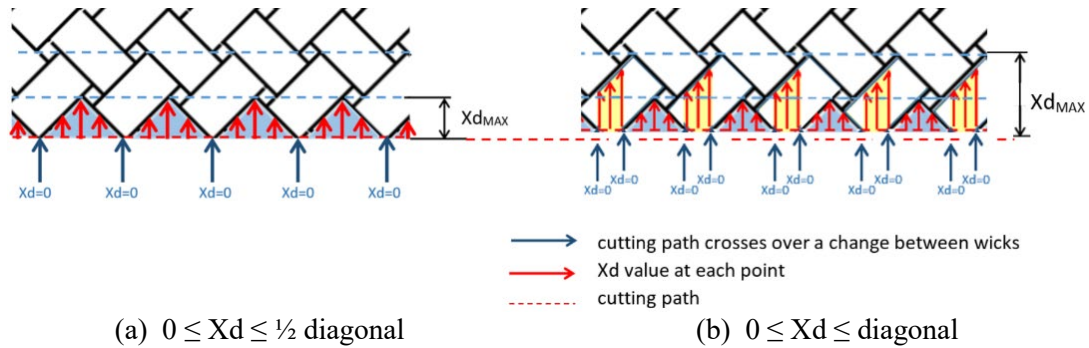


Figure 9. X_d variation with $\phi=45^\circ$ and $\phi=135^\circ$.

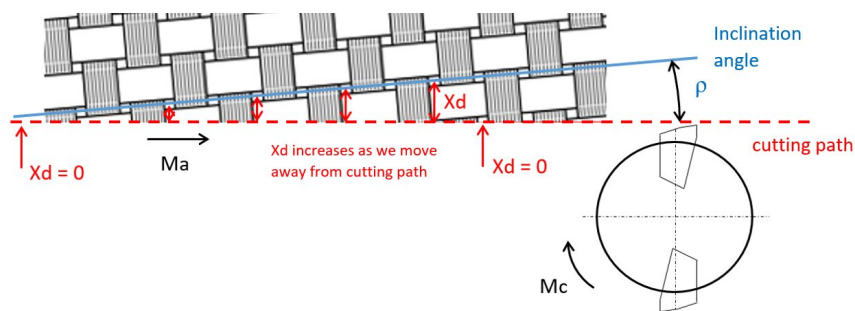


Figure 10. Cutting path slightly inclined.

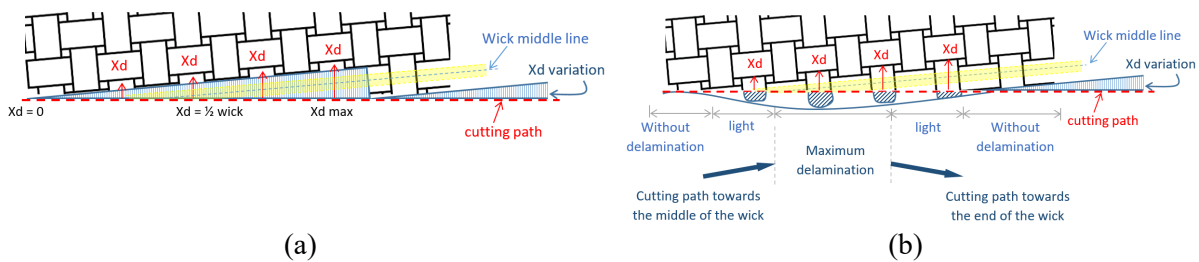


Figure 11. Delamination and X_d variation. (a) X_d and (b) Delamination.

The effect of the slightly fabric inclination during the machining process produces a defect called wave effect of delamination (figure 12).

4.3. Random value of X_d

X_d parameter and Type II delamination take random values in the following cases:

- There is a slight inclination between the cutting path and the main direction of 45° - 135° of the fabric.
- The fabric is deformed and the orientation of the yarns do not form any known angle or do not coincide with the cutting path. This may be due to the fact that the fabric has been deformed during the injection of the resin in the manufacturing process of the laminate.

In the first case, the angle of inclination of the yarn (ρ) is measured from the cutting speed to the direction of the yarns that retain the same fiber orientation in a counter-clockwise direction (figure 13).

Yarns with $\phi = 135^\circ$ orientation are slightly inclined a ρ angle (yellow yarns). These yarns produce delamination in the same direction, but not of the same size, depending on where the cutting tool incises on the yarn.

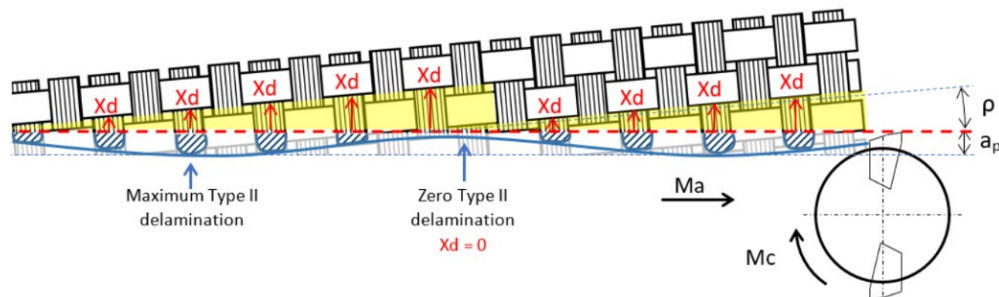


Figure 12. Wave effect in delamination.

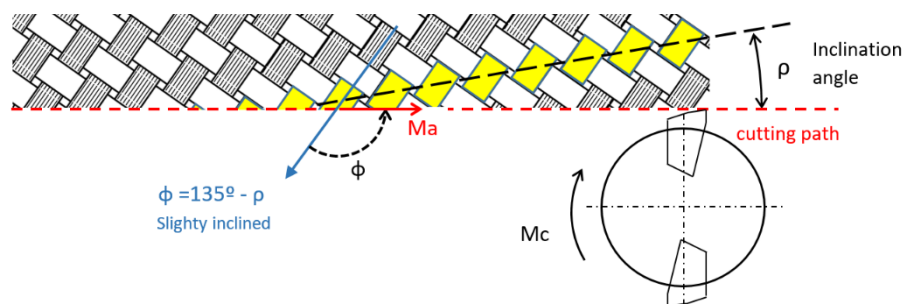


Figure 13. Fabric yarns with uniform orientation.

On the other hand, fabric orientation between two contiguous yarns has a difference of 90° , which corresponds to 135° minus 45° . When the cutting path of the milling tool crosses the space between two yarns, the orientations of the yarns have opposite directions. In figure 14, yellow yarns show fibers with 135° orientation and blue fibers with 45° orientation.

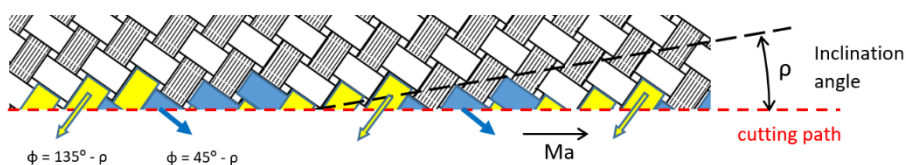


Figure 14. Change of orientation due to the crossing between yarns.

Delamination orientation corresponds at each instant to the orientation of the yarn that crosses the cutting path. For this reason, when the path is inclined with respect to the main direction of the fabric, delamination takes place in a crosswise way according to the orientation of the fabric yarn at the cutting point.

Delamination under these conditions is irregular and is shown in figure 15. In this figure there is an inclination angle (ρ) of 10° respect to the fiber orientation angle of 45° . It distinguishes between areas with and without delamination depending on the point where the yarn is cut and the fabric orientation.

In this case, delamination varies between light and dense depending on the value of X_d at each point of the cutting path, since inside each yarn the parameter X_d also varies (figure 16). Delamination is larger if the tendency is from the incision towards the center of the yarn. Conversely, if the trend is towards the end of the yarn, delamination decreases.

In the second case, when the fabric is deformed, the X_d is random in nature, and consequently, the

delamination produced is also completely random, with the same pattern explained above with respect to how it is produced.

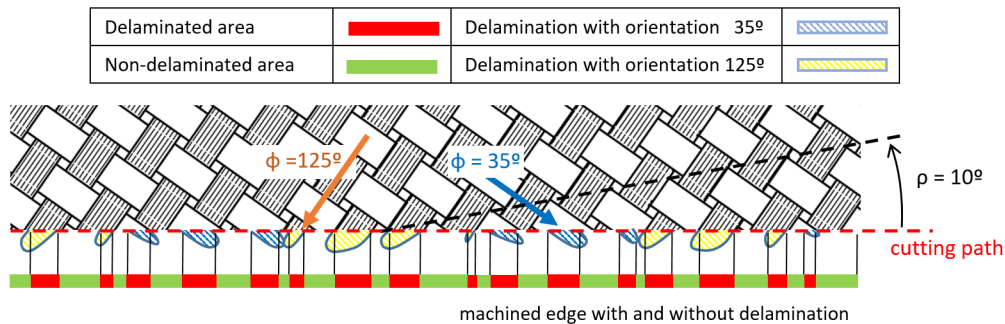


Figure 15. Random delamination.

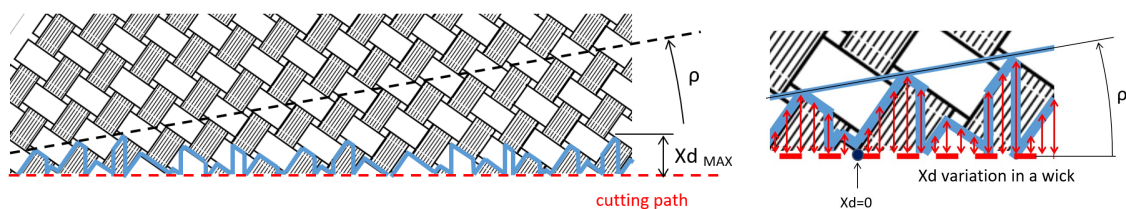


Figure 16. X_d variation for a fabric at 45°-135° slightly inclined.

5. Conclusions

In this article, angles to characterize milling process are defined for edge trimming and grooving operations, giving a robust definition, and showing the relationship between them. Furthermore, possible cases of delamination that can be found in the machining of fabric-reinforced composites have been exposed, taking into account X_d parameter. X_d parameter is defined as the distance of the warp yarn from the trimmed edge until the next dip below the crossing fill. This parameter depends mainly on the orientation of the fabric fiber and the width of the roving, the wick size, as well as the angle of inclination of the fabric with the cutting path. Attending to X_d , it is observed that different forms of delamination of different magnitudes can occur. This parameter can take a constant value, to follow a uniformly varying pattern, or to be completely random. Therefore, delamination can be random or difficult to predict.

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