AUTOMATED FIBER PLACEMENT DEFECTS: INSERTION AND POST-CURE ASSESSMENT

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ABSTRACT

Automated Fiber Placement (AFP) is a process used to manufacture advanced composite structures in the aerospace industry. The occurrence of defects during the layup process is a major drawback for AFP. Often, inspection and corrective measures are needed to meet specifications. These corrective measures are typically time consuming and prone to human error. A better understanding of the effect of AFP defects is essential for appropriate analysis. To achieve that, typical AFP defects have to be reproduced and studied through both experiments and numerical simulations. This paper aims to: (1) propose best practices on how to intentionally insert AFP defects in laminates, and (2) quantify their post-cure persistence through microscopic imaging. The focus is on four primary defects that predominately occur during AFP: gaps, overlaps, twists, and wrinkles. These defects are intentionally inserted at precise locations in laminae oriented at 0°, 90°, and ±45°. A step by step procedure is developed for the manual defect insertion as an effort to standardize the manufacturing process. Several composite panels are produced using the proposed techniques. The persistence of these defects can be depicted through magnified images captured using a microscope. These images can be used for accurate modeling of the post-cure shape of defects, which is necessary for future numerical simulation studies.

Keywords: Automated Fiber Placement, Defects, Gap, Overlap, Twist, Wrinkle.
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1. INTRODUCTION

Automated Fiber Placement (AFP) is gaining advantage over hand layup processes due to improvements in productivity and repeatability. The AFP process consists of laying multiple strips of fibers, named tows, over a prescribed path on the tool using a numerically controlled machine. A roller along with a heating mechanism provide the necessary compaction and temperature for the tows to adhere to the substrate. Typical material used in the AFP process is thermoset pre-impregnated carbon fiber tows, with a recent increase in the usage and exploration of thermoplastic and dry fiber material. Several process parameters such as layup speed, temperature, pressure, and tow tension can be varied to obtain a good layup quality. However, several defects can still occur during the process and necessary repairs may be needed. A detailed description of AFP defects cause, anticipation, existence, significance, and progression is presented in [1]. In order to improve the time consuming process of visually inspecting the placed parts, newly automated inspection systems are heavily researched [2]. Depending on the size of the produced defect, manual repair may be necessary such that the defect does not have a detrimental effect on the structure. In order to answer this question, several testing programs are carried to understand the effect of defects. These tests aim to quantify the degradation in the strength and stiffness properties, for different loading cases such as tension, compression, shear [3], static or dynamic cases [4], as well as their effect on the progressive failure of the laminate [5]. In addition to experimental investigations, numerical studies are also carried to validate and predict their occurrence [6].

In order to reproduce these defects in a consistent manner, this paper aims to propose best practices on how to intentionally insert AFP defects in laminates which can be done either automatically during AFP programming, or manually inserted during the manufacturing process. The focus will be on four most commonly occurring AFP defects: gap, overlap, twist, and wrinkle. Even though defects such as gap and overlaps seem easy to induce, it may not be the case for complex tools. In addition, and up to the authors' knowledge, there has not been a step by step procedure on how to intentionally reproduce twists and wrinkles in the context of AFP defects. Furthermore, the shape of the post-cured defect may be different than the originally placed ones, hence, in this paper, microscopic images are acquired to quantify their post-cure persistence.

This paper is planned as follows: in Section 2, the methodology of inserting AFP defects is explained. In Section 3, the produced defects are captured using microscopic imaging. Finally, concluding remarks are presented in Section 4.

2. DEFECT INSERTION

In this section, defects insertion is discussed for gaps, overlaps, twists, and wrinkle. The placement of the defect along the main three orientations (0°, 90°, and 45°) is presented. When possible, these defects are programmed and placed using the AFP machine (gaps and overlaps). Otherwise, the procedure for hand placement of these defects is presented.

2.1 Gap/Overlap

A gap is when two adjacent tows are not placed perfectly next to each other leaving an empty spacing between them, whereas an overlap is when two adjacent tows are overlaid [1]. The AFP machine can be programmed to intentionally reproduce gaps or overlaps at specified locations. Depending on the direction of the layup, and the cutting profile of the coupons, many designs can be created to meet the objective.

For instance, for a gap/overlap running across the width of the coupon (90° layer, see Figure 1), the lamina can be divided into two separate regions during the programming phase. Those two regions can then be spaced apart with the desired gap width, or they could be overlaid with the intended overlap width. Multiple coupons can be therefore extracted from the layup having the same defect width. For a gap/overlap running along the length of the coupon (90° layer see Figure 2), splitting the lamina into only two regions will result in a very long laminate. Therefore, for each intended coupon to be cut, the layer containing the defect is split into two and shifted with the desired amount of spacing to obtain the gap or overlap defect. Hence, for n coupons, the lamina is split into $n + 1$ regions and spaced accordingly. A similar approach can be applied to a gap/overlap along the 45° (or -45°) by splitting the layer containing the defect into two regions. If the defect needs to be placed exactly in the middle of the coupon, the cutting profile can be shifted around the defect, and the shape of the laminate can be changed to a parallelogram to reduce waste from the two unused portions.

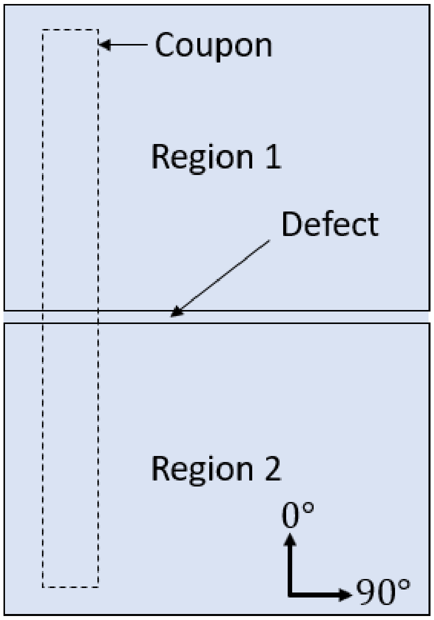


Figure 1 Gap or overlap defect across 90° layer

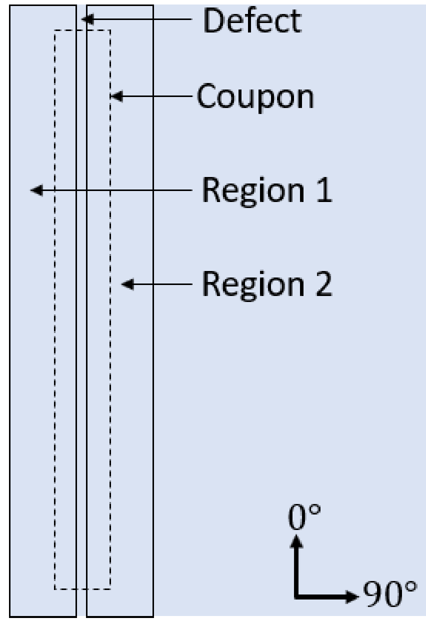


Figure 2 Gap or overlap defect along 0° layer

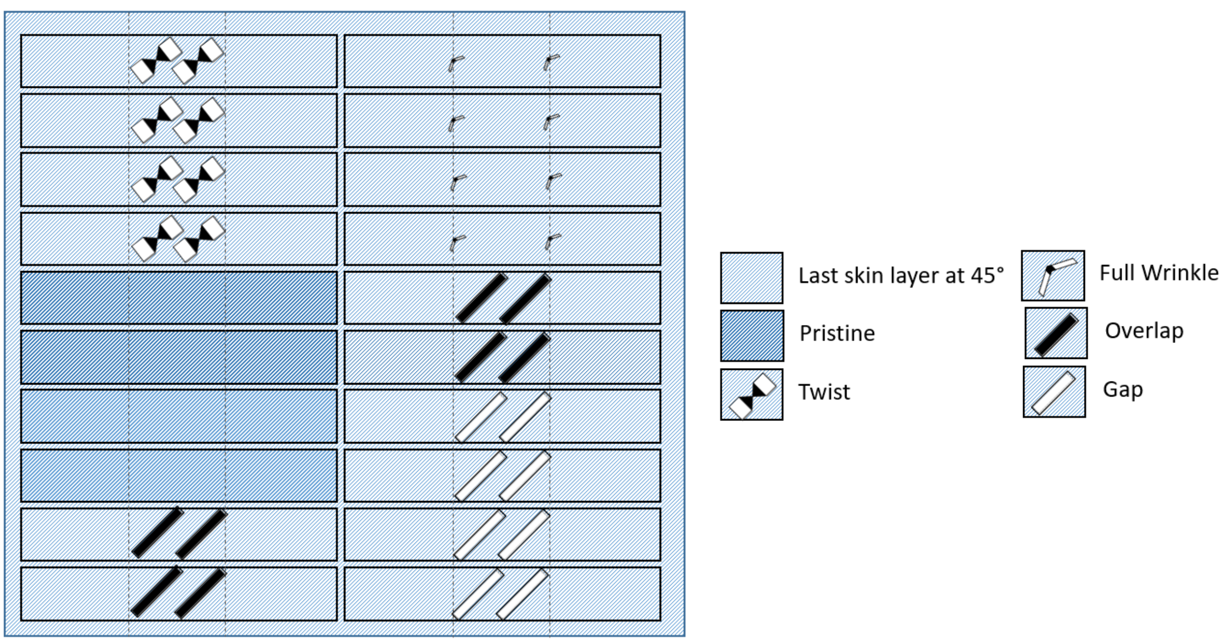


Figure 3 Skin-doubler layup with defects inserted in a 45° layer

For the case of more complicated layup such as the one shown in Figure 3, automatic programming for gap/overlap insertion is not possible and manual intervention is required. The layup shown in

Figure 3 consists of a 12 layers skin placed using AFP tows, and an additional 12 layers doubler/stiffener that is hand placed using woven material. The cutting profile of the coupons is aligned such that the stiffener is centered along their length and having a size equal to the two overhang areas. These coupons are intended to be tested under 3-point bend loading conditions. It is required that the location of the defect is to be aligned at the edge of the doubler in the last layer of the skin oriented at +45°. In addition, the defect cannot extend beyond the coupon's boundaries, so it does not interfere with the neighboring ones. In such a case, manual intervention is required to insert a gap or overlap at the exact location. To facilitate the manual operation, a blueprint of Figure 3 is reproduced on a see-through rigid plastic bag and the locations of the defects are marked. To replicate a gap, the following procedure is used: (1) cut the tow at the boundaries of the coupon, (2) peel the tow from the substrate, (3) slit the tow at the required gap width, (4) place the remaining of the tow in its original location. To replicate an overlap, the following procedure is used: (1) slit a tow with the required gap width, (2) place the slit tow at the defect location. A summary for the manual defect insertion with schematics is shown in Table 1.

2.2 Twist

A twist occurs when the tow rolls axially 180° onto itself and then gets flattened by the AFP roller usually resulting in a bowtie shape [1]. A twist usually occurs due to improper material feeding accompanied with complex AFP head rotation, hence twists cannot be programmed to be intentionally placed automatically at a specific location, and manual insertion is necessary. To replicate a twist, the following procedure is used: (1) partially peel the tow from the substrate, (2) twist the tow 180° at the required length , (3) place the tow in its location using a roller. Depending on the desired length of the twist, the fully twisted side should be placed while keeping the tow under tension to have additional control over the placement process. A photograph of an uncured twist inserted using the above procedure is shown in Figure 4.

Figure 4 Twisted tow before autoclave cure

2.3 Wrinkle

A wrinkle is an out-of-plane deformation of the tow due to excess in length in the material fed compared to the actual length of the path. Usually, partial wrinkles develop on the inner edge of steered tows when a critical radius is exceeded [7]–[9]. For linear paths, full wrinkles (or sometimes referred to as puckers) occur due to excess feeding of a tow that gradually accumulates ahead of the roller and eventually emerge to the surface [1]. They can also form if the placement is occurring over a compliant surface where additional tow length is fed and the surface springs back to its original shape[1]. In order to reproduce this defect at a specified location manual intervention is required.

The following procedure is used to reproduce a full wrinkle: (1) Peel the tow from the substrate, (2) insert a pen at the defect location and perpendicular to the tow, (3) place the tow on top of the pen using a roller (see Figure 5), (4) remove the pen, and flatten the wrinkle using a roller Depending on the size of the insert (pen for this case), the amplitude of the wrinkle can be controlled. The resulting shape of the full wrinkle is shown in Figure 6.

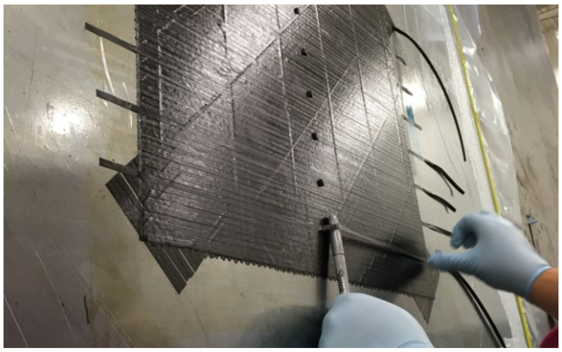


Figure 5 Manual insertion of a wrinkle

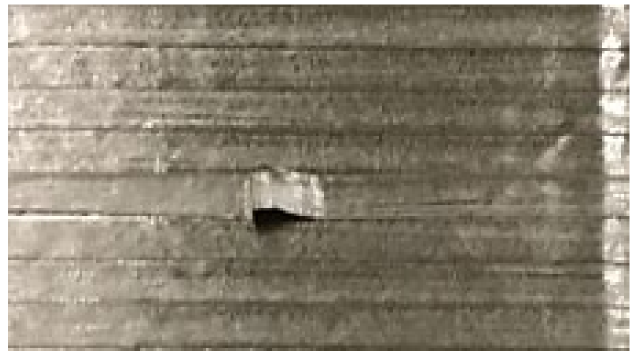
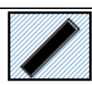


Figure 6 Pre-cured shape of a full wrinkle

Table 1: Summary of manufacturing notes for hand-inserted defects

Defect	Identity Card	Tows Schematics	Manufacturing Notes
Pristine			
Gap			Cut the tow at the boundaries of the coupon Peel the tow from the substrate Slit the tow at the required gap width Place the remaining of the tow in its original location
Overlap			Slit a tow with the required gap width Place the slit tow at the defect location
Twist			Partially peel the tow from the substrate Twist the tow 180° at the required length Place the tow in its location using a roller
Full Wrinkle			Peel the tow from the substrate Insert a pen at the defect location and perpendicular to the tow Place the tow on top of the pen using a roller Remove the pen, and flatten the wrinkle using a roller

3. POST-CURE ASSESSMENT

Using the procedure presented in the previous section, several laminates are manufactured at the McNair center using the Lynx AFP machine from Ingersoll Machine tools. The laminates consist of 7 layers with the following stacking sequence: $[45/90/-45/\bar{0}]_s$. The gaps and overlaps defects are inserted automatically using the AFP machine, whereas the twists and wrinkles are manually placed. All defects were placed in the 0° orientation. This section details the curing, specimen preparation, and the obtained post-cure micrographs of the inserted defects.

3.1 Panel Curing and Specimen Preparation

Once the panels are fiber placed properly and the defects are inserted in their intended locations, the layup is bagged with a caul plate on top of the panel. The layup is cured in an autoclave according to the cure cycle provided by the material supplier (Figure 7). After curing the panels, a water jet or a diamond saw cutter are used to cut the coupons out of the panels. The edges of the coupons are then polished using sandpaper with the following grits respectively: 180, 240, 400, 600, 800, and 1200. For the case of coupons with defects running along the 0° such as the gap and overlap, the defects can be easily observed on the edges of the coupon. However, for the case of the twist and wrinkle where the defect is embedded in the middle of the coupon, additional cutting planes are necessary to observe the post-cure shape of the defects. These cutting planes are detailed in the following sections for each case.

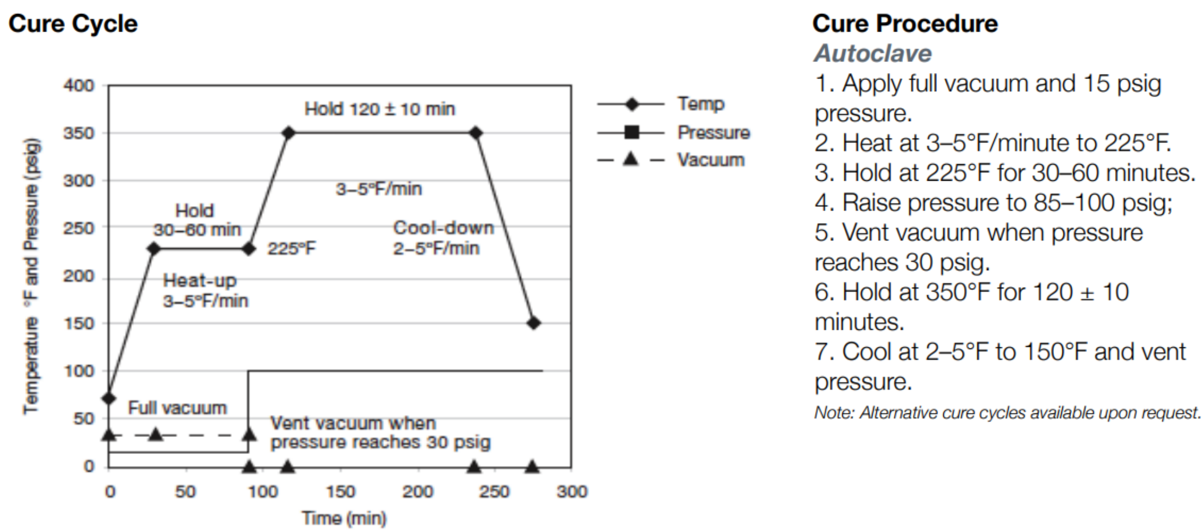


Figure 7 Recommended autoclave cure cycle for 8552 resin obtained from the material provider [10]

3.2 Microscopic Images

A digital microscope is used to capture the images of the defects on the edges of the coupons. The images of main four investigated defects are presented in this section.

3.2.1 Gap

The obtained images of the gap inserted automatically using the AFP machine are shown in Figure 8 and Figure 9. At 500X magnification, image stitching is necessary to capture the overall length of the gap depicted in Figure 8. It can be observed that the gap is filled with resin during the cure cycle and no visible voids are formed. In addition, the thickness of the resin rich area is smaller than the typical cured lamina thickness indicating that fibers are shifting from neighboring layers to fill the gap during the cure cycle.

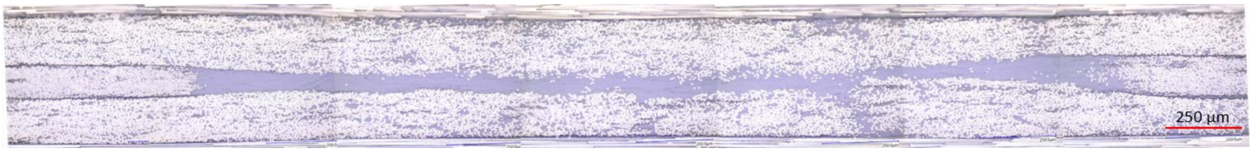


Figure 8 Stitched microscopic images of a gap

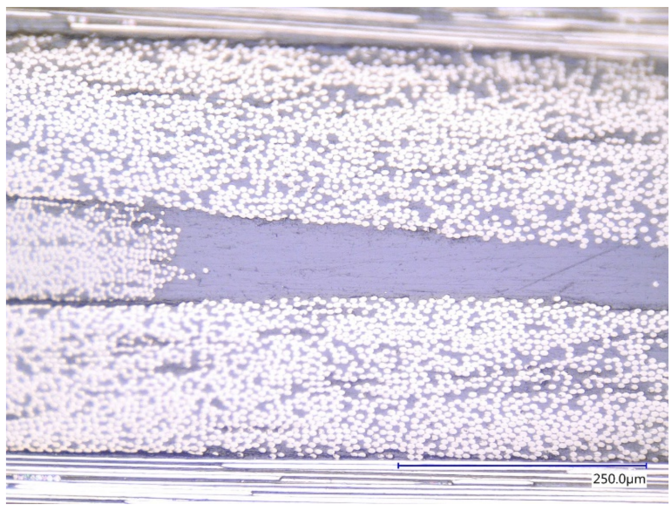


Figure 9 Microscopic image of a gap at 500X magnification

3.2.2 Overlap

In a similar manner, the coupons with an embedded overlap are prepared, and images of the defect are captured along the edges using a digital microscope. The stitched image of the overall defect is shown in Figure 10 and a closeup of the overlap is shown in Figure 11. At the overlap location, an in increase in the layer's thickness can be observed. In addition, the interface between the overlap and the original 0° layer appear to mostly vanish compared to the interface between the other layers where a resin rich area is easily identified.

Figure 10 Stitched microscopic images of an overlap

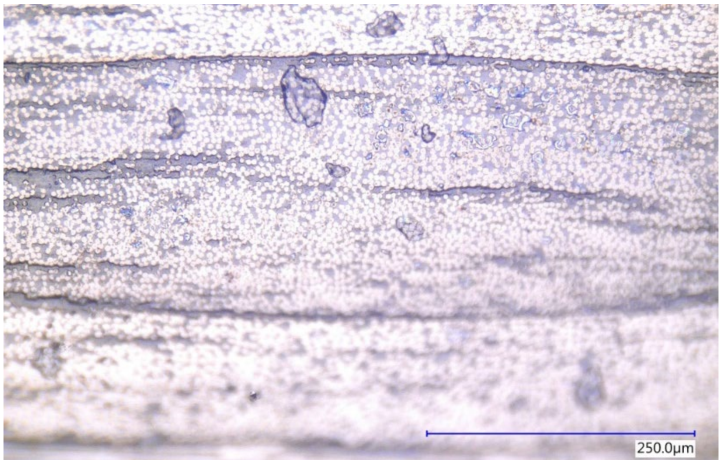


Figure 11 Microscopic image of an overlap at 500X magnification

3.2.3 Twist

Detecting a twist or a wrinkle embedded in the middle of the coupon is difficult by just looking at the edges in a similar way as gaps and overlaps. Therefore, additional cutting planes are needed at different cross-section to fully capture these defects. This process will result in the destruction of the coupons which cannot be used for testing in later stages. The cutting planes for the coupons with embedded twist and wrinkle are shown in Figure 12 and Figure 13 respectively. For the twist running along the length of the coupon, multiple cutting planes (cut 1 through 4) are used to observe the progression the defect. However, for the wrinkle, a single cutting plane in the middle of the coupon (cut 1) is sufficient to observe the post-cure state of the defect.

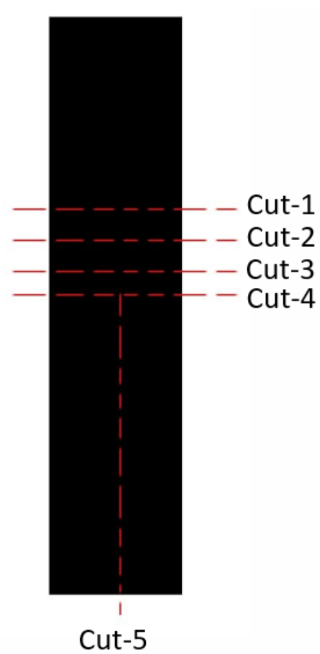


Figure 12 cutting planes for the twist defect

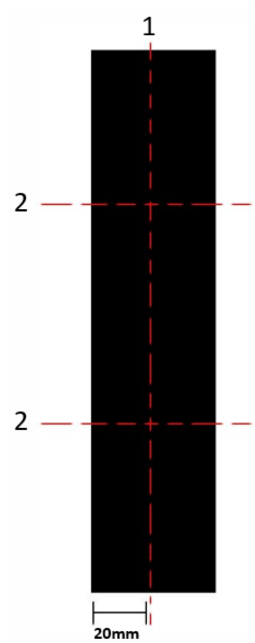
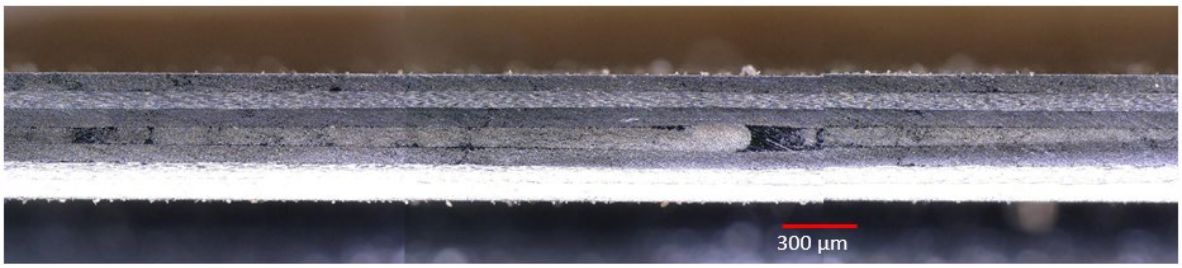
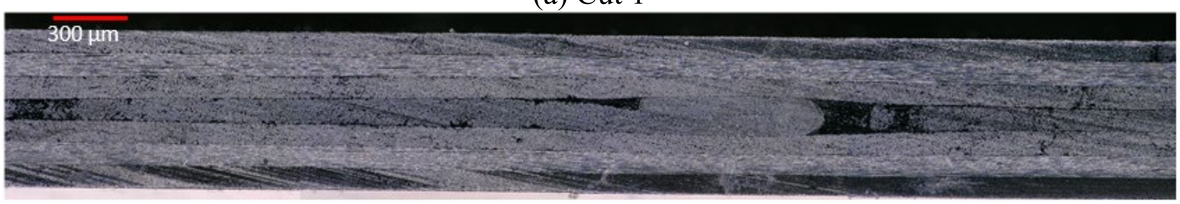


Figure 13 Cutting planes for the wrinkle defect

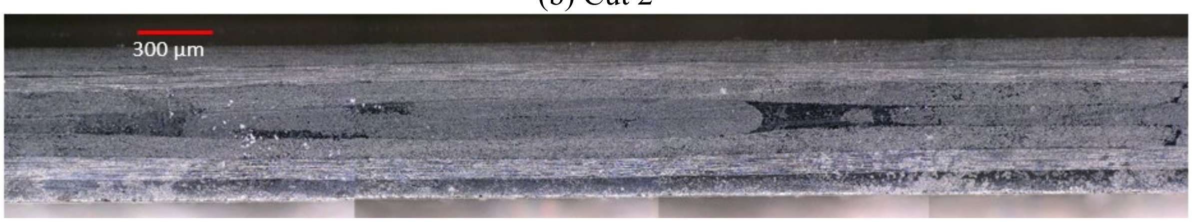
Using the procedures described in the previous section, a 4 inches long twist is hand-placed in the panel and the resulting coupon is cut along the multiple planes as described in Figure 12. For each cut, the specimen is polished accordingly to obtain a smooth surface. The resulting images captured using the digital microscope are shown in Figure 14 for cutting plane 1 through 4 respectively. The progression of the twist formation is depicted starting with cut 1 where a small resin rich area is observed next to a fold both having a size of around 200 µm. The size of tow folded over itself as well as the size of the resin rich area increase from cut 1 through 4. Cut 4 corresponds to the mid-section of the twist which is characterized by an increase in the thickness of the layer since the tow is fully folded over itself and two resin rich areas from each side.



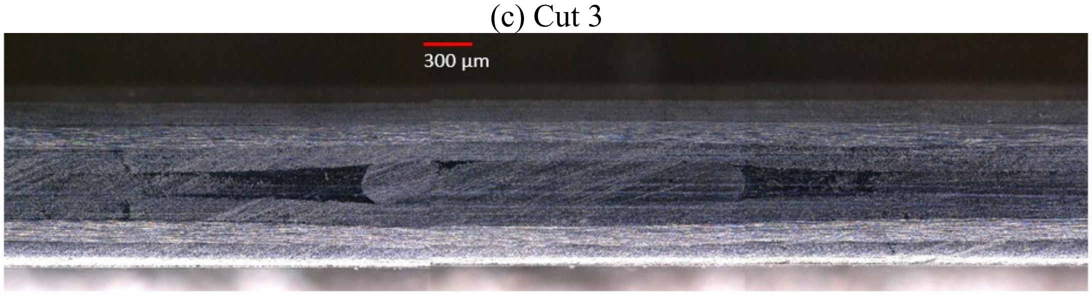
(a) Cut 1



(b) Cut 2



(c) Cut 3



(d) Cut 4

Figure 14 Microscopic images of a twist at different cross-section at 50X magnification

3.2.4 Wrinkle

A wrinkle is hand placed using the steps described earlier, and the resulting cured coupon is cut and polished along cutting plane 1 as shown in Figure 13. The resulting image using the digital microscope at 50X magnification is shown in Figure 15. The post cure shape of the wrinkle is much different than the hand-placed one: the originally out-of-plane full wrinkle is folded over itself after the roller has passed over it while placing the consecutive layer. This resulted in a local increase of the lamina thickness, and resin rich pockets has formed on both sides of the wrinkle during the autoclave curing process.

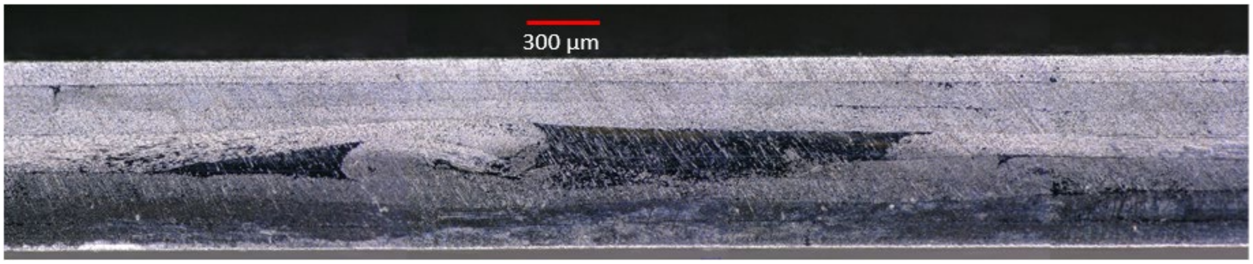


Figure 15 Microscopic image of a wrinkle at 50X magnification

4. CONCLUSIONS

In this paper, best practices on how to intentionally insert AFP defects in laminates are proposed, and their post-cure persistence is quantified using microscopic imaging. Four primary defects that predominately occur during AFP are investigated: gaps, overlaps, twists, and wrinkles. For the case of gaps and overlaps, automatic insertion using the AFP can generally be programmed by splitting the lamina including the defects into 2 or more regions. These regions can be shifted apart or overlapped with the exact defect width. For the case where the defects cannot be programmed, a step by step procedure is developed for the manual defect insertion especially for twists and wrinkles. Several composite panels are produced using the proposed techniques. The post-cure persistence of the defects is depicted through magnified images captured using a digital microscope. For gaps and overlaps running along/across the whole length or width of the specimens, the persistence of these defects can be depicted easily on the edges. For the case of twists and wrinkles which are isolated near the center of the specimens, additional cutting planes are necessary to obtain the magnified images. It is concluded that the obtained post-cure shape of the defects is not necessarily the same as the pre-cure one due to the resin flow in the composite part during the autoclave curing cycle. These images will be used for accurate modeling of the post-cure shape of defects, which is necessary for future numerical simulation studies.

5. ACKNOWLEDGMENT

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