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Multi-pass layup process for thermoplastic composites using robotic fiber placement

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ABSTRACT

Robotic fiber placement is a promising technique to manufacture complex components for industry. Compaction pressure, hot gas torch temperature and laying velocity are the key molding factors for fiber placement process, and their optimal selection directly affects the product performance. Small compaction pressure, low gas temperature and fast laying velocity lead to incomplete interlaminar adhesion and high porosity. However, excessive compaction pressure, high gas temperature and slow laying velocity lead to excessive resin extrusion from the contact surface of the two layers, thus affecting the overall structural rigidity of the laminates. At the same time, due to the forming characteristics of fiber placement process, the compaction pressure has an impact on each underneath layer under the influence of heat transfer and laying velocity, which results in different interlaminar bonding strength between the different layers. This study aims at analyzing and optimizing the robotic fiber placement process parameters to obtain the composite laminate with the homogeneity of interlaminar bonding strength. Based on analyzing the heat transfer from current contact surface to each one underneath, the multi-pass compaction pressure from non-deformable roller affecting the underneath layers is investigated, and experiments are conducted to verify the optimizing method.

1. Introduction

With the dual requirements of high strength and reduced weight for aircrafts, ships, automotive components and other industrial equipments, the demand for composite material products has increased substantially, and composite materials processing technology is developing rapidly [1]. Each processing technology aims to ensure and improve the product performance, as well as reducing manufacturing costs and time. Fiber placement technology combines the advantages of both the filament winding and the tape placement, enabling fabrication of the complex composite components that conventionally require extensive hand layup [2]. Utilizing other methodologies with the fiber placement technique will provide new and additional advantages. An example includes the laser based measurement technique added to the fiber placement technique, this will make the placement process more precise than before [3–6]. Another important aspect related to combining a robotic manipulator with the fiber placement technique, such a robotic fiber placement (RFP) technology has many advantages for fabricating a composite product, including precise thickness control in placement process, real-time compression molding, low porosity, almost unlimited fiber placement angles, less material waste, and many more [7–9]. Due to the flexibility of the above and resulting benefits, a number of research institutions are conducting research and verification work for robotic fiber placement technique.

In recent years, researchers have paid increasing attention to investigating the process parameters affecting the performance of the composite components. Sonmez and Hahn [10] considered the interlaminar bond strength, weight reduction through thermal degradation, and crystallinity as the quality parameters in the process modeling. The stress, heat transfer, crystallization, degradation, and bonding models have also been developed. Aized and Shirinzadeh [11] performed many experiments to analyse gas torch temperature, fiber laying head speed, and fiber compaction force, and the process is optimized using response surface method. Pitchumani et al. [12] optimized the line speed and heat input variation to maximize interfacial bond strength and minimize fabrication time, based on considerations of material degradation through weight reduction, final void content, and dimensional change of the tows. Sonmez and Akbulut [13] developed a tape placement process optimization to minimize the peak tensile residual stress, and increase the productivity. The numerical results showed that a laminate with acceptable quality could be produced through optimization. Schell

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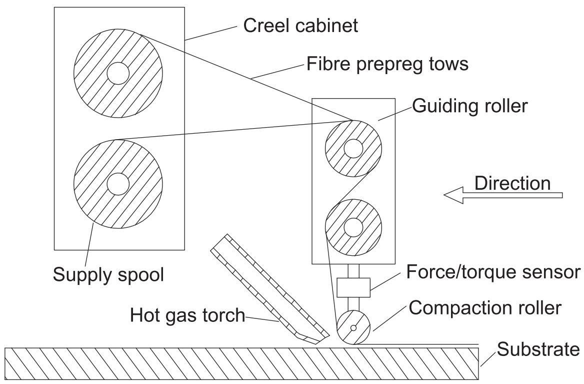

Fig. 1. Schematic diagram of the robotic fiber placement [17].

et al. [14] investigated the fusion bonding in thermoplastic composites by computational and experimental analysis. Based on various thermal loading and bonding quality fluctuations resulted from the process sequence, and three practical ways for quality improvement were also proposed. Heider et al. [15] developed an in situ non-linear optimization technique to maximize the throughput and maintain a desired minimum quality, based on artificial neural networks. Rao et al. [16] investigated the influence of compaction load, layup speed and temperature on the adhesive properties of automated fiber placement grade towpreg, and suggested the optimum parameters to yield the predicted peel force in fiber placement process.

In summary, many researchers found the performance of products is affected by compaction pressure, laying velocity, hot gas torch temperature, compaction roller temperature, substrate temperature, composite surface roughness and other parameters. It is recognized that the compaction pressure, hot gas torch temperature and laying velocity could directly affect the interlaminar bond strength, and has a significant effect for the holes and bubbles that may form in the interlaminar contact surface of a composite component. Therefore, investigating the process parameters that play an important role for enhancing the performance of composite components is required.

This study aims at investigating the influence of each layer's compaction pressure affecting the several underneath layers, based on analyzing the process characteristics of the composite material laminate placement. The organization of this paper is as follows: Section 2 provides the theoretical analysis of fiber placement process for thermoplastic composite component. Due to the thermal properties of the prepreg tow, the heat transfer of composite laminate along the thickness direction is analyzed. Ensuring the consistency and control of the hot gas torch temperature, laying velocity and other process parameters, the equations of each layer placement for achieving the same interlaminar bonding strength are developed in Section 3. Results of the experimental verification are reported in Section 4, and the conclusions and future research directions are presented in Section 5.

2. Analysis of the thermoplastic composites RFP process

2.1. Robotic fiber placement process analysis

Robotic fiber placement process is laying composite prepreg tows onto the surface of a tool/substrate using a set of placement process parameters. Fig. 1 shows the schematic diagram of the robotic fiber placement process.

In the composite prepreg fiber placement process, the prepreg tows are led by the guiding roller into the placement area, heated by the hot gas torch to a molten state, and bonded with the substrate laminates in the fusion zone as compressed by the compaction roller. In the fusion zone, compaction roller provides a positive force to the pregreg tows in the vertical direction, so that the prepreg tows are bonded tightly with substrate laminates, and thus reducing the porosity of the product by ejecting bubbles from the fusion zone. Through the molding process of prepreg fiber placement, laying process is actually the process of prepreg composites continually being fusion bonded with substrate laminates, which takes place at the contact surface between the fresh prepreg material and the substrate [18].

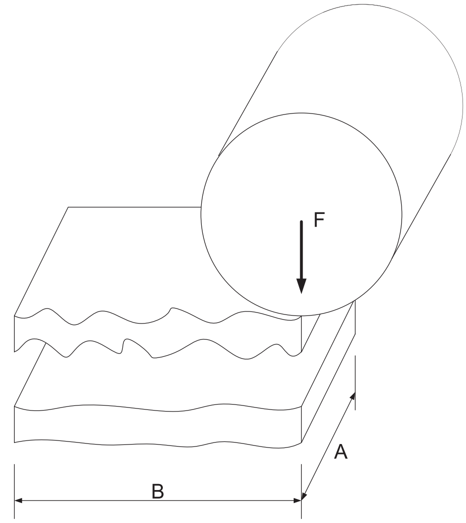

Fig. 2. Schematic diagram of surface condition in placement process.

2.2. Intimate contact process

In the production process of prepreg fiber material, the fibers are dipped in the specific resin, then dried as the desired prepreg composite tows. Due to the character of the prepreg composite material and the particularities of production process, it results in an inconsistent surface roughness for the composite tows, as well as irregular surface topography and micro geometry. Fig. 2 shows a schematic diagram of the composite surface condition in the placement process. Because the required laying material is fresh, there are a large number of concave and convex shapes on the surface. The substrate laminate has already been compressed by the compaction roller, thus the surface would be smoother.

Following Lee and Springer, the irregular layer surface can be represented by a surface consisting of a series of same size rectangles [19]. In order to investigate the laminate composites placement process, rather than the bonding of the two-layer composites, some modifications need to be performed to the theory developed by Lee and Springer. Because the substrate laminate has been compressed by the compaction roller, the upper surface can be simplified by a flat surface. Then the upper surface of a fresh composite material will become smoother by pressure from compaction roller, this surface can also be simply defined by a flat surface. The lower surface of the upper layer is still fresh before placement process; hence this surface can be represented by a surface consisting of a series of same size rectangles. The model is shown in Fig. 3.

In the placement process, the prepreg tows are heated to a given temperature by the hot gas torch. When the compaction roller exerts force on the prepreg tows, the shape and geometry of the tow's surface will deform. Hence, the composite prepreg tows closely contact the substrate laminate in the contact area. Fig. 4 shows the interlaminar contact surface of the prepreg tows prior to experiencing the force from compaction roller.

Fig. 5 shows the interlaminar contact surface of the prepreg tow after experiencing the force from compaction roller.