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Characteristics of stress wave propagation of carbon fiber/epoxy laminates fabricated by high-speed automated fiber placement

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Abstract

Study of stress wave is of great significance to investigate the formation mechanism of manufacturing defects and nondestructive testing technology. Aiming to reveal the characteristics of stress wave propagation of carbon fiber/epoxy tows in high-speed automated fiber placement (AFP), in this paper, stress distribution and strain energy density (SED) of laying tows are calculated using the finite element method (FEM). The waves velocity and waves equation of carbon fiber/epoxy composite are obtained using the least square method and numerical analysis. Furthermore, characteristics of stress wave propagation under the different processing parameters and laying time are presented, and laws of peak and stability of stress waves response to different compaction force and laying speed are discussed. Finally, a group of processing parameter (S=33m/min, F=300KPa) is determined which could control the stress waves and release the strain energy efficiently.

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*Keywords:*Carbon fiber/epoxy composite; High-speed automated fiber placement; Stress wave; Processing parameters evaluation.

1. Introduction

Carbon fiber/epoxy laminates, which include a series of the properties such as light weight, anti-fatigue ability, high specific strength, are widely used in the aerospace industry [1]. Automated Fiber Placement (AFP) is used on complex surfaces and utilizes single or multiple narrow, slit tapes or tows to make up a given total prepreg band width, their productivity is 5-20 times higher than artificial fiber placement or semi-AFP [2].The production machines are concerned that how to guarantee the better production quality in rapid manufacturing at present [3]. Some advanced AFP machines produced by MAG CINCINNATI, INGERSOLL, MTORRES, which have the ultimate laying speed about 50-60 m/min [4]. In this paper, the high-speed mean that laying speeds are greater than 27m/min.

The laying tows are affected significantly by the coupling of a variety of stress waves in high-speed AFP process. The transfer, convergence and reflection of stress waves would be able to generate the different manufacturing defects. Therefore, the reduction of the peak and the increase of the stability of stress waves can reduce the possibility of the formation of manufacturing defects. More importantly, the manufacturing defects could be identified by detecting the characteristics of stress waves, this process is called nondestructive testing (NDT). Wang and Chen [5] presented a theoretical and experimental investigation of the scattering behavior of extensional and flexural plate waves by a cylindrical inhomogeneity. The scattering behavior model was established which can characterize the interaction of plate waves with damages. Guy [6] used finite element and experimental method to reveal the interaction of the Lamb waves with the defects, which provides a feasible method for identifying the extent of damage with the plate-like composite structure. Thus, the identifying characteristics of the propagation process of stress wave along the tow have important implications for the application of NDT in high-speed AFP process.

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For the characteristics of stress wave propagation in the materials, many scholars have conducted a series of research. Some studies [7-9] showed that the velocity of stress wave propagation and the amplitude of particle vibration are closely associated with material properties. Zhuang [10] first investigated the influence of interface scattering on finite-amplitude shock waves by impacting flyer plates. Tasdemirci A [11-13] studied the characteristics of propagation and distribution of stress wave in multi-layer composites made of metal, ceramics and EPDM rubbers. The previously mentioned researches focused on the transfer process of stress waves under a single non-continuous load in the composites, however, the process of high-speed AFP includes a series of complex loads and diverse types of stress waves, and there are some limitations that the characteristics of stress wave propagation are revealed using one or two dimensional stress wave model.

In this paper, to control stress wave and energy efficiently in high-speed automated fiber placement (AFP) process, characteristics of stress wave propagation under continuous impact for carbon fiber/epoxy composites are studied. The rest of this paper is organized as follows. In section 2, the strain energy density (SED) of meso-mesh in the laying tows are analyzed, the effect of the stress waves on the whole energy distribution is found under the different processing parameters. In section 3, wave velocities of carbon fiber/epoxy composite are calculated using the least square method. Lastly, the characteristics of stress wave propagation are revealed under the different processing parameters, the most advantageous processing parameter is assessed by which has the lower peak and superior stability.

2. Strain energy density

The strain energy density (SED) which varies with processing parameters are closely associated with the formation and expansion of defects in the process of AFP and service of composites [14]. There are two main sources of SED in AFP process, one is the sharp accumulated energy under the compaction force of the nip roller. The other is the transfer, convergence, reflection and accumulation of stress waves through the medium. The carbon fiber/epoxy composites are anisotropy materials, which is a complex process for researching on their stress waves. Furthermore, high-speed AFP is a manufacturing method of continuous impact with a variety of types of stress waves, which enhances the complexity of this study. High-speed pre-heating AFP process and several major stress waves are shown in Fig.1:

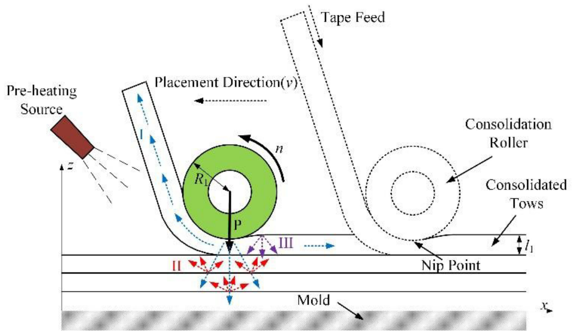

Fig.1 High-speed pre-heating AFP process and several major stress waves

In Fig.1, the AFP process, some types of stress waves and their propagation paths are listed including shock wave, loading wave, and unloading wave. According to propagation direction, there are shear wave (S-wave) and primary wave (P-wave). In this figure, I is P-wave and S-wave synthesized by several waves, II is reflection waves of interlamination, and III is unloading waves.

Mechanical properties of a carbon fiber/epoxy prepreg are shown in Table 1:

Table 1. Mechanical properties of a bisphenol A epoxy matrix prepreg.

Density	E1	E2,E3	v12,v13	v23	G12,G13	G23
1.49 g/cm^3	121 GPa	8.6 GPa	0.27	0.4	4.7 GPa	3.1 GPa

where E1, E2 and E3 is the modulus of elasticity in the different directions. v12, v13 and v23 is the poisson's ratio in the different planes. G12, G13 and G13 is the shear modulus in the different planes.

SED of a mesh is calculated using finite element method (FEM). Firstly, FEM model is established which includes roller, prepreg tow and laminates in high-speed AFP. The laying speed is set as 27m/min, 30m/min and 33m/min respectively. The compaction force is considered to be 150KPa, 200KPa, 250KPa and 300KPa respectively. In terms of laying speed and compaction, 12 groups of boundary conditions could be obtained. In this study, the simulation time is set to be 125μs. The bottom of laminates, which is formed by 4 unidirectional layers, are fully constrained. The actual length of lay-up tow is 280mm, and contact type between the laying tow and the laminates is set as rough. To analyze the characteristics of stress waves in a particular roll nip, choosing No.175 mesh which could be deemed to the feature unit (Fig.1) as the analytical object (Fig.2).

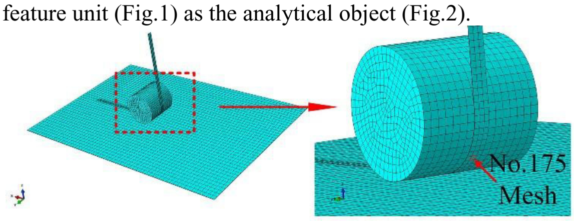

Fig.2 FEM model and position of No.175 mesh in high-speed AFP process.