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Experimental study on relationship between processing parameters and stress wave propagation during automated fiber placement process

H Y Fu[1], W Q Li[1], S Z Sun[1] and Z Y Han[1,2]

[1]School of Mechatronics Engineering, Harbin Institute of Technology, No. 92, Xidazhi Street, Harbin 150001, China

Email: hanzy@hit.edu.cn

Abstract. Automated fiber placement (AFP) is an important manufacturing method of composites, which has been widely used in the field of aerospace. Unreasonable processing parameters could lead to some manufacturing defects including pores, bubbles and cracks. In this paper, the propagation characteristics of stress waves are believed to be closely related to the defects during AFP process. Experiments are conducted to collect stress wave signal under different processing parameters (pressure, velocity and temperature) during manufacturing process. And the relationship between the processing parameters and the characteristics of stress waves is explored by Control Variate Method (CVM). Finally, the effects of laying parameters on stress amplitude, response speed and duration are summarized.

1. Introduction

Due to the advantages of light weight, high strength and flexible forming methods, carbon fibre/epoxy laminates are widely applied to manufacture aircraft components and their prospects become more and more popular in the field of aerospace [1-2]. AFP, which is rapidly developed in the past 30 years, is an important manufacturing method for carbon fiber composite materials [3-4]. It is suitable for forming structures with complex surfaces and smaller structures than general ones because of its flexible and controllable width. AFP could utilize single or multiple narrows to realize a given total prepreg band width [5-6]. If forming laying process is unreasonable, the laminates could be forced to cause various defects such as pores, bubbles, cracks, which will affect their mechanical properties.

The formations of defects in composite material are closely associated with the characteristics of stress waves. For instance, excessive shear stress between the adjacent layers could cause delamination, and the crack tip could result in stress concentration phenomenon leading to further extension of micro cracks [7-9]. The effect of the structure of mediums on stress waves could provide some references to evaluate the quality of products made by different materials. At present, the internal defect detection of wood structure have maturely developed based on stress wave theory [10-12]. The relationship among stress waves velocity, the moisture content of wood and tree species has been found. And there is statistically linear relationship between wave resistance and bending modulus of elasticity [13]. It is more complicated that stress waves propagate in the anisotropy laminates because of the interaction among incident waves, reflected waves and scattered waves. Therefore, study of the characteristics of stress waves during laying process does not only make contribution to optimize laying process, but also provide the reference of manufacturing defects detection.

The porosity of composite laminates is proved to affect stress wave characteristics. Ju Y [14-15] prepared different porosity samples by imitating natural structure of gravel and sand, and conducted SHPB experiments for cylindrical samples. By analyzing the experiment results, they found that the amplitudes and the amount of wave peaks could grow up with the increase of porosity, and stress waves could affect the form of detects when they propagate in the composite laminates. Yan G [16] used high-order plate theory to analyze the scattering in composite laminates and established a damage detection system through calculating the speed of stress wave propagation. Guo Z [17] built a relational model between detects and stress waves for thin plate under dynamic loads, and revealed that the formation of detects results from the interaction of stress waves.

In this paper, the effect of processing parameters on the characteristic of stress waves is discussed by variable parameter experiments. The variable-controlling approach is used to compare the effect of laying pressure, laying temperature and laying velocity on stress waves by analyzing the real-time signal. Finally, the effects of laying parameters on stress amplitude, response speed and duration are summarized.

2. Experiment setup for collection of stress wave signal

In an attempt to reveal the relationship between laying parameters and the characteristics of stress wave propagation, three factors and three levels of normal experiments are designed. Different parameters have different impacts on the quality of products. Laying velocity not only decides productivity, but also influences the time of laying pressure and pre-heating. Appropriate laying velocity could ensure the stickiness and smoothness of laminates as well as an acceptable level of efficiency. The force situation of tows is determined by the laying pressure. Overloading could lead to excessive deformation and under loading could cause incomplete join, bubbles and even warps. Viscidity/overlay ability is affected by laying temperature. The viscidity of tows increases with temperature rising. Stronger viscidity makes it difficult to separate the tow from the wrap, and weaker viscidity could lead to slip between the tow and the mold. Therefore, it is important to ensure a group of appropriate laying parameters.

Table 1. Experimental parameters.

Parameter	Factor1	Factor2	Factor3
F(mm/s)	10	15	20
P(N)	350	600	850
T(℃)	40	50	60

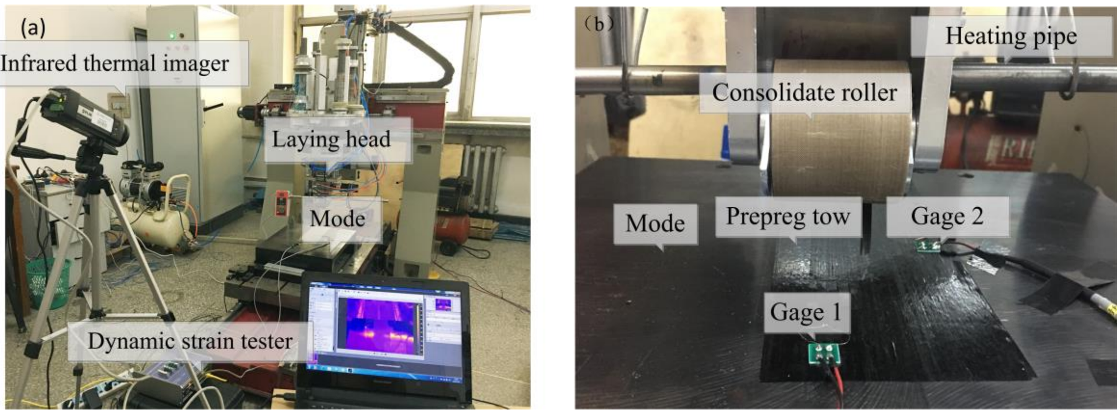

Figure 1. Laying stress wave test experiment platform: (a) Laboratory equipment; (b) Laying roller and foundation.

Experimental facilities are shown in Figure 1, the experimental platform is based on the five-axes automated fiber placement machine produced by HIT numerical control laboratory, which can adjust laying pressure by air pump, laying velocity by servo motor and laying temperature by variable power heater. Experimental material is No.6511 carbon fiber prepreg with the width of 5mm produced by Guangwei company, China. The properties of the prepreg are shown in Table 2. Dynamic strain tester with strain gages is used to collect the real-time stress signal from test point, which its resolution can achieve to 0.1με and the strain detection error can be no more than 0.02%. The strain gauge resistances are 120Ω±2% and the sensitivity coefficient can reach to 2.0±1%. The temperature is observed by infrared thermal imager, which can detect the temperature range of 0-300℃. Because of the differences (such as elasticity modulus and density) between fiber prepregs and the rectangle metal mold that is made by No.45 steel with the thickness of 5cm. If the strain gauges are pasted to the surface of mold directly, the excessive stiffness of mold will limit the deformation of the stress gauge which can not reflect the actual deformation of the fiber prepreg. Before collecting stress wave signal, five layers (100mm×300mm) of prepregs have been laid on the mold as a foundation in order to avoid the impact of slight deformation of the mold. Two strain gages are attached to the specify locations on the fifth layer and kept distance from the laying path to prevent the roller press the strain gages directly. The stress signal is collected when the roller moves, and there are five tows distributed in a layer, which results in five cycles in a group of the collected signal.

Table 2. Material parameters.

Matrix type	Prepreg resin content	Cured ply thickness	Prepreg width	Normalised tensile strength	Normalised tensile modulus
6511	33%	0.14mm	5mm	1846Mpa	120Gpa

3. Analysis of experiment results

3.1. Laying pressure

Laying a tow is divided into four processes as shown in Figure 2. Firstly, the consolidation roller drops down, and loads to the foundation. Secondly, when the roller reaches the predetermined pressure, it would roll toward the strain gage for attaching the tow onto the surface of the upper layer. Then the roller continues to move forward to the end position, and unloads at the end position. The stress waveforms collected at test point show a regular change, which is closely related to the relative position of roller and strain gages.

When laminates are energized, stress spreads out in the form of waves and reflects when propagating to the boundary of the laminates. The stress wave propagates in the form of transverse and longitudinal waves in the laminates with boundary; the direction of transverse wave propagation is perpendicular to the direction of vibration, while the direction of longitudinal wave propagation is the same as the direction of vibration. The incident stress wave interacts with the reflected stress wave to form a complex stress state.

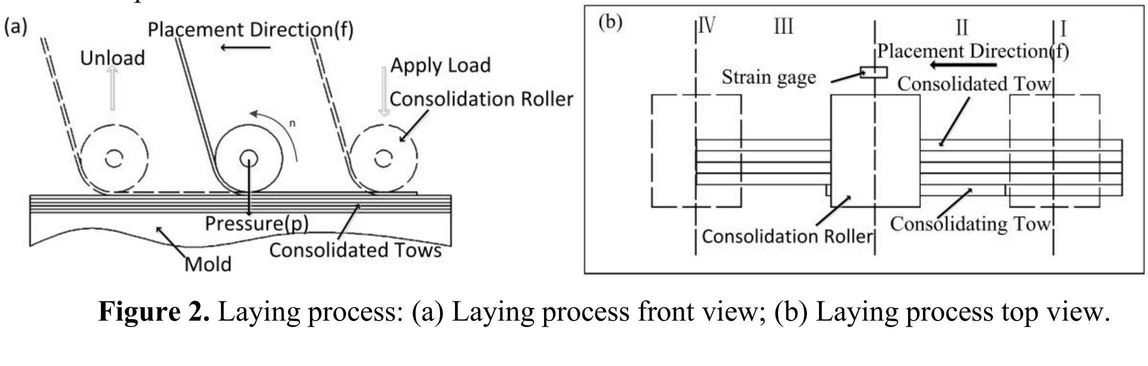

Figure 2. Laying process: (a) Laying process front view; (b) Laying process top view.

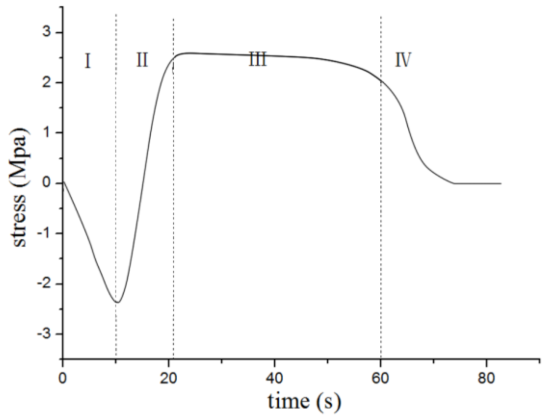

Figure 3. The stress wave waveform during laying process.

The stress wave signal of a certain laying process is shown in figure 3. In the first stage of this experiment, the laying head press vertically and the distance between the laying head and the test point is not changed, the stress state of the test point mainly dependents on the interaction of the incident stress wave with the reflected stress wave. In the following stage, as the laying head rolling forward, friction is created in the fibre direction. The stress state of the test point is not only affected by the stress wave but also by the small tension in the fiber direction. This complex stress state varies with the distance between the excitation and the test point. As the distance between the roller and the test point is shortened, the effect of friction is becoming more obvious which reach to the maximum in the vicinity of the test point and then remain stable relatively. At the end of laying path, the stress gradually reduces to zero in unloading process. It is worth noting that the magnitude of the stress wave is positively correlated with the magnitude of the pressure according to Figure 4.

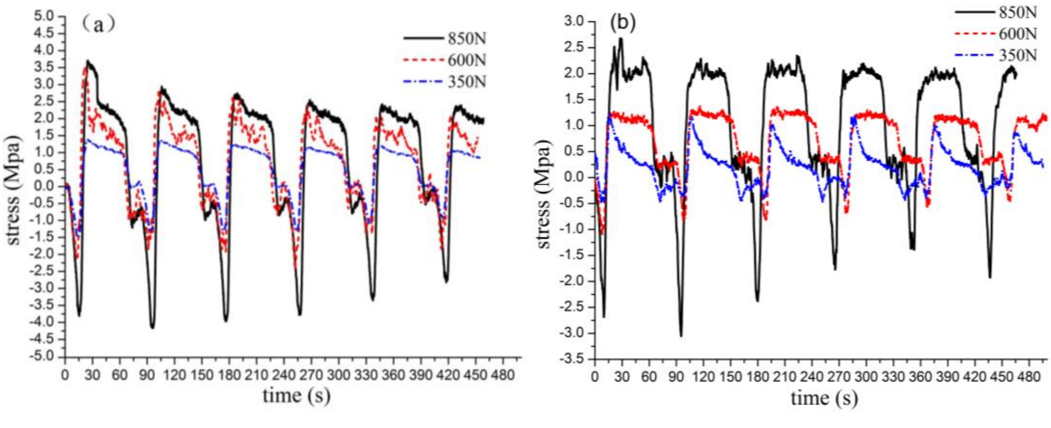

Figure 4. Real-time stress wave curves of laying process under different pressures: (a) f=15mm/s, t=60℃; (b) f=15mm/s, t=40℃.

3.2. *Laying temperature*

Figure 5 shows that the real-time stress wave signal is collected at different temperatures under the same speed and pressure. In order to find the effect of temperature parameters on the stress wave during the laying process, three different parameters of 40℃, 50℃and 60℃ are selected. It could be seen from Figure 4 that the higher laying temperature is, the greater the maximum of the stress wave is, especially at the speed of 20mm/s and the pressure of 350N. The maximum of stress wave at the temperature of 60℃ reaches 1.7Mpa. The maximum of stress wave at 50℃ is about 0.8Mpa, but it is only 0.6Mpa at 40℃.

From the waveform point of view, the waveform of high temperature stress is generally steeper than that of lower temperature. On the one hand, it is due to the temperature drift of the strain gauge that is affected by different temperature effects. On the other hand, the degrees of melting and fluidity of the epoxy resin in the prepreg increase with temperature, which makes stress status more sensitive.

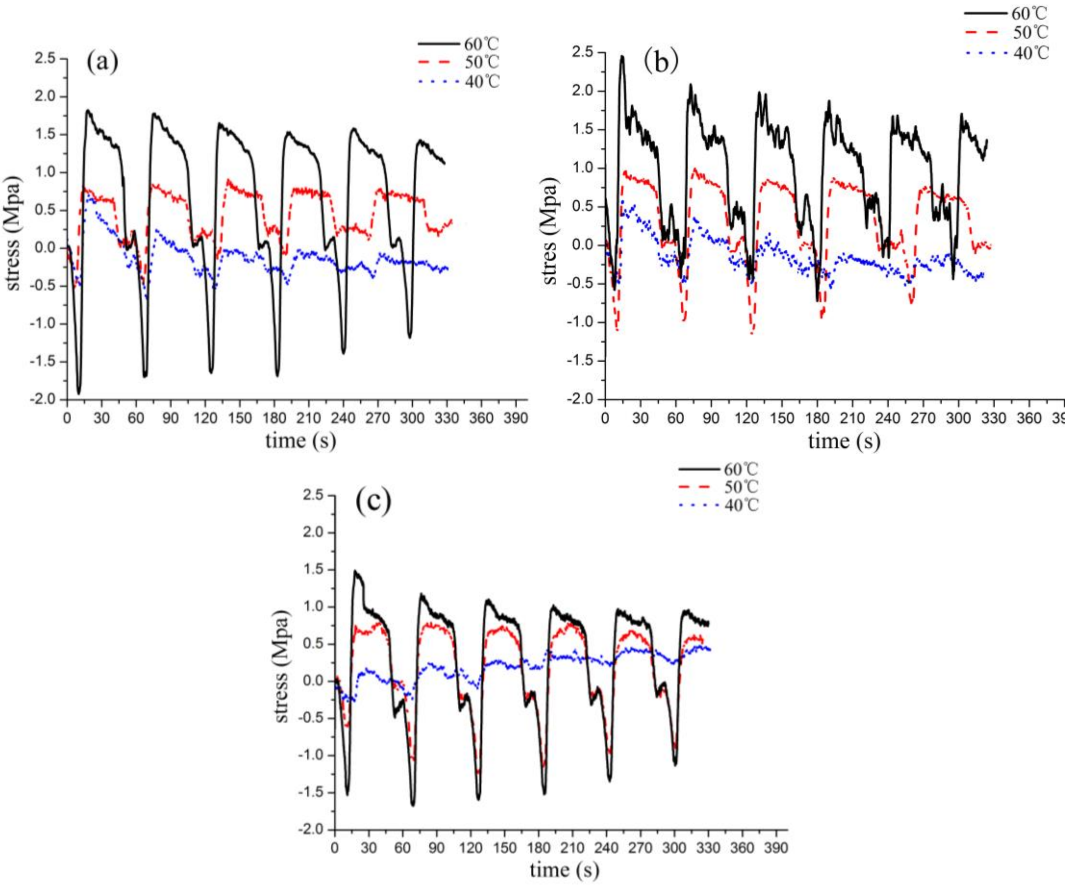

Figure 5. Real-time stress wave curves of laying process under different temperatures: (a) f=20mm/s, p=850N; (b) f=20mm/s, p=600N; (c) f=20mm/s, p=350N.

3.3. Laying velocity

The laying head presses the tow onto the foundation with a certain pressure, which is equivalent to applying a continuous excitation to the foundation. The stress fluctuation generated by the excitation propagates outside in the form of the shear wave and the longitudinal wave through the material. When stress wave is propagated to boundary, it would reflect. Also the pores and the cracks in the material will scatter the stress waves. The reflection and scattering of stress waves are accompanied by the propagation of energy. To a certain extent, the magnitude and the speed of the stress waves can indicate the amount of energy absorbed by the foundation.

Since the data of this experiment is collected while roller moves, the continuous excitation of the laying roller makes its response signal very complicated. Taking account of this situation, the sampling frequency is set to 10Hz because the collected stress wave signal is the accumulation effect of complex high frequency stress wave signal in a short time at this frequency. It can be seen from the above figures, the faster the laying speeds is, the shorter the stress waves are, and the higher the frequency is. The effect of speed on the stress waves is not noticeable. In addition, the stress waveforms under the same laying temperature and pressure are similar.

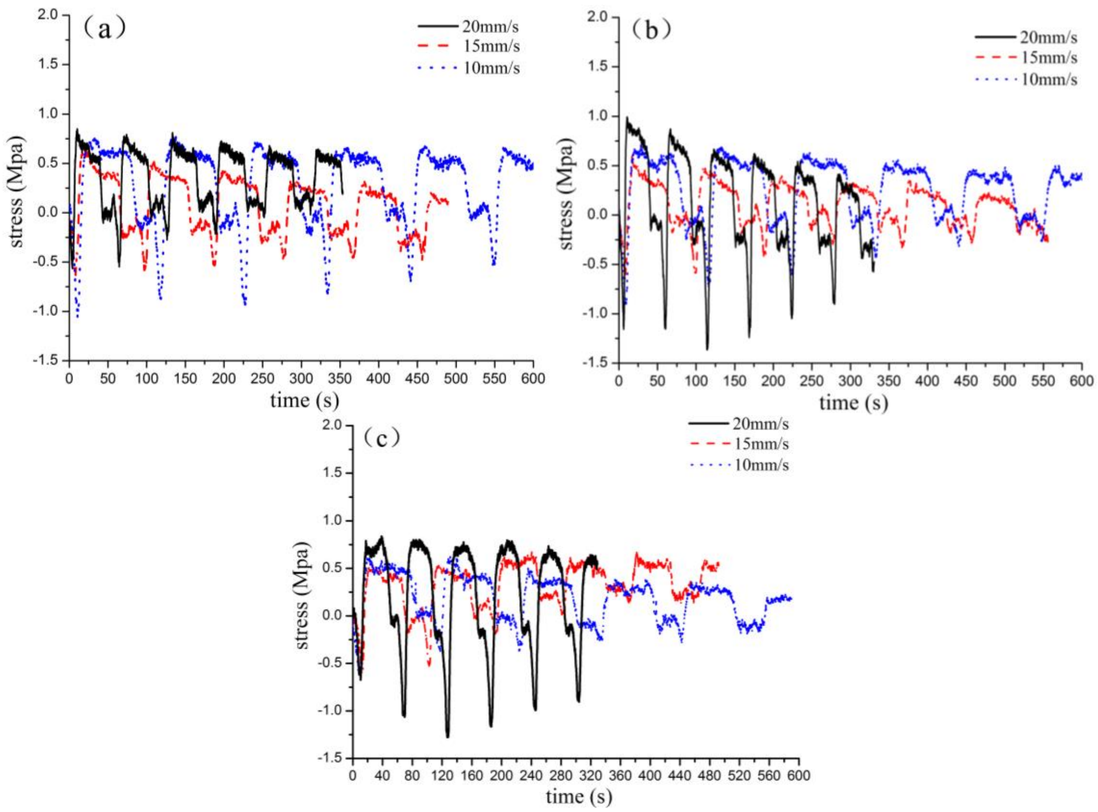

Figure 6. Real-time stress wave curves of laying process under different velocities: (a) t=50℃, p=850N; (b) t=50℃, p=600N; (c) t=50℃, p=350N.

In addition, with the purpose of studying the effect of different parameters on the magnitude of the stress wave an analysis is conducted. The correlation between the amplitude of stress wave data and parameters in 27 groups of experiments is analysed by means of gray relational analysis theory. By calculating the relative correlation between the data and the different parameters of each group, it can be found that the maximum correlation with the stress amplitude is the laying pressure (correlation coefficient 0.56), followed by temperature (0.53), the smallest is speed (0.51).

4. Conclusion

Laying pressure mainly determines the curves amplitude of the stress waves. With the different loading statuses and the different distances between the pressure roller and the strain gage, the curves of stress waves also present different trends. The fluidity of resin is affected by the laying temperature. The response speed of the stress wave is quick under the condition of strong fluidity of resin. And the increase of the temperature causes the thermal stress of the material to increase, where the stress curve amplitude is enlarged. The response speed of the stress waves collected at the test point has positive correlation to the laying speed, which is the most obvious in the latter two stages. The decay rate of the stress wave decreases with laying speed, and laying speed has no significant effect on the amplitude of the stress wave. Future work is going to explore the relationship between stress waves and defects.

Acknowledgments

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