Study on Automated Placement Setting Agent and Placement Process of Dry Fiber

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Abstract: During the automated placement process of dry fibers, the positioning and fixation of dry fiber gauze belts are achieved by spraying setting agents. The amount of the setting agent is difficult to control when it is sprayed manually. Furthermore, it can also affect the permeability of the preform, resin injection and the quality of the vacuum assisted resin infusion (VARI) molding, resulting in a decrease in the mechanical properties of composite materials. This study utilizes dry fiber automated placement equipment and an automated spraying system to manufacture preform structures, followed by VARI process to prepare composite samples with varying setting agent contents. Subsequently, mechanical characterization including interlaminar shear, bending and tensile testing is conducted to investigate the influence of setting agent content on both the manufacturing process and the mechanical properties of composite products. The results show that the interlaminar shear strength, bending strength and tensile strength of the sample gradually decrease with the increase of the content of the setting agent. The optimal setting agent content for automated laying of dry fiber is determined to be 4%—6%, balancing the preformed body's layup quality and its impact on mechanical properties. Compared with agent-free samples, this range results in reductions of 3% in interlaminar shear strength, 9% in bending strength, 11% in bending modulus, and 13%—16% in tensile strength.

Key words: automated placement technology of dry fiber; room temperature setting agent; preform preparation; vacuum assisted resin infusion (VARI) molding

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0 Introduction

Automated fiber placement (AFP) is one of the fastest developing and most effective composite automated molding manufacturing technologies in recent years[1-2]. As the core functional component, the machine of automated fiber placement is fixed on a gantry or mounted using an industrial robot, which results in a more flexible wire laying equipment configuration and smaller size and cost[3]. The material used in the spreading technique is classified as thermosetting and thermoplastic prepregs depending on the resin, and the common widths are 3.175 and 6.35 mm[4-5].

Vacuum assisted resin infusion (VARI) is a process that can achieve the integrated molding of large components with high production efficiency, short molding cycle and low cost of production. VARI is gradually becoming a new generation of major composite molding technologies at home and abroad. Currently, the quality of the preform has an important influence on the performance of the final molded part[6-8].

Some scholars at home and abroad have studied the application of dry fiber placement preform-liquid forming technology in composite materials

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and other fields[9-10]. The Russian United Aircraft Manufacturing Corporation (UAMC) used it to make preforms from thermoplastic dry fibers and then molded them in a curing oven using the VARI process, and successfully applied them to the MS-21 single-aisle airliner[11-12]. It not only reduced the manufacturing cost, but also improved the quality and productivity of the manufactured components. In addition, Boeing, Airbus and other manufacturers have conducted extensive research in this area[13]. "Wings of Tomorrow" program of Airbus is developing the high-efficiency liquid forming technology for wing siding[14]. Domestic MA700 project has been verified on the spoiler and landing gear hatch, which proves that the liquid forming technology is feasible for manufacturing[15]. However, the application in the main structure of the aircraft still needs to break through technical bottlenecks in material selection, design, manufacturing process and inspection.

Rudd et al.[16] firstly verified the feasibility of the automatic spreading technique for the preparation of preforms and found that the performance of the preforms prepared by the automatic spreading technique was not much different from that of normal molded parts, and also saved 20%—40% of the material. Belhaj et al.[17] used the technique of automatic spreading of dry fibers and investigated the effect of overlap or gap between dry fibers on the permeability of preforms. The effect of overlap or gap between dry fibers on the permeability of preforms was investigated and preforms of different morphologies had different mechanical properties. Aziz et al.[18] used TexGen simulation software to develop a TexGen model for dry fiber preforms. The results showed that the gap size between dry fiber auto lay-up filaments is a key parameter for achieving permeability. Matveev et al.[19] investigated the bending of filaments during the dry fiber lay-up and found that increasing the temperature could cause the dry lay-up prepreg bending, which in turn affected the stiffness of the member. It was also concluded that increasing the temperature could reduce the critical radius of bending of the dry lay-up filament prepreg.

Rizzolo et al.[20] investigated the effect of two different curing methods, which are ultrasonic consolidation and hot compression molding, on the properties of preforms and found that the properties of composite components obtained by the two methods may be diametrically opposed for different resin proportions of fibers. Lu et al.[21] built analytical models to predict the nip point heating temperature during the automated dry fiber placement process under different deposition velocities and different current inputs. The predictions from the analytical Joule heating model during fiber deposition show good agreement with the experimental temperature measurement.

In addition, the addition of setting agents would change the interfacial properties of carbon fiber resin-based composites, and many scholars have done plenty of studies on interface modification. Li et al.[22] used physical modification method of rapidly spraying carbon fiber (CF) surface by carbon nanotubes (CNTs) gas-phase dispersion to strengthen the interfacial bonding between CF and matrix. The results showed that interlaminar shear strength, tensile strength and compression strength of the CF composite fibers increased by 12.07%, 8.73%, and 13.83%, respectively. Mirsalehi et al.[23] conducted a detailed evaluation of the interphase of multi-walled CNTs modified epoxy resin/CF composites. Results show that the thickness ratios of the hard and soft interphase regions of the epoxy/CF composites increase 84% and 200%, respectively after adding the weight percent of 0.5% and 1.0% multi-walled CNTs. The elastic modulus and hardness nanocomposite are 41% higher matrix containing 1.0% (weight percent) multi-walled CNTs than those without multi-walled CNTs, and the plastic deformation resistance of the matrix is 37% higher. Fang[24] improved the interfacial properties of composites by coating polyethyleneimine modified carboxylic multi-walled CNTs in aqueous solution onto the surface of the CF to form a net-

work structure. The interfacial shear strength (IFSS) increased by 24.6%, and further resulted in 16.2% and 5.3% improvement in tensile strength and flexural strength, respectively. The CNT can form gradient interfacial structure with various thickness at the interface. And the gradient transition interphase could help to transfer stress uniformly. Therefore, the composites based on CNT-modified fibers have better mechanical properties.

As a structural component, composite materials formed by automated placement of dry fibers must meet the requirements of structure and strength. With the continuous development of automated placement of dry fibers-VARI molding, the matching of dry fiber woven fabric automated placement and wrapping process is now studied to obtain the optimal placement and wrapping process through experiments, which is of great significance for the subsequent practical engineering applications.

1 Experiment

1.1 Experimental materials

The materials used in this work include: carbon fiber woven fabric (SYT49S-12K-N1B-2, surface density 256 g/m^2); a polyurethane-based three-component setting agent (Changzhou Eka New Materials Technology Co., Ltd., mass ratio 100∶5∶5 for the three components); vinyl resin (30-200P, Huachang Polymers); methyl ethyl ketone peroxide as setting agent and cobalt naphthenate as accelerator (Changzhou Leeper Composite Materials Co., Ltd.); mass ratios of resin: curing agent: accelerator to be 100∶2∶0.2.

1.2 Sample preparation and treatment method

The equipment used in this paper includes automated dry fiber placement equipment (ADFRP, as shown in Fig.1) and automatic agent spraying equipment (Fig. 2) designed and manufactured by Research Center of Composites of Nanjing University of Aeronautics and Astronautics, oven, vacuum assisted resin infusion (VARI) molding equipment, and mechanical testing instruments.

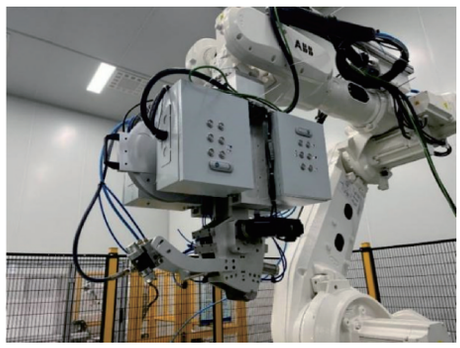


Fig.1 Automated placement head for two filament bundles of dry fibers

Fig.2 Automatic agent spraying equipment

The setting agent has good compatibility with the resin and does not affect the interlaminar properties of the composite, so it is important that the setting agent is selected to match the resin matrix[9]. In this experiment, vinyl resin 30-200P is selected in the automatic spraying equipment at room temperature.

As shown in Fig.3, vinyl ester resin has a large number of hydroxyl groups (—OH), which give the resin a certain polarity, viscosity and immersion, and facilitate the bonding between the resin and the fiber material. Polyurethanes also contain a large number of hydroxyl groups, which make the fixative immersive and viscous to the fiber material. Therefore, polyester polyol (adipic acid-based polyester diol) and isocyanate (diisocyanate with diol expansion) are selected as the main components of the polyurethane setting agent, and three setting agents are selected: two single-component setting agents (MP001 and MP002) and a three-component setting agent including adhesive agent TP001, curing agent TP002, and auxiliary agent TP003 with mass ratios of 100∶5∶5. The characteristic parameters of the three types of fixing agents are shown in Table 1.

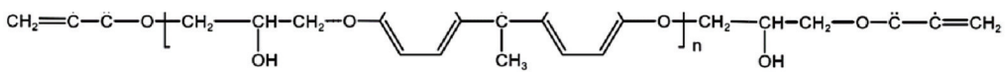
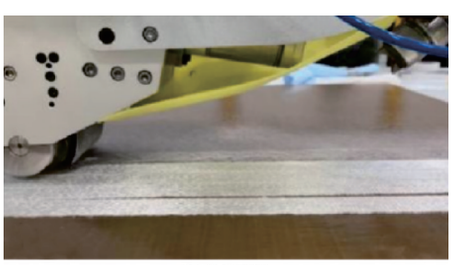


Fig.3 Molecular structure of vinyl ester resin

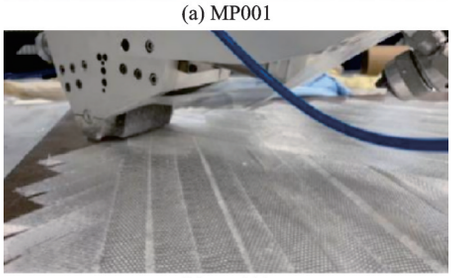
Table 1 Characteristic parameters of setting agents

Type		System	Solid content (150 ℃, 20 min)	Viscosity (25 ℃, 40 min)/(mPa•s)	Weight ratio	Diluted solvent
Monocomponent	MP001	Polyurethane	60%±2%	400±200	—	Ethyl acetate
	MP002	Polyurethane	60%±2%	400±200	—	
Three-component	TP001	Polyurethane	60%±2%	400±200	100	
	TP002	Isocyanate	75%±2%	—	5	
	TP003	—	<1%	—	5	

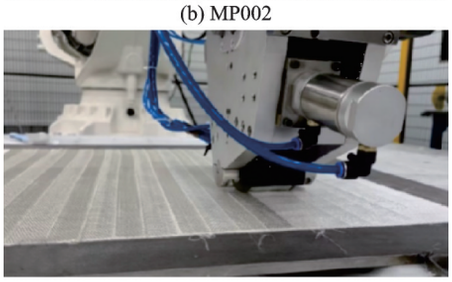
Three types of setting agents are used for placement experiments using ADFRP equipment, and the placement results and spraying effects are compared separately. The spraying effects are shown in Fig.4, and the viscosity of all three types of setting agents meets the bonding force required for automatic spreading of dry fibers.



(a) MP001



(b) MP002



(c) TP001+TP002+TP003

Fig.4 Pictures of dry fibers using three setting agents

Preforms are manufactured by using ADFRP equipment with different agent contents (0%, 1%, 3%, 4%, 6%, 8%, 10%). The size of all groups of samples is 400 mm × 400 mm, with the layers of 12. Fig.5 shows the manufactured preforms. The preform is placed on the mold surface pre-coated with the release agent, followed by VARI processing (Fig.6) under vacuum pressure exceeding 0.098 MPa and holding for 20 min to finish curing process. The resin and the setting agent are prepared according to the mass ratio of 100∶2∶0.2. After vacuuming, the vacuum infusion of resin glue is carried out, and the required time is recorded. After curing at room temperature for 24 h, the curing process is accelerated by putting the samples in an oven at 100 ℃ for 2 h.

Fig.5 Manufactured preforms

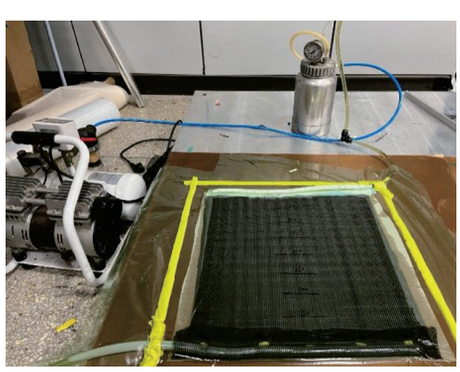


Fig.6 VARI molding process

1.3 Mechanical property test

(1) Interlayer shear performance test

In this experiment, the short beam method is used to test the interlaminar shear strength of composite parts after automated placement of dry fibers with different contents of setting agent-VARI molding. The preparation of samples is carried out by using ASTM D2344M standard[25] with at least 5 samples for each group. The length and width of samples are six times and two times the thickness of samples, respectively. The width and thickness of each sample are measured and recorded as shown in Fig.7 and Fig.8. The CMT51065 testing machine of Shenzhen Sansi Company is used to test the interlaminar shear performance, with the loading rate of 1 mm/min, the diameter of the loading head of 6 mm, and the diameter of the bearing fillet of 3 mm. The sensor has a measurement range of 100 kN. When the load drops 30%, the test is stopped, and the load-displacement test data is recorded.

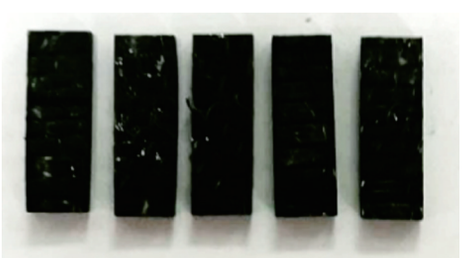


Fig.7 Samples for interlayer shear test

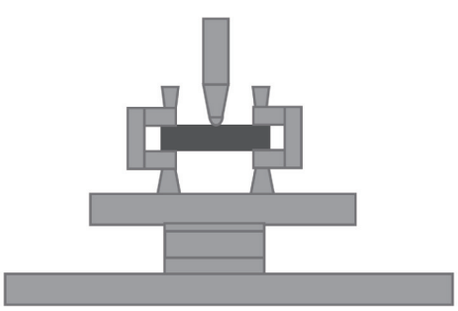


Fig.8 Schematic diagram of interlayer shear test

The interlaminar shear strength of the sample is calculated as follows

$$F^{\mathrm{sbs}} = 0.75 \times \frac{P_{\max}}{bh} \tag{1}$$

where F^{sbs} is the interlayer shear strength; $P_{\max}$ the maximum load measured for the test; b the measured width of the sample; and h the thickness measured for the sample. The width and thickness of each sample is measured and recorded before the test.

(2) Bending performance test

In this paper, the three-point bending method is used to measure the bending properties of preforms with different setting agent contents. According to ASTM D7264/D7264M-07 standard[26] for the preparation of samples, each test prepares at least five samples. Fig.9 shows the prepared bending samples. The length of samples is twenty times the thickness and the width is 15 mm. An CMT51065 type testing machine produced by Shenzhen Sanshi for bending tests is used to conduct the bending performance test, with the ratio of the span and thickness of 16∶1, the radius of the loading head of 5 mm, the sensor range of 100 kN, and the loading speed of 1 mm / s.

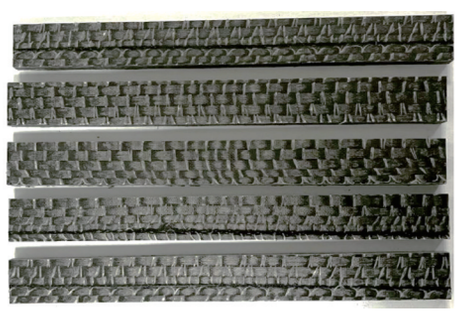


Fig.9 Bending samples

The bending strength of the sample is calculated as follows

$$\sigma_{\mathrm{f}} = \frac{3P_{\max} l}{2bh^2} \tag{2}$$

where σ_{f} is the ultimate bending strength and l the span of the sample.

(3) Tensile performance test

The standard ASTM D3039/D3039M-08 is used for conducting tensile testing. The sample size is shown in Fig.10, and the size of tensile samples is 250 mm×25 mm. 3M DP420 epoxy AB adhesive is used to fix reinforcement plates on the tensile sample. The purpose of using reinforcement plates is to minimize the stress vector generated on the sample surface during the fixture load application

process. The size of the reinforcement plate is 50 mm×25 mm×2 mm. The thickness and width of the sample gauge is measured and recorded after the aluminum sheet is fully solidified. The test loading rate is selected as 1 mm/min. When testing the tension, it is necessary to use an extensometer or stick a strain gauge to measure the deformation within the gauge length of the sample, so as to obtain the longitudinal tensile modulus (Fig.11). The load-displacement data is recorded until the sample is completely damaged or the load is decreased by 30%.

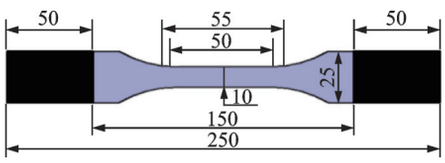


Fig.10 Size of samples for tensile performance test

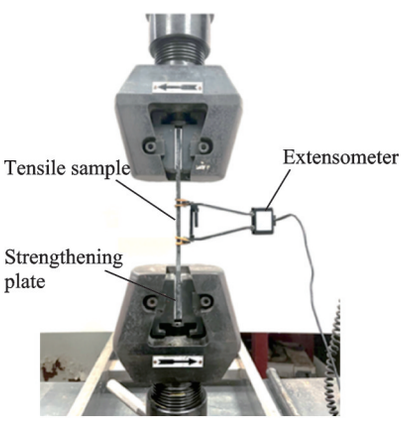


Fig.11 Schematic diagram of the tensile test

The formula for calculating the tensile strength of the sample is as follows

$$\sigma_t = \frac{P_{max}}{bh} \tag{3}$$

where σ_t is the ultimate tensile strength.

The calculation formula for tensile modulus of elasticity is as follows

$$E_t = \frac{\Delta P \times l}{b \times h \times \Delta l} \tag{4}$$

where E_t is the tensile modulus of elasticity; ΔP the load increment of the accident line segment on the load deformation curve; and Δl the deformation increment within the gauge length l corresponding to the load increment ΔP.

2 Results and Analysis

2.1 Results and analysis of interlayer shear test

The interlayer shear test data of samples with different contents of setting agents are analyzed and processed. The interlayer shear test data are shown in Table 2.

Table 2 Interlayer shear test results

Agent content/%	Average interlaminar shear strength/MPa	Standard deviation/MPa	Discrete coefficient/%
0	25.34	0.58	2.29
1	25.43	1.62	6.36
3	25.14	1.04	4.14
4	24.83	1.21	4.87
6	24.63	0.90	3.65
8	23.79	0.83	3.49
10	23.27	0.51	2.19

It can be seen from the Table 2 and Fig.12 that the average interlaminar shear performance of composite parts formed by automated dry fiber placement-VARI gradually decreases with the increase of the content of setting agent. The average interlaminar shear strength decreases from 25.34 MPa to 23.27 MPa. The interlaminar shear strength of the sample with 10% setting agent is 8% less than that of the sample without setting agent, and the standard deviation and dispersion coefficient of the sample are relatively small, which indicates that this process is relatively stable. The increase of setting agent content affects the bond strength between the resin and reinforcing fiber layers. The setting agent

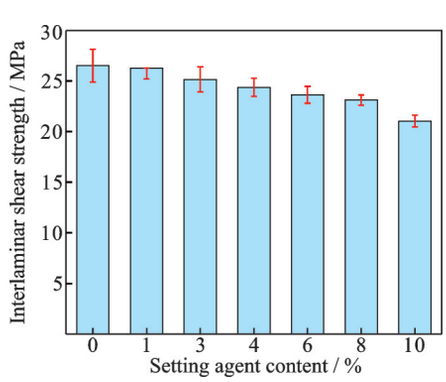


Fig.12 Interlaminar shear strength of samples with different setting agent contents

content of 1%—3% has the least effect on the mechanical properties of the composite products, but it cannot satisfy the setting effect required for automated lay-up. When the content of the setting agent is 4%—6%, it satisfies the setting effect required for automated laying while having an acceptable influence on the mechanical properties of the samples.

Fig.13 shows the delamination caused by interlayer shear failure of the sample, which takes the form of interlayer shear failure and non-elastic deformation. By observing the magnification of the delaminated sample, it can be seen that the number of delamination is mainly concentrated at the junction of the setting agent and the fiber layer. The setting agent will reduce the interlayer bonding performance of the fiber and resin. The increase of the content of the setting agent results in the accumulation of the setting agent, creating stress concentration points and reducing the interfacial bonding strength.

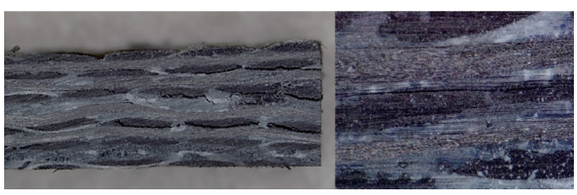


Fig.13 Delamination cracks caused by sample failure

2.2 Results and analysis of bending experiment

The test data of bending samples with different contents of setting agents are analyzed and processed. The average bending strength, standard deviation, and dispersion coefficient test data of the bending test are shown in Table 3.

Table 3 Bending test data statistics

Agent content/%	Average bending strength/MPa	Standard deviation/MPa	Discrete coefficient/%
0	339.17	8.38	2.47
1	320.52	24.06	7.51
3	323.31	28.91	8.94
4	313.56	14.49	4.62
6	310.54	12.71	4.09
8	308.81	28.92	9.36
10	289.70	26.11	9.01

From Table 3, it can be seen that the average bending strength of samples with different setting agent contents decreases as the setting agent content increases. The average bending strength of the sample decreases from 339.17 MPa to 289.7 MPa with an increase of the setting agent content, which decreases by 14%. The standard deviation and dispersion coefficient are relatively small, indicating that the degree of dispersion of each group of samples is small, and the degree of data difference is small.

Fig.14 shows the bending modulus of samples with different setting agent contents, indicating that the bending modulus decreases gradually as the setting agent content increases. The bending modulus of the sample without the setting agent is 34.57 GPa, while the sample with 10% setting agent content has a bending modulus of 28.51 GPa, showing a reduction of 17%. With lower setting agent contents, there is no significant effect on the adhesive strength between the resin and the reinforcing fibers, nor on the penetration of the VARI molding resin. However, as the setting agent content increases, the sample thickness increases, and the fiber volume content decreases, leading to a gradual reduction in both bending strength and bending modulus. Within the setting agent content range of 4%—6%, the mechanical properties of the samples are relatively less affected, indicating a potential balance between shaping performance and mechanical property.

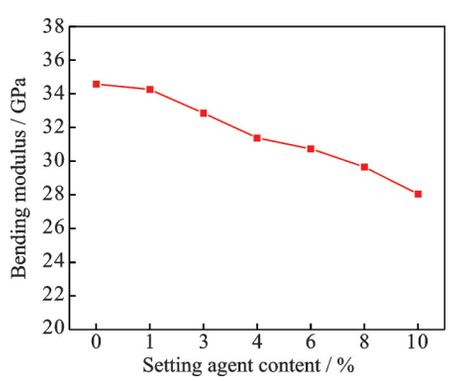
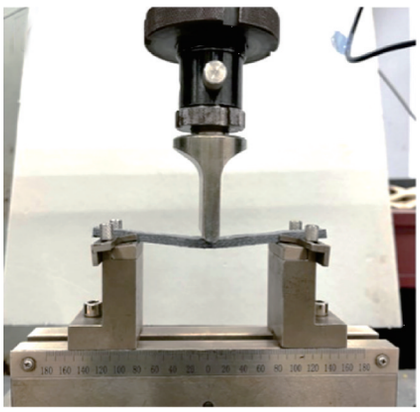
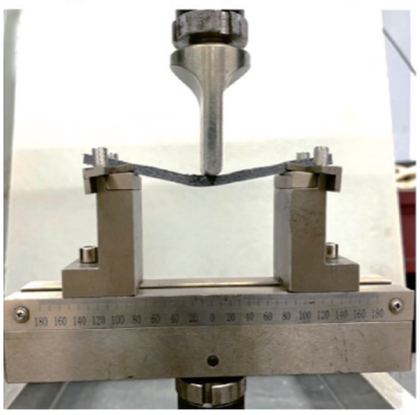


Fig.14 Bending modulus of samples with different setting agent contents

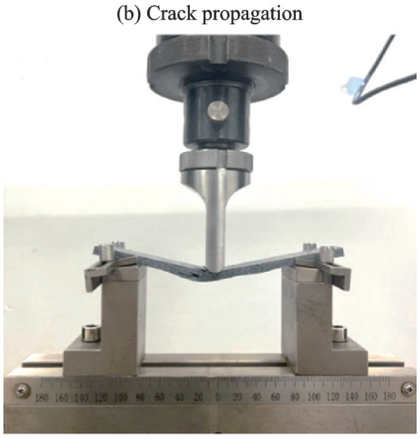
Fig.15 and Fig.16 show the delamination and cracks caused by the failure of the bent sample. It can be seen that a diagonal transverse crack has



(a) At the beginning of the loading



(b) Crack propagation



(c) Complete failure

Fig.15 Process of bending loading

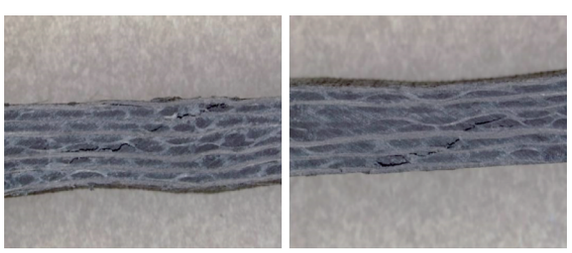


Fig.16 Cracks generated by bending failure

been generated in the sample, and the load action causes the matrix resin failure, causing the failure of the workpiece. Cracks mainly occur in the resin-rich area, and due to the increase of the setting agent, stress concentration occurs between the resin and the reinforcing fiber, which reduces the bonding strength between the resin and the reinforcing fiber and reduces the interface strength. Setting agent causes a decrease in the bending strength of the sample, and shows a trend of decrease in bending performance with the increase of the content of the setting agent.

2.3 Results and analysis of tensile test

The test data of tensile samples with different contents of setting agents are analyzed and processed. The average tensile strength, standard deviation, and dispersion coefficient test data of the tensile test are shown in Table 4.

Table 4 Statistics of tensile test data

Agent content/%	Average tensile strength/MPa	Standard deviation/MPa	Discrete coefficient /%
0	493.09	24.91	5.05
1	468.58	24.12	5.15
3	428.67	32.89	7.67
4	428.15	11.91	2.78
6	412.73	19.72	4.78
8	401.71	18.48	4.61
10	352.22	20.31	5.77

From Table 4, it can be seen that the average tensile strength of samples with different setting agent contents gradually decreases as the setting agent content increases. The average tensile strength of the standard sample without the setting agent is 493.09 MPa, and the sample with setting agent content of 1% has little effect on fibers and resins due to the low content of spraying setting agent, resulting in a small decrease in tensile strength. As the content of the setting agent increases, the tensile strength of the sample changes slightly, with an average tensile strength of 428—401 MPa. When the content of the setting agent is 10%, the average tensile strength of the sample is 352.22 MPa, and the tensile strength decreases significantly, which is 29% lower than the standard sample without setting agent.

Fig.17 shows the tensile load-displacement

curves of samples with different setting agent contents, and Fig.18 illustrates the fracture modes observed during the tensile test. At the beginning of the tensile testing, the sample's load increases linearly. As load rises, a sudden drop occurs before the ultimate threshold, resulting in a small stepped curve. At this point, the sample's fibers break, causing the occurrence of cracks. As the load continues to be applied, the load curve resumes its upward trend until it reaches the sample's ultimate threshold, at which point the sample fails. The peak loads of the samples with different setting agent contents show minimal variation, with the ultimate load averaging around 2.3 kN. However, as the setting agent content increases, the thickness of the preform and the final part increases, which reduces the fiber volume content and ultimately leads to a decline in tensile strength.

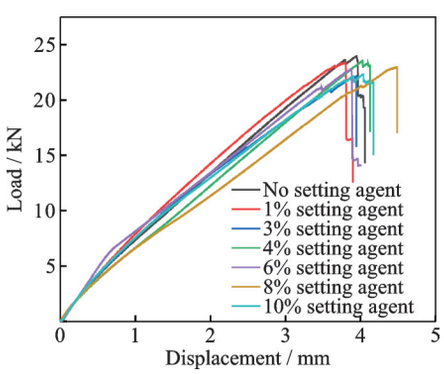


Fig.17 Tensile load-displacement curves

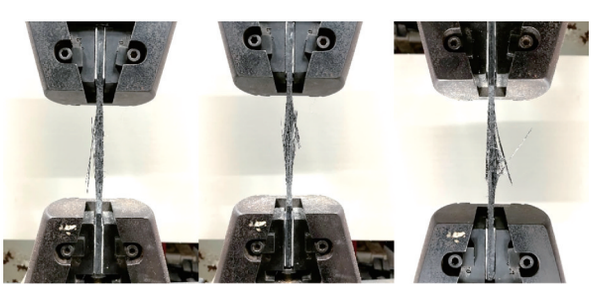


Fig.18 Fracture modes of tensile test

3 Conclusions

(1) The interlaminar shear strength, bending strength, bending modulus, and tensile strength of the samples gradually decrease with the increase of setting agent content, showing a decrease of 8%, 14%, 17% and 29% separately for samples with 10% setting agent, compared with samples without setting agent.

(2) The accumulation of the setting agent causes stress concentration, which weakens the interlayer bonding between fibers and the resin. This results in a reduction in overall interfacial adhesion, accompanied by decreases in interlaminar shear strength, bending strength, and bending modulus of the sample. Additionally, the increased setting agent content leads to sample thickening, which reduces the fiber volume content and subsequently lowers the tensile strength.

(3) The mechanical properties of composites decrease with the increase of the setting agent content. When the setting agent content is 1%—3%, it has the least effect on the mechanical properties of composite products, but it cannot satisfy the shaping effect needed for dry fiber automated placement; and when the content of setting agent is 8%—10%, the mechanical properties of the sample decrease significantly. When the content of setting agent is 4%—6%, the content of setting agent meets the shaping effect, and meanwhile, it has less influence on the mechanical properties of the sample.

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干纤维自动铺放定型剂与铺放工艺研究

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摘要:在干纤维自动铺放过程中,需通过喷涂定型剂来定位和固定干纤维纱带。人工进行定型剂的喷涂时,定型剂用量难以控制,定型剂的用量还会影响预成形体的渗透性,影响树脂的灌注,进而造成缺陷;也会影响真空辅助树脂注塑(Vacuum assisted resin infusion, VARI)成形的质量,从而引起复合材料制件力学性能的下降。本文采用干纤维自动铺放设备和自动喷胶设备进行预成形体自动铺放,并通过VARI成形工艺,制备不同定型剂含量的复合材料制品,然后进行层间剪切、弯曲、拉伸等力学性能测试,探究定型剂用量对VARI成形工艺和复合材料制品力学性能的影响。结果表明,随着定型剂含量的增加,样品的层间剪切、弯曲与拉伸强度逐渐降低。定型剂含量在4%~6%时,定型剂含量能获得较好的自动铺放成形定型效果,同时对试样的力学性能影响较小,与不含定型剂的试样相比,其层间剪切强度低3%,抗弯强度低9%,弯曲模量降低了11%,拉伸强度降低了13%~16%。

关键词:干纤维自动铺放技术;常温定型剂;预成形体制备;真空辅助树脂注塑成形