Research on Prepreg Tape Cutting Platform with Two Cutters

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(Received 7 March 2017; revised 3 December 2017; accepted 27 April 2019)

Abstract: The concept of cutting platform is proposed and realized based on the latest two-step automated tape laying (Two-step ATL) technology, which separates prepreg cutting process from tape laying to improve productivity for large parts with small features. Two-step ATL is more efficient than conventional layup because ply patches are pre-cut in a separate operation. The concept of the prepreg tape cutting experimental platform with two cutters is introduced. Further, based on the automatic tape laying trajectory planning software, a two-cutter cutting algorithm is proposed. Cutting experiments are reported to validate both the concept of cutting platform and cutting algorithm.

Key words: two-step automated tape laying (Two-step ATL); cutting platform with two cutters; cutting algorithm; cutter distribution

CLC number: V261 **Document code:** A **Article ID:** 1005-1120(2019)03-0442-07

0 Introduction

Automated tape laying (ATL) can be considered as an additive manufacturing, which is widely used in the aerospace and renewable energy industries. Its advantages are high layup rates and capability to manufacture large parts[1]. Recent applications of ATL include wing skin of F-22 and C-17, stabilizer skin of Boeing 777 and A340, center wing box of A380 and so on[2-3]. ATL integrates the functions of cutting, locating, paving, compaction and so on[4]. Tapes are laid on the surface of the mould along a pre-defined trajectory and consolidated by a roller. Labor force and material waste rate are largely reduced. Compared with other process forms, ATL is overwhelming in quality, repeatability, accuracy and production efficiency[5].

In conventional single-phase ATL, tape cutting and laying are processed simultaneously. Some issues are existed in ATL, for example, it is unable to cut some specific boundary shape, and the cutting scrap cannot be eliminated in the process of laying[6]. In order to solve such problems, France Forest-Line developed a nesting technology for ATL layup in 1980s, often referred to as a two-step layup.

The original concept of two-step ATL is raised by the US and Japan[7-8]. But France Forest-Line developed the equipment first. Its two-step ATL equipment is composed of two parts. Advanced composite cassette edit/shear system(ACCESS) and automatic tape laying system(ATLAS). Ply patches are pre-cut, stored on a ply-backing and wound back onto a roll on the ACCESS system and then laying without cutting on the ATLAS. The machine of ACCESS has two ultrasonic cutters to handle complex boundary shape[9-10]. The process flowchart of Forest-Line two-step ATL is shown in Fig.1.

Domestic research on two-step ATL is still in its infancy stage. Compared with conventional ATL, tow-step ATL has the advantages as follows:

(1) Capablity of handling complex boundary shapes.

(2) The local reinforcement part that can be conducted in the main laying process.

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How to cite this article: WEN Liwei, HUANG Xiaochuan, QIN Lihua, et al. Research on Prepreg Tape Cutting Platform with Two Cutters[J]. Transactions of Nanjing University of Aeronautics and Astronautics, 2019,36(3):442-448.
http://dx.doi.org/10.16356/j.1005-1120.2019.03.008

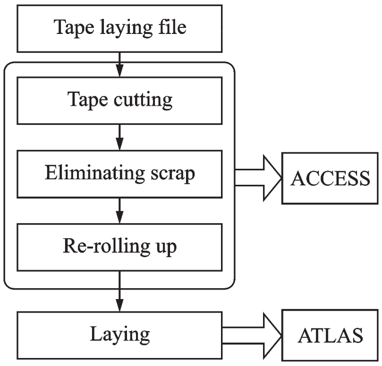


Fig.1 Flowchart of Forest-line's two-step ATL

(3) Reduction of 5%—10% in cutting scrap.

(4) Re-use of ACCESS machine for at least two ATLAS machines, which can improve productivity greatly[11].

Two-step ATL is a kind of rising technology with promising future. However, its development in China has been lagging behind the world level. In order to fill the gaps, a concept of cutting platform is proposed in this paper. As previous stated, pre-cutting is decisive in two-step ATL. Thus, a thorough study of boundary based cutting information generation method and experiments are presented.

1 Two-Cutter Prepreg Tape Cutting Platform Design

1.1 Design ideas

The principle and process of two-cutter tape cutting platform are shown in Fig.2.

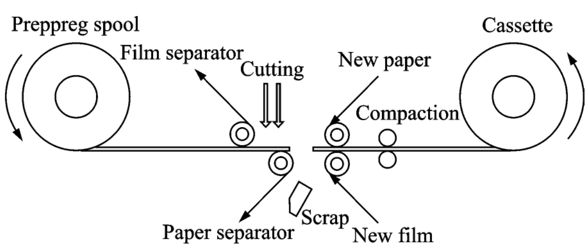


Fig.2 Principle diagram map of prepreg cutting platform

Both sides of prepreg tape are protected by backing paper and isolation film. A spool unrolls prepreg before cutting. According to the cutting files, two cutters cut the tapes after they pass through the film separator[12]. After cutting and eliminating scraps, tapes with new film and paper are re-rolled up in the cassette.

The tape cutting platform has two ultrasonic cutters. Compared with one cutter, this platform is able to cut complex boudnary without revolving the prepreg spool. That is, the spool rotates continuously in the same direction, which improves cutting effecicy.

Three different boundary shapes are shown in Fig.3. Boundaries 1 and 3 can be cut by one cutter by changing the directions of prepreg spool; while, bounday 2 can only be cut by two cutters without revolving prepreg spool. In order to cut shapes similar to boundary 2, two cutters are used in tape cutting platform.

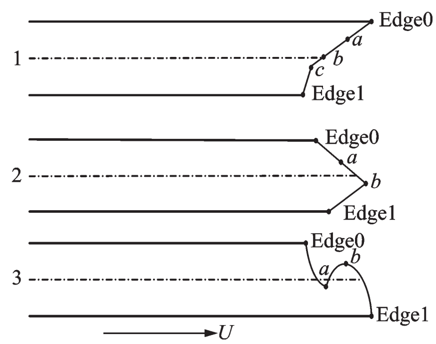


Fig.3 Different types of laying boundary

1.2 Overall design

Prepreg tape cutting platform is designed according to the existing motion axes on the splicing and rewinding machine which is owned by R & D Center for Composite Industry Automation, Nanjing University of Aeronautics and Astronautics (NUAA).

1.2.1 Design and control of prepreg spool

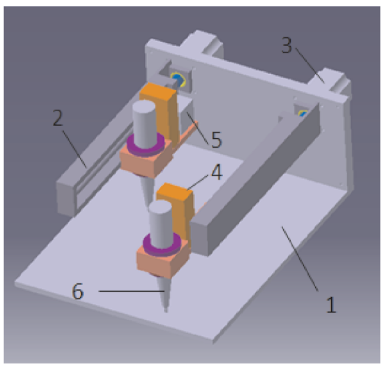
The mechanism of correct deviation is placed on the spool. When prepreg roller deviates from center position, a executing system pushes the roller back to rectify deviation. According to the length of each tape and different types of laying boundary, spool rotates and decides prepreg position. At the same time, the spool holds the prepreg tension in a proper range. Thus, encoders are attached to spool to ensure closed-loop control.

1.2.2 Design and control of film separator spool and paper separator spool

Film separator collects isolation films before cutting, which makes the prepreg easier to cut. Cutting scraps are remained on paper and eliminated after cutting by paper separator. For this reason, film separator spool and paper separator spool are controlled by torque motors. Torque motor provides constant torque opposites to the motion of prepreg tape, in order to maintain prepreg tension. The output torque of motor is monitored by magnetic particle clutch.

1.2.3 Design and control of two-cutter platform

The design principle diagram of prepreg tape two-cutter platform is shown in Fig.4.



1—Cutting board; 2—Rolling guide screw;
3—Feed drive motor; 4—Pressing cylinder;
5—Cutter rotating motor;
6—Ultrasonic cutter

Fig.4 Design principle of two-cutter tape cutting platform

The platform consists of six parts, including cutting board, rolling guide screw, feed drive motor, pressing cylinder, cutter rotating motor, and ultrasonic cutter. Feed drive motor drives the rolling guide screw and guides the cutter set on them. Cutter rotating motor controls the angle of the cutter along the cutting direction all the time by trasmission belt which connects the motor and cutter tightly. Pressing cylinder moves the cutter up and down by an electromagnetic valve. The moving distance of pressing cylinder is controlled by a pole whose size is divided on it. Given that the thickness of the prepreg is 0.125 mm usually and minimum scale of that pole is 0.01 mm, positioning accuracy of the cutters is 0.01 mm. It is adjusted to make sure the cutter can cut the tape successfully. And the tape's cutting is dependent on the vibration by ultrasonic cutters[13-14].

In summary, this platform has two feed drive motors and two cutting rotating motors owing to two cutters. After rotating motors drive the cutters at their certain angles, the prepreg is cut according to synchronizaion movement of prepreg spool axis and cutter feed axis.

1.3 Two-cutter tape cutting experimental platform building

According to previous states of cutter platform, the experimental platform of two-cutter tape cutting is shown in Fig.5.

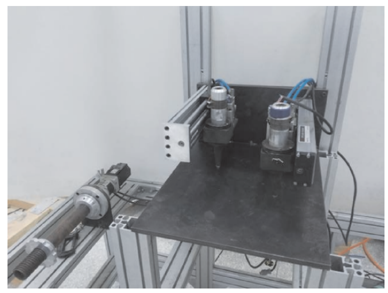


Fig.5 Cutting experimental platform with two cutters

2 Cutting Algorithm

In this paper, cutting algorithm is based on trace file and boundary file, which are generated by ATL trajectory planning method[15].

In trace file, all track points are indentified, including track number, all the points (lying on the centre of w wide prepreg tape, $w/2$) coordinates (Cartesian coordinate) of one track and their normal vector.

Boundary file stores the information of mould boundary points, with fixed intervals. These points' coordinates are arranged clockwise from the start point of laying.

In cutting algorihtm, all the cutter's control information is renerated. Algorithm flow is presented as follow.

2.1 Coordinate transformation

Both track points and normal vector coordinate points are built in Cartesian. It is hard to calculate cutting parameter directly. Coordinate transformation is necessary from the globe to the local coordinate system $\{E\}$[16]. Therefore, Cartesian X, Y, Z transforms to the local coordinate U, V, W by a homogeneous transformation matrix ${}_{E}^{0}\boldsymbol{T}$.

$$ {}_{E}^{0}T=\begin{bmatrix} {}_{E}^{0}\boldsymbol{Q}_{3\times 3} & & & \alpha_x \\ & & & \alpha_y \\ & & & \alpha_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{1} $$

where ${}_{E}^{0}\boldsymbol{Q}_{3\times 3}$ is a rotation matrix; $[\alpha_x \quad \alpha_y \quad \alpha_z]^{\mathrm{T}}$ a translation matrix. The orientation of U goes along tape's moving direction. Simultaneously, V is normal to U in the cutting plane. The orientation of cutters downing is $U\times V$ momently, as shown in Fig.6.

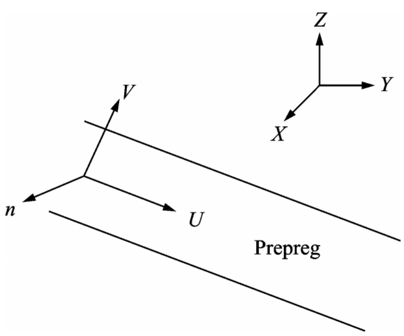


Fig.6 Coordinate transformation

As shown in Fig.7, S is the mold surfae, traj is one of the trajectories, and P_n is a dispersed points of this trajectory. The start point P_{start} and end point P_{end} are mapped to P'_{start} and P'_{end} which are in the local coordinate system $\{E\}$. The mapped points are shown in Fig.8.

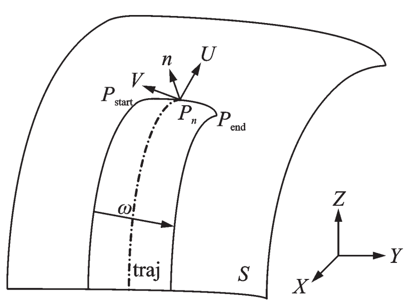


Fig.7 Mould boundary

Suppose a boundary point p_i. Its Cartesian coordinate is $[x_i, y_i, z_i]$, and its local coordinate is $[u_i, v_i, 0]$ according to Eq.(1).

$$ {}^{0}\boldsymbol{p}_i = {}_{E}^{0}\boldsymbol{T}\, {}^{E}\boldsymbol{p}_i \tag{2} $$

where ${}^{0}\boldsymbol{p}_i$ is the value in the Cartesian and ${}^{E}\boldsymbol{p}_i$ is in the local coordinate system. Therefore

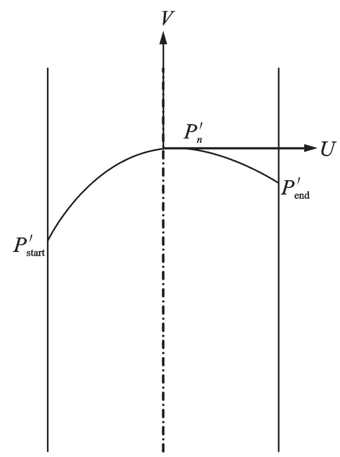


Fig.8 Mould boundary mapping to $\{E\}$

$$ {}^{E}\boldsymbol{p}_i=\begin{bmatrix} u'_i \\ v'_i \\ 0 \\ 1 \end{bmatrix} = {}_{E}^{0}T-1\cdot {}^{0}\boldsymbol{p}_i = \begin{bmatrix} {}_{E}^{0}\boldsymbol{Q}_{3\times 3} & & & \alpha_x \\ & & & \alpha_y \\ & & & \alpha_z \\ 0 & 0 & 0 & 1 \end{bmatrix}^{-1} \cdot \begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix} \tag{3} $$

All the points is mapped to the $\{E\}$ from Cartesian by Eq.(3).

2.2 Key cutting points

There must exists boundary point P_{near} that is the nearest one to the start point $\text{Traj}_{\text{start}}$ of track n on the disperse mould boundary, as shown in Fig.9. The first point is found whose distance from $\text{Traj}_{\text{start}}$ is longer than $w/2$, P_{start} and P_{end}. Then cutting points Edge0 and Edge1 are obtained whose distance from $\text{Traj}_{\text{start}}$ is equal to $w/2$.

From Edge0 to Edge1, all the cutting points are key. Similarly, points Edge0$'$ and Edge1$'$ which are key cutting points on the end of track can be obtained in the same way.

Suppose P'_i and P'_{i+1} are already mapped adja-

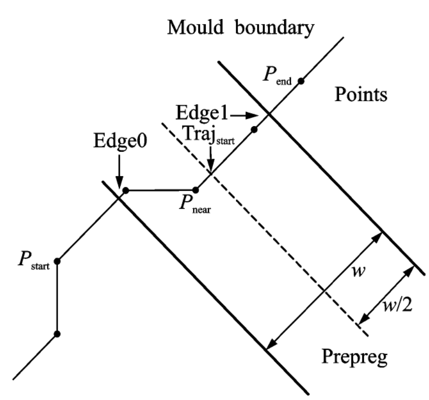


Fig.9 Sketch of laying trajectory and mould boundaries

cent points. The length of tape moving ΔU and the distance of cutter moving ΔV are shown in Fig.10.

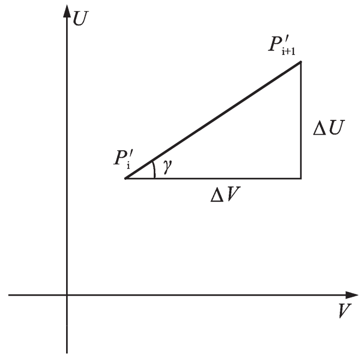


Fig.10 The relationship of U and V

The difference value in the direction of U and V is

$$\begin{cases}\Delta U = P'_{i+1,U} - P'_{i,U} \\ \Delta V = P'_{i+1,V} - P'_{i,V}\end{cases} \tag{4}$$

So cutters need to rotate the angle γ along the direction of V, which is

$$\gamma = \arctan(\Delta U/\Delta V) \tag{5}$$

2.3 Cutters distribution

After key cutting point calculation, the cutters distribution can be given by calculating the changing times of adjoining points coordinate difference along with U from Edge0 (Edge0′) to Edge1 (Edge1′). It means changing from positive to negative or from negative to positive. Nothing should be noted if there is not any changing. It is shown in Fig.11.

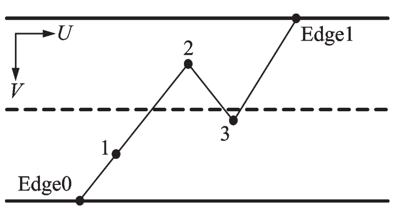


Fig.11 Diagram of the trajectory boundary

$$\begin{aligned} U_{\text{Edge01}} &= U_1 - U_{\text{Edge0}} > 0 \\ U_{12} &= U_2 - U_1 > 0 \\ U_{23} &= U_3 - U_2 > 0 \\ U_{3\text{Edge1}} &= U_{\text{Edge1}} - U_1 > 0 \end{aligned} \tag{6}$$

Therefore, total times of changing are noted. The cutter distribution according to total times of changing is shown in Table 1.

2.4 Cutting information planting

Cutting information is attached to the trace file, including angles of cutter rotation, feed ratio and up/down actions of cutters.

Table 1 Two-cutter distribution

Total times of changing	Boundary shape	Cutter number
0	“\”	1
	“/”	2
1	“>”	“\”to 1“/”to 2
	“<”	“\”to 1“/”to 2
>1	—	give up

3 Experiments

An experimental cutting plantform is built up as shown in Fig.5. Cutting experiments are conducted to find out its problem.

3.1 Experimental conditions

According to the cutting conditions in the ATL, 40 kHz ultrasonic frequency is chose in the experiments. T300 carbon fibre reinforced epoxy resin composite is used, and resin content is approximately 30%.

3.2 Experiments and analysis

3.2.1 Cutting

The cutting experiment in carried out on the two cutters platform. The sketch of cutting is shown in Fig.12.

Cutter 1 is nearer to the prepreg spool than cutter 2. When cut boundary “>”, cutter 1 starts to cut the “\” boundary at point 0 first. Then cutter 2 cut

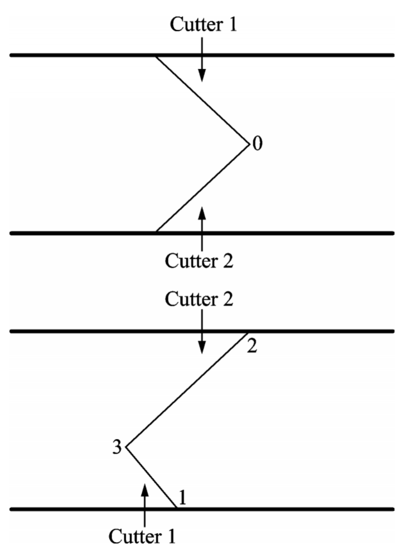
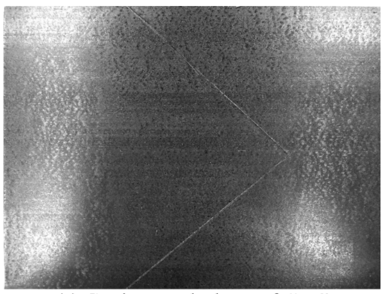


Fig.12 Sketch of double cutting

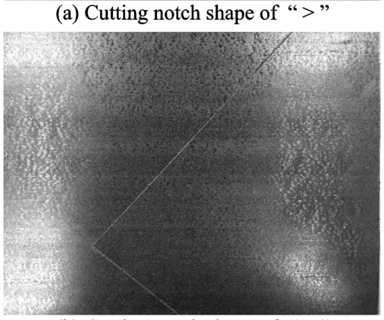
the “/” boundary at the point 0 similarly by linear interpolation with spool when spool picks up the tape under it. Cutting boundary “＜” is similar to boundary “＞”. The start point of cutter 1 is point 1, but the start point of cutter 2 is point 2. In the other words, cutter 1 cuts the tape from point 1 to point 3 first, then cutter 2 cuts from point 2 to point 3.

3.2.2 Results

To ensure prepreg is cut smoothly, according to previous studies, velocities of U axis and V axis are set to 500 mm/s and 10 mm/s, respectively. The result of the experiments is shown in Fig.13.



(a) Cutting notch shape of “>”



(b) Cutting notch shape of “<”

Fig.13 Results of cutting

As shown in Fig.13, the results of cutting are in good agreement with calculation, and two-cutter cutting experimental platform can realize its function. The experimental results show that concept of cutting platform is valid and cutting algorithm is correct.

4 Conclusions

Designing the prepreg cutting platform with two cutters and cutting algorithm based on two-step ATL is studied. CAD based cutter information generation algorithm is proposed. Experiments of two-cutter cutting prepreg are carried out to verify the platform.

Experimental results show that prepreg cutting platform is able to cut boundaries with convex or concave polyline-shape by two cutters without revolving the prepreg spool. The experimental platform validates both the concept of cutting platform and cutting algorithm, and promotes the development of two-step ATL.

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Acknowledgement This work was supported by the National Science and Technology Major Project (No. 2016ZX04002-005).

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Author contributions Dr. **WEN Liwei** designed and conducted the experiment and wrote the manuscript. Mr. **HUANG Xiaochuan** conducted the experiment. Dr. **QIN Lihua** conducted the experimental evaluation. Dr. **WANG Xianfeng** and Prof. **LI Yong** commented on the manuscript and approved the submission.

Competing interests The authors declare no competing interests.

(Production Editor: Xu Chengting)