Research on Temperature Control Multilayer Manufacturing Method Based on Paving Quilting Cutting System

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Abstract. With the increasing investment of the country in the field of satellite manufacturing, the mode of satellite manufacturing is gradually changing from single development to batch production, and the existing research and production capacity is facing great challenges, so it is urgent to establish a product system to meet the requirements of multi-task, multi-model and batch production. This paper elaborates the automatic manufacturing process of multilayer insulation components in satellite thermal control system. Firstly, through designing special tooling, improving system design, optimizing process flow, and then conducting process tests, the optimal parameters are obtained and applied, which improves the production efficiency, stabilizes the production quality and meets the needs of large-scale scientific research and production.

1. Introduction
In satellite thermal design, thermal insulation measures are often needed for some instruments, components or skins to minimize heat loss in order to control their working temperature. Sometimes, it is necessary to prevent the impact of high temperature heat sources or fluctuating thermal environment on instruments or components and minimize heat flow to these specific instruments or areas. Thermal insulation measures are needed in these cases.\textsuperscript{[1]}

Thermal control measures are divided into active thermal control and passive thermal control. Temperature control multilayer insulation module is a very important means of passive thermal control. With the rapid growth of satellite scientific research and production tasks in recent years, the traditional manufacturing technology of temperature-controlled multilayer insulation module has some shortcomings, such as slow speed, on-board sampling, and the quality of production is greatly affected by the level of operators. The manufacturing method is facing new challenges. Through investigation and analysis, a lot of experiments and explorations have been carried out. It is considered that the multilayer temperature control manufacturing method of paving quilting cutting system is an effective innovation to improve the level of temperature control, improve production management mode, promote the process of production and improve production efficiency.\textsuperscript{[2]}

2. Optimization and improvement of satellite temperature control workflow

2.1. Traditional production process
Spacecraft temperature control multilayer fabrication has always adopted the process of manual production, from blanking, laying, to sewing, and finally tailoring are all manufactured by pure manual method. The production efficiency is low, the production cycle is long, and the quality of finished products depends on the level of operators.

2.2. Optimized production process

By using multilayer automatic paving quilting cutting system, the manufacturing process can be optimized, the multilayer processing time can be greatly reduced, the efficiency of multilayer processing can be improved, and the assembly cycle of spacecraft can be shortened. Paving quilting cutting system includes paver, quilting machine and automatic tailoring machine, quilting machine includes quilting machine body and quilting machine control system, automatic tailoring machine includes tailoring machine body and tailoring machine control system, as shown in Figure 1.

![Figure 1. Paving quilting cutting system.](image)

1- Receiving area, 2- Cutting area, 3- Cutting Machine Control System, 4- Receiving area, 5- Quilting machine body, 6- Paving machine, 7- Sewing area, 8- Control system of quilting machine

The optimized manufacturing process for paving and quilting links are showed as described below. Firstly, the single layer aluminized polyester film and polyester mesh are placed on 10 passive rollers of the paver, and the active rollers of the paver are used to roll out 2-unit and 3-unit semi-finished products. After each winding, a certain length of semi-finished products will be taken off for use. According to the total number of samples to be sewn, the number of 2-unit and 3-unit semi-finished products is determined. For example, 20-unit samples are composed of 4 semi-finished products of 2-unit and 4 semi-finished products of 3-unit. On this basis, the aluminized polyester film substrate is placed on a passive roller, together with other 2-unit and 3-unit semi-finished products, after the front leveling treatment and surface integrity treatment, it is sewed into the quilting machine to form a multi-layer semi-finished product which meets the actual requirements for subsequent tailoring. [3]

2.3. Aspects to be improved

After a period of exploration and testing, the following aspects need to be further optimized:

In terms of paving materials:
- (1) Because the tension cannot be controlled, the multi-layer material is easy to form folds, and the scroll has no anti-drop device;
- (2) The way of feeding is complex, which cannot guarantee the neatness of multi-layer edges.
- (3) Laying length cannot be calculated;

In terms of quilting:
- Quilting tests are needed to determine the optimal parameters.

3. Key technologies of automatic paving

In view of the aspects to be improved in the paving process, the following key technologies are implemented to improve and solve them.
3.1. Anti-slip technology of winding damping adjustment
The multi-layer thermal insulation module is composed of aluminized polyester film and polyester mesh. There are many wrinkles in the manufacturing process because the tension cannot be effectively controlled. In this study, the method of damping adjustment is used to control the tension. The winding damping adjustment and anti-roll slippage tooling are shown in Fig. 2.

(1) Damping adjustment: The left and right rolling bearings play a supporting role and reduce the winding friction. The damper adjusting block at the end of the winding shaft moves the damper block up and down by adjusting the handle and adjusting the bolt. The lower surface of the damper is designed as a circular arc, which matches the winding shaft. When winding, the winding damping can be adjusted by adjusting the position of the damper block in the upper and lower directions.

(2) Anti-roll slip: The anti-roll sliding movable frame is made into a closed form, which can prevent the roll from sliding when winding. The frame is connected with the base through the left and right movable pins. When the multi-layer material of the reel needs to be loaded and unloaded, the movable pins can be pulled out, and the closed frame can be opened to carry out the loading and unloading operation. In order to realize the convenience of loading and unloading, both sides of the frame can be opened.

Through the processing of 12 rolls of paver and installation of 12 sets of tooling, the winding test shows that the device is convenient to use and adjust, and has good reliability, as shown in Figure 3.

3.2. Winding feeding technology
In order to flatten the front end of the composite multi-layer material, the winding feeding tooling is designed as shown in Fig. 4. It can fix the composite multi-layer material reliably on the reel and effectively reduce wrinkles.

A groove is designed and machined on the reel. The composite multilayer material is smoothly put into the groove, and then the multilayer material is compressed in the groove by a slender shaft with certain elasticity. In order to ensure reliable fixing, the slender shaft material uses engineering plastics with certain elasticity, and according to the thickness and groove width of multi-layer material, the diameter of slender shaft is designed with a certain interference. Several winding process tests show that the scheme is convenient, fast and reliable, and helps to reduce the winding fold.
3.3. Paving length measurement technology

In order to make quantitative paving, it is necessary to measure the length of paving. Length measurement can be achieved by using meter wheel and meter device widely used in plastic, wire and paper industries, as shown in Figure 5. The disc of meter wheel is pressed on the multi-layer material with a certain pressure. When the multi-layer material moves due to winding or quilting, the friction between the disc and the surface of the multi-layer material drives the disc to rotate. NPN signal is generated by rotating disc and transmitted to meter. The meter device processes the signal and displays it on meter device by digital display after calculation.

4. Automatic quilting test

Through the design of automatic quilting test, the optimal parameters are obtained to improve the quality of quilting.

4.1. Evaluation index of test

The quality of automatic quilting is evaluated by two indexes: fold rate E and edge error D of multi-layer material. The above two indexes are checked and calculated under different quilting process parameters. By comparing the E and D values under different parameters, the quality of multi-layer materials can be evaluated. The definition and calculation methods of the two evaluation indicators are as follows:

(1) Fold rate
The quilting stitches of multi-layered material blocks with good quilting are carefully cut, and the fold rate is calculated layer by layer. The fold rate is expressed by variable E, which is a dimensionless variable with values ranging from 0 to 1.

20-unit multi-layered material are 41 layers in each layer. If the untreated area of each layer is Sn, n=1~41, and the spreading area of each layer is Qn, n=1~41, then the fold rate of each layer is en (n=1~41):

\[ e_n = \frac{|Q_n - S_n|}{S_n} \]  

(1)

The overall average fold rate E of multi-layered materials is defined as:

\[ E = \frac{1}{41} \sum_{n=1}^{41} e_n \]  

(2)

The key to obtain the folding rate of multi-layer samples under certain technological parameters is to obtain the area of a certain layer after deployment. Because the folds of each layer produced by paving and quilting operations are relatively random, the edge shapes of each layer material after expansion are irregular.

In order to obtain the expanded area of irregularly shaped layers of material, the flow chart is shown as below:

① The multi-layer material is scanned by a flat scanner, and the true color image is obtained, and the shape of each layer is acquired.

② Image processing is carried out by using MATLAB. Taking a material as an example, the true color image is obtained, which is not easy to process, so it is transformed into gray image.

③ The gray-scale image is binarized. In the process of binarization, appropriate thresholds are selected to make the material and background completely separate.

④ The binary image in MATLAB corresponds to a matrix, assuming that it is a matrix. The elements of a matrix corresponds to 0 or 1, white corresponds to 1, and black corresponds to 0. If it is a common material, the total number of elements whose median value is 0 can be directly calculated to obtain the total number of pixels proportional to the area. However, due to the reflective and porous
properties of multi-layer materials, some elements whose value is 1 will also be produced inside the material. If the above method is still used, the calculation of the area will have a great error. The present method is similar to that of calculus. Assuming that the matrices corresponding to binary images have columns, the maximum and minimum index (i.e. the boundary index of each column) of the elements with a value of 0 is obtained by a simple algorithm. The total number of pixels with a value of 0 in each column is obtained by subtracting them. Then, the total number of pixels within the boundary of multi-layer materials can be obtained by adding the total number of pixels in each column. The total number of pixels is proportional to the area. From this, the area of each layer of multilayer material can be obtained.

⑤ The fold rate of a layer material is calculated by formula (4.1), and the fold rate of the whole sample is calculated by formula (4.2).

(2) Edge error

Edge error refers to the maximum value of dimension error of multi-layer sample whose edge is perpendicular to the direction of travel. It is expressed by variable D in mm. The edge error is obtained by measuring the dimension errors perpendicular to the direction of travel, which are most dependent on the outer edge and most dependent on the inner edge.

4.2. Design of test matrix and test analysis

Select 20 units of multi-layer experiments to verify the maximum working capacity of the machine. The 20-unit multilayer insulation material is composed of 4 groups of 2-unit semi-finished products and 4 groups of 3-unit semi-finished products. The parameters that can be changed in the quilting process of multi-layer insulation materials are: quilting needle spacing, needle foot distance. According to the typical working conditions, the horizontal number is 4. Table 1 gives the factor level table.[4]

Table 2 shows the result of fold rate analysis of automatic quilting. Each row in the table represents a test operation condition. A total of 16 automatic quilting tests need to be completed, and 16 multi-layer test results are obtained. Each test has two parameters of wrinkle rate and edge error as the evaluation index of the test results. The fourth fold rate is the average fold rate.[5]

Table 1. Factor level table of optimized automatic quilting test.

| Factor | Quilting needle spacing | Needle foot distance |
|--------|-------------------------|----------------------|
| 1      | 50                      | 25                   |
| 2      | 100                     | 50                   |
| 3      | 150                     | 75                   |
| 4      | 200                     | 100                  |

In the process of data processing, the maximum fold rate and the average fold rate are weighted and combined to get a comprehensive weighted score. From the test data, the following conclusions can be drawn:

(1) The maximum fold rate and average fold rate obtained by the experiment No. 14 are the smallest, which are 2.4235% and 0.6290% respectively. The comprehensive weighting value is the smallest. It shows that the corresponding technological parameters of quilting needle distance 100 mm and needle foot distance 75 mm are the optimal technological parameters.

(2) When the distance between the thread and the needle is moderate, the quilting effect is the best. The comprehensive ranking sum of the four levels of quilting needle distance and needle foot distance was calculated through comprehensive screening of the data, as shown in Table 3. The following conclusions can be drawn:

(1) From the general trend, the distance between quilting needle distance and needle foot distance is parabolic distribution, the middle parameters are better, and the max and min values are worse.

(2) The quilting stitch distance level is 100 rows 1, and the stitch distance level is 75 rows 2. The overall trend is consistent with the actual situation.
Table 2. Analysis results of fold rate.

| No. | quilting needle spacing | Needle foot distance | Test result |
|-----|-------------------------|----------------------|-------------|
| 1   | 50                      | 25                   | 0.775       |
| 2   | 100                     | 50                   | 1.706       |
| 3   | 150                     | 75                   | 2.596       |
| 4   | 200                     | 100                  | 2.849       |
| 5   | 50                      | 50                   | 1.539       |
| 6   | 100                     | 25                   | 7.154       |
| 7   | 150                     | 100                  | 3.426       |
| 8   | 200                     | 75                   | 2.390       |
| 9   | 50                      | 75                   | 3.239       |
| 10  | 100                     | 100                  | 2.226       |
| 11  | 150                     | 25                   | 1.896       |
| 12  | 200                     | 50                   | 3.572       |
| 13  | 50                      | 100                  | 6.585       |
| 14  | 100                     | 75                   | 0.629       |
| 15  | 150                     | 50                   | 1.377       |
| 16  | 200                     | 25                   | 5.834       |

| Factor                  | Fold rate(E) | Maximum m fold rate | Maximum E-weighting | Average E-weighting | Comprehensiv e weighting | Comprehensiv e ranking |
|-------------------------|--------------|---------------------|---------------------|---------------------|--------------------------|-----------------------|
| Quilting needle spacing | 0.775        | 5.6353              | 6                   | 2                   | 8                        | 3                     |
| Needle foot distance    | 1.706        | 3.8920              | 5                   | 5                   | 10                       | 5                     |
|                        | 2.596        | 12.5315             | 12                  | 9                   | 21                       | 10                    |
|                        | 2.849        | 8.8549              | 9                   | 10                  | 19                       | 9                     |
|                        | 1.539        | 8.7813              | 8                   | 4                   | 12                       | 7                     |
|                        | 7.154        | 32.1464             | 16                  | 16                  | 32                       | 16                    |
|                        | 3.426        | 12.2168             | 11                  | 12                  | 23                       | 12                    |
|                        | 2.390        | 6.5068              | 7                   | 8                   | 15                       | 8                     |
|                        | 3.239        | 10.6529             | 10                  | 11                  | 21                       | 11                    |
|                        | 2.226        | 3.6762              | 4                   | 7                   | 11                       | 6                     |
|                        | 1.896        | 3.2685              | 2                   | 6                   | 8                        | 4                     |
|                        | 3.572        | 14.9314             | 14                  | 13                  | 27                       | 13                    |
|                        | 6.585        | 15.5398             | 15                  | 15                  | 30                       | 15                    |
|                        | 0.629        | 2.4235              | 1                   | 1                   | 2                        | 1                     |
|                        | 1.377        | 3.4770              | 3                   | 3                   | 6                        | 2                     |
|                        | 5.834        | 13.7275             | 13                  | 14                  | 27                       | 14                    |

Table 3. Overall analysis results of fold rate.

| No | quilting needle spacing | The sum of comprehensive rankings | Needle foot distance | The sum of comprehensive rankings |
|----|-------------------------|-----------------------------------|----------------------|-----------------------------------|
| 1  | 50                      | 36                                | 25                   | 37                                |
| 2  | 100                     | 28                                | 50                   | 27                                |
| 3  | 150                     | 28                                | 75                   | 30                                |
| 4  | 200                     | 44                                | 100                  | 42                                |

4.3. Edge error analysis
Table 4 is the detailed measurement results of edge errors. The maximum edge errors of all edges are measured, and the maximum edge errors of the whole block are obtained by comparing the data of four edges.

By analyzing the measurement results in Table 4, the following conclusions can be drawn:

(1) The maximum edge error of serial number 14 is 4mm, ranking 3rd, within acceptable range;
(2) There are six groups whose edge error is more than 10 mm, and the serial numbers are 3, 4, 7, 8, 9 and 13. From Table 3, we can see that the fold rate ranks 8, 9, 10, 11, 12 and 15 respectively. The ranking is relatively low, which proves that the fold rate value is also large, and the parameter setting cannot achieve good results.

Figure 6 shows a physical photograph of a multi-layer material sample. The sample size is 250mm×260mm.

5. Conclusion
Aiming at the research and exploration of temperature-controlled multi-layer material fabrication method based on paving quilting cutting system, this paper improves the performance of the system through the key technology of automatic paving, designs the test scheme and evaluation index scientifically, carries out automatic quilting test, and obtains the optimal process parameters after analysis.

At present, the system has been successfully applied in the multi-layer material production process of satellite models. Compared with manual operation, it can save more than 50% of the operation time, and does not occupy the main line working time. On the premise of ensuring the production quality, it
greatly improves the production efficiency of multi-layer materials, and provides a strong guarantee for the sustainable development of satellite models.

Table 4. Edge error result and analysis.

| No | quilting needle spacing | needle foot distance | test result |
|----|--------------------------|----------------------|-------------|
|    |                          |                      | Edge error  | Side 1 | Side 2 | Side 3 | Side 4 | Maximum value | ranking |
| 1  | 50                       | 25                   | 3          | 1      | 3      | 1      | 3      | 3             | 1       |
| 2  | 100                      | 50                   | 8          | 1      | 4      | 2      | 8      | 8             | 7       |
| 3  | 150                      | 75                   | 12         | 7      | 5      | 7      | 12     | 12            | 13      |
| 4  | 200                      | 100                  | 13         | 7      | 2      | 4      | 13     | 13            | 14      |
| 5  | 50                       | 50                   | 10         | 3      | 6      | 10     | 2      | 10            | 10      |
| 6  | 100                      | 25                   | 6          | 1      | 1      | 1      | 6      | 6             | 5       |
| 7  | 150                      | 100                  | 24         | 5      | 5      | 24     | 6      | 24            | 16      |
| 8  | 200                      | 75                   | 10         | 10     | 3      | 5      | 6      | 10            | 11      |
| 9  | 50                       | 75                   | 11         | 3      | 4      | 4      | 11     | 11            | 12      |
| 10 | 100                      | 100                  | 6          | 6      | 6      | 3      | 4      | 6             | 6       |
| 11 | 150                      | 25                   | 3          | 2      | 2      | 3      | 3      | 3             | 2       |
| 12 | 200                      | 50                   | 8          | 8      | 2      | 1      | 2      | 8             | 8       |
| 13 | 50                       | 100                  | 16         | 4      | 16     | 2      | 5      | 16            | 15      |
| 14 | 100                      | 75                   | 4          | 3      | 2      | 2      | 4      | 4             | 3       |
| 15 | 150                      | 50                   | 8          | 3      | 4      | 8      | 2      | 8             | 9       |
| 16 | 200                      | 25                   | 5          | 5      | 2      | 2      | 3      | 5             | 4       |

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