FABRICATION OF THE THICK COMPOSITE STRUCTURE

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Abstract

Recently intensive research and development work have been done on bearingless rotor systems to improve flight performance, reliability and maintainability of rotorcraft. Kawasaki Heavy Industries also have developed all composite bearingless main rotor systems for over ten years. The critical components of the bearingless rotor system, such as a hub plate and torsion elements, are very thick complex shaped composite parts which are comprised of highly complex lay-ups. To fabricate these components with excellent quality and reasonable cost, an innovative automated lay-up and a new molding process are required. For this purpose, we developed a robotic roving placement system and a new molding process named MIP (Matched-die Isostatic Pressing). These new manufacturing methods contribute to the improvement of quality and reliability and also to the cost reduction. This paper will describe our unique fabrication process of thick complex contoured composite parts such as bearingless rotor hub components.

Introduction

In the recent helicopter industry, intensive research and development work have been done on bearingless rotor systems to improve flight performance, reliability and maintainability of rotorcraft (Ref.1). Kawasaki Heavy Industries also have developed all composite bearingless main rotor systems for over ten years (Fig.1). From FY1987 to FY1991, we designed, manufactured and tested two prototypes of all composite bearingless rotor system based on our original concept (called prototype model in the following sentences) under contract with Japan Defense Agency and finally verified good performance as expected by the flight testing on a OH-6J helicopter (Ref.2 and 3). Fig.1 shows the rotor system of the prototype model for flight testing. The hub plate and torsion elements, which were main components of the rotor system, were very thick and complex shaped GFRP parts.

The above-mentioned development of prototype models was a great success. However, solutions of the following manufacturing problems were required to scale up the prototype model and carry out the series production as a practical type bearingless rotor system (called production model in the following sentences).

(1) Development of Automated Lay-up of Roving Prepreg

A large quantity of roving prepreg was used for main load-carrying members of the hub plate, torsion element and main rotor blade spars. It was necessary to develop an automated lay-up technique to lay up complex patterns efficiently and precisely because hand lay-up was almost impractical due to much labor cost and the possibility of human errors. Especially it was also required to be applicable to the wrap-around lay-ups at the lug portion.

(2) Development of New Molding Process by which Excellent Dimensional Accuracy and Internal Quality are Obtained

Because of the use of short term flight test, the hub plate and torsion elements of the prototype model were made of 120℃ cure type prepreg, which was easier to mold than 180℃ cure type, and were molded by a conventional matched-die molding. But considering reduction of the strength caused by water absorption during long term operation, the production model would use 180℃ type prepreg which had higher hot/wet

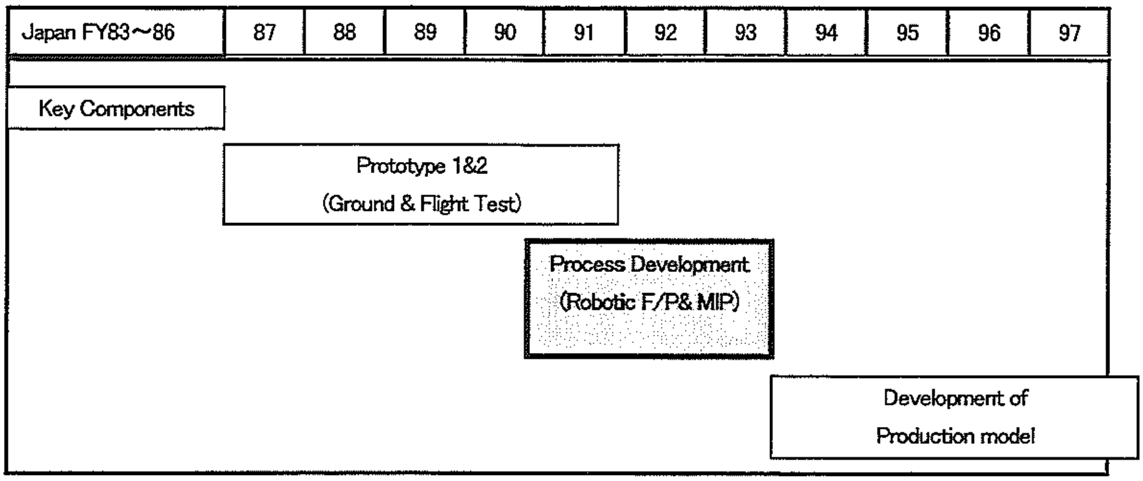


Fig.1 Development Schedule of The Bearingless Rotor System

strength. However, as compared with 120℃ type prepreg, in case of the 180℃ type prepreg, it is likely having internal defects such as voids caused by vaporization of volatile and/or delaminations caused by thermal stress. Therefore, it was expected that it was difficult to maintain a good internal quality constantly by using a conventional matched-die molding process because it was difficult to control internal molding pressure properly. In addition to this, the possibility of internal defects would become more and more evident due to increased thickness (more than 60mmt) than the prototype model. Therefore, the development of a new molding process, which was able to always realize both excellent dimensional accuracy and excellent internal quality, was required.

From the above points of view, we carried out the process study to solve these manufacturing problems before the development of the production model (Fig.2). This paper will introduce two new manufacturing technologies from the study and its application to the fabrication process of thick and complex shaped composite rotor hub components

Process Development

Robotic Roving Placement System

Background The key components of Kawasaki composite bearingless rotor system are a hub plate where flapping motion is allowed and torsion elements

① Hub Plate ② Torsion Element

③ Elastomeric Damper ④ Rotor Blade Assy

⑤ Fairing Assy

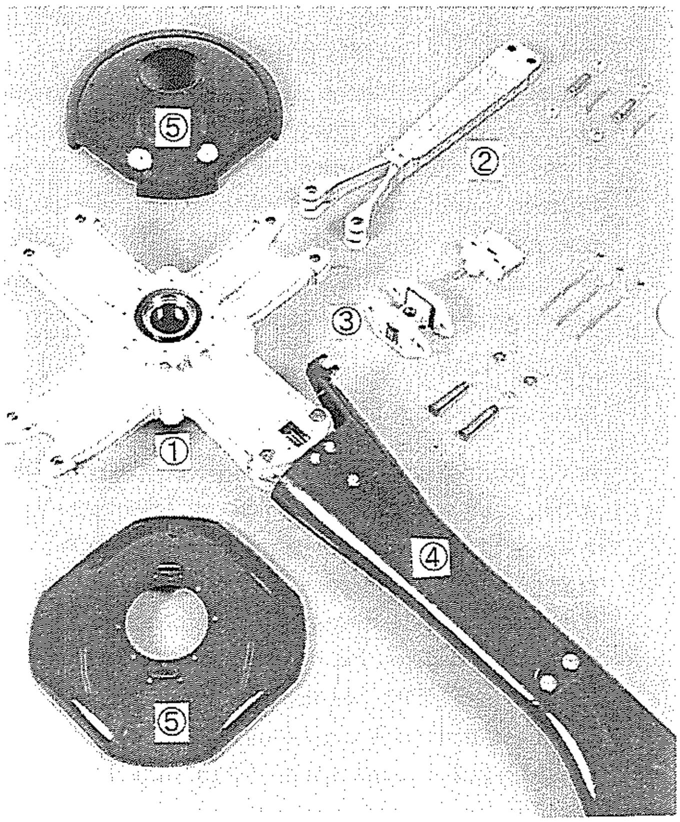


Fig.2 Prototype 2 Bearingless Rotor Hub for Flight Testing (Ref.2)

where lead-lag motion and feathering motion are allowed. One of the biggest features of our bearingless rotor system is that it is designed the spanwise positions of each effective hinge are separated enough to have no interference between effective hinges to prevent the instability caused by pitch-flap-lag coupling (Ref.2 and 3). To realize this, the lay-up patterns and cross sections of each portion of these components are carefully designed. This is elegant design, but manufacturing difficulty is high because of requiring highly complex lay-ups and complex contoured shapes. Especially, how to lay-up a large quantity of roving prepreg by complex patterns is a big problem.

Fig.3 shows a example of lay-up patterns for the hub plate. A large quantity of roving prepreg is also used for spars of the main rotor blade. Total required length of roving prepreg per each part for the production model is about 18km for the hub plate, 3km for the torsion element and 15km for the main rotor blade.

Hand lay-up is almost impractical because of much labor cost and the possibility of human errors. A conventional polar winding is also difficult to apply because of the complexity of lay-up patterns and a lot of cutting ends (many of the patterns are not endless).

<u>Development of Prototype Machine</u> In such a situation we have developed robotic roving placement systems based on original ideas since the development of the prototype model. As the basic concept, we did not choose the way to lay-up directly on the mold, but the way to lay-up flat pattern sheets by robot and subsequently lay-up the flat pattern sheets on the mold by hand (Fig.4). This choice made the machine simple, low cost and practical.

1st prototype machine was applied to the hub plate lay-

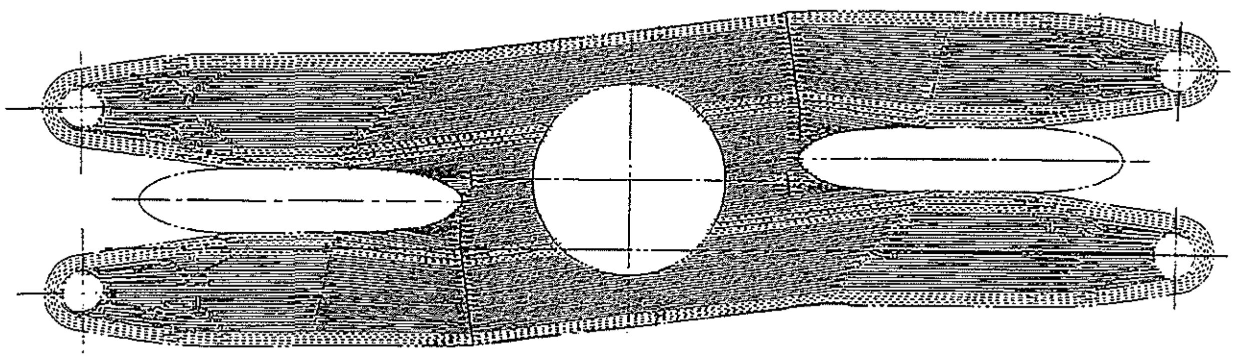


Fig.3 Typical Lay-up Pattern for Hub Plate

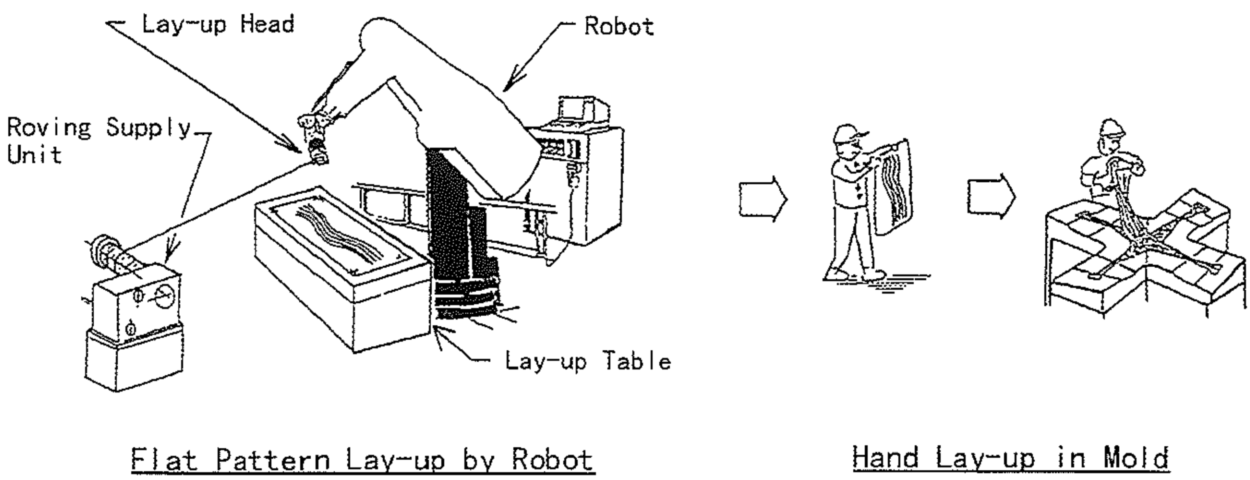


Fig.4 Basic Concept of Robotic Roving Placement System

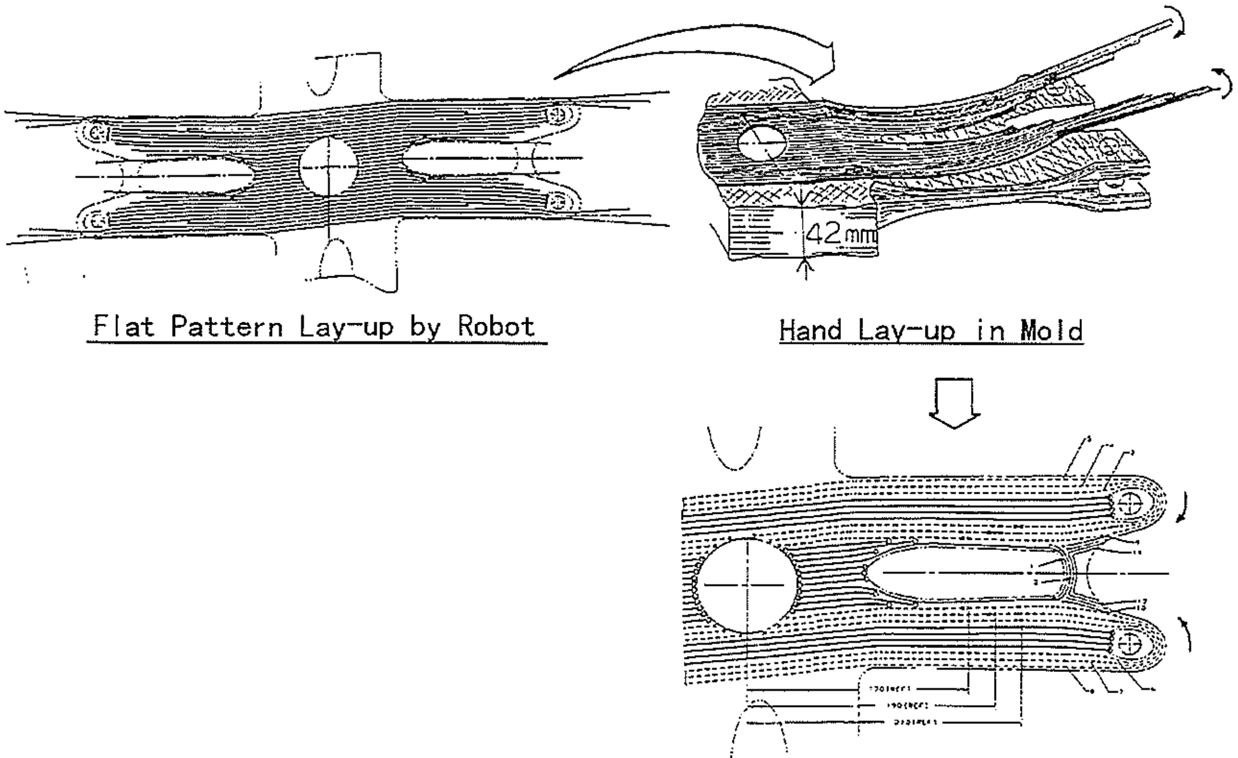


Fig.5 Lay-up Method of wrap-around Lag at Prototype Model

up of the prototype model and confirmed the effectiveness. However, it was also made clear that the following points had to be improved.

- The lay-up head had no capability for the wrap-around lay-up. In the case of prototype hub plate, we laid-up flat patterns by robot and subsequently carried out wrap-around lay-ups by hand on the mold (Fig.5). This was time consuming operation and also less desirable than endless lay-up from design point of view.
- Sometimes low tack material was difficult to laid-up on the lay-up table. On the other hand high tack material sometimes caused jams when unreeling
- Lay-up speed did not yet reach to the level of production use.

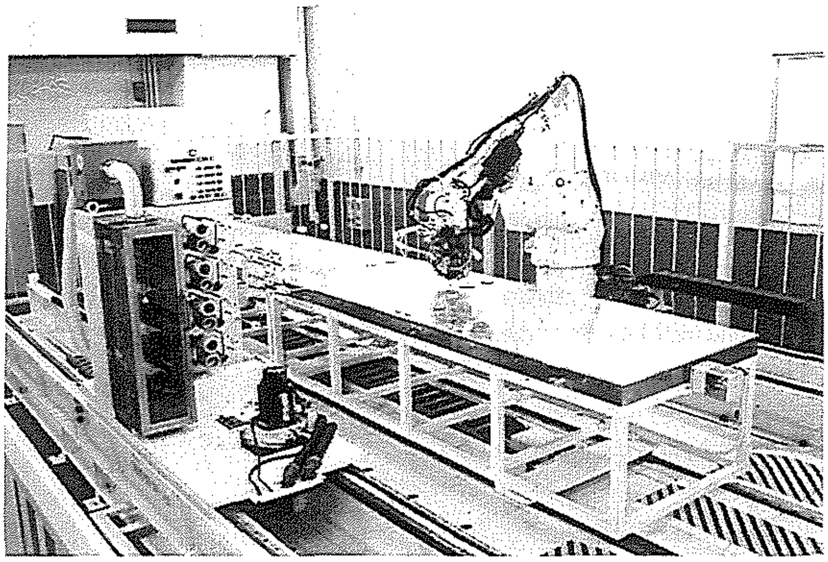
Development of Practical Machine We developed a practical machine as a result of various improvements on the problems as mentioned above (Fig.6). This machine was a simple and relatively inexpensive but very effective system. Other features and constitution of our patented machine are as follows.

(1) Robot

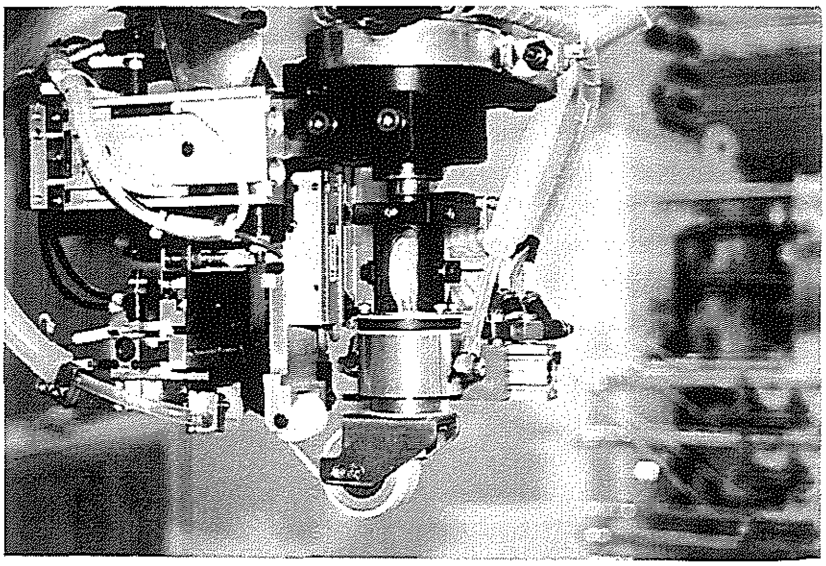
- Kawasaki JS-30 6 axes robot with 5.5m travel axis as 7th axis

(2) Lay-up head

- Lay-up (max. 25m/min), cut and hold max. four rovings at the same time
- Realize wrap-around lay-up without complex control and programming by simple caster action of the lay-up roller.
- Tack control capability by hot air blowing
- Simple and compact (about only 10kg)



(1) Overall View



(2) Lay-up Head

Fig.6 Robotic Roving Placement System - Practical Machine

(3) Roving supply unit

- Supply max. four rovings to the lay-up head maintaining constant tension independently
- Realize good unreeling capability with no influence of tackiness by buck tension function of each reel
- With 5.5m travel axis as 8th axis

(4) Lay-up table

- Table size : 1mW×6mL
- Heating capability for tack control
- Automatically transported to set up area after finishing lay-up operation

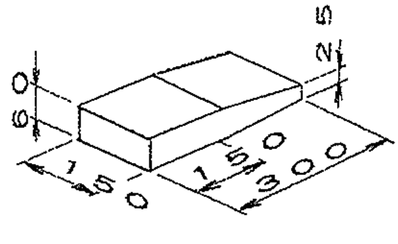
This machine makes it possible to lay-up all roving lay-up patterns automatically and contributes to the significant cost reduction.

MIP Molding Process

Background The hub plate and the torsion element have a large thickness changing (over 60mmt~2mmt) and complex cross sections, and are required severe dimensional accuracy from the flight characteristic consideration. In addition, excellent internal quality is required because those components are the most important primary structure. The following problems exist in molding process of these components by conventional methods.

(1) Conventional Matched-die Molding

In this method, high dimensional accuracy can be obtained. However, in case of insufficient quantity of lay-up, sufficient pressure will not be applied to prepreg in the mold, so voids caused by vaporization of volatile will be easily formed. On the other hand, an excessive amount of lay-up will result in cracking because of excessive out-of plane pressure and/or over thickness because of closing a mold imperfectly. Furthermore, unbalance of lay-up quantity will result in fiber wrinkles when closing a mold. Such internal defects, especially, voids and a crack more than 5mm or a large fiber wrinkle, are not permitted in rotor hub components. Considering deviation of the resin content and/or the fiber areal weight of the material and so on, the process windows of very thick and complex contoured parts are very narrow. Consequently, this method is not suitable for the production of our rotor hub components.



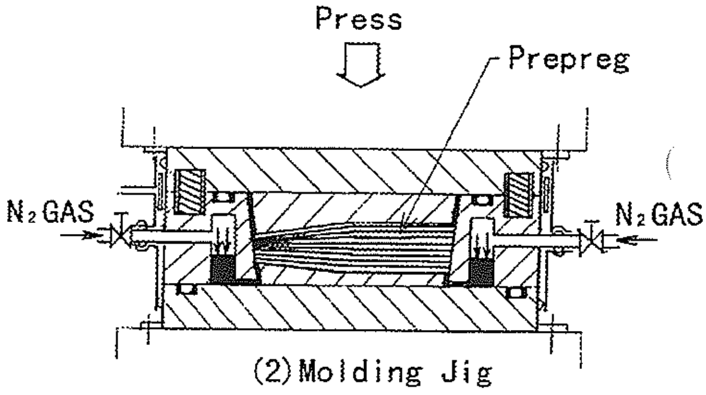


Fig.7 Element Manufacturing Test

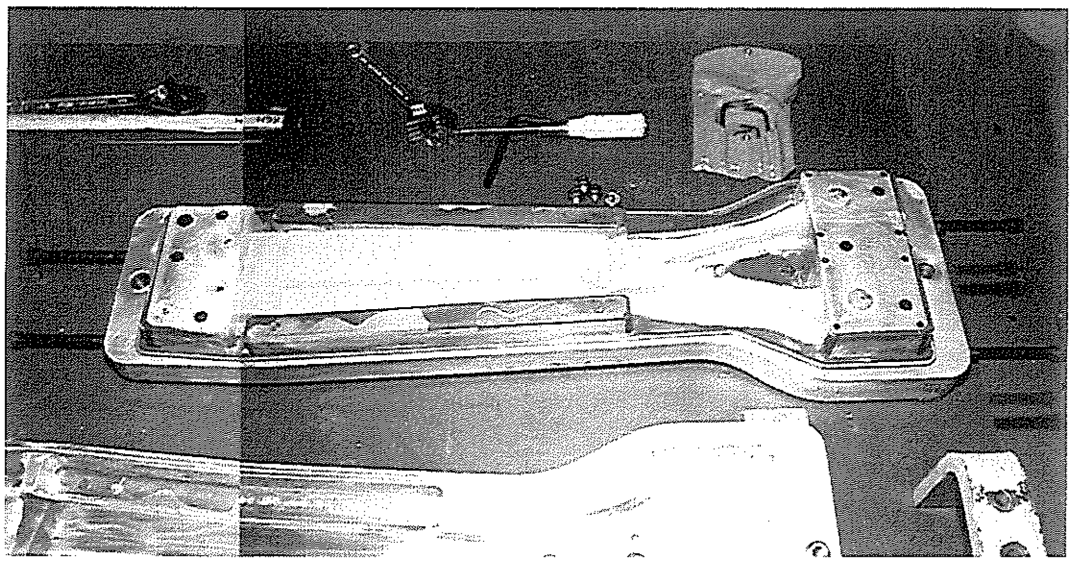


Fig.8 Sub-scale Manufacturing Test Specimen and mold

(2) Autoclave Molding

In this method, uniform pressure always can be applied to prepreg in a mold, so good internal quality can be easily obtained. However, since the part thickness varies due to the deviation of the resin content and/or the fiber areal weight of the material and so on, high accuracy in the part thickness will not be obtained constantly especially in the case of thick parts such as rotor hub components..

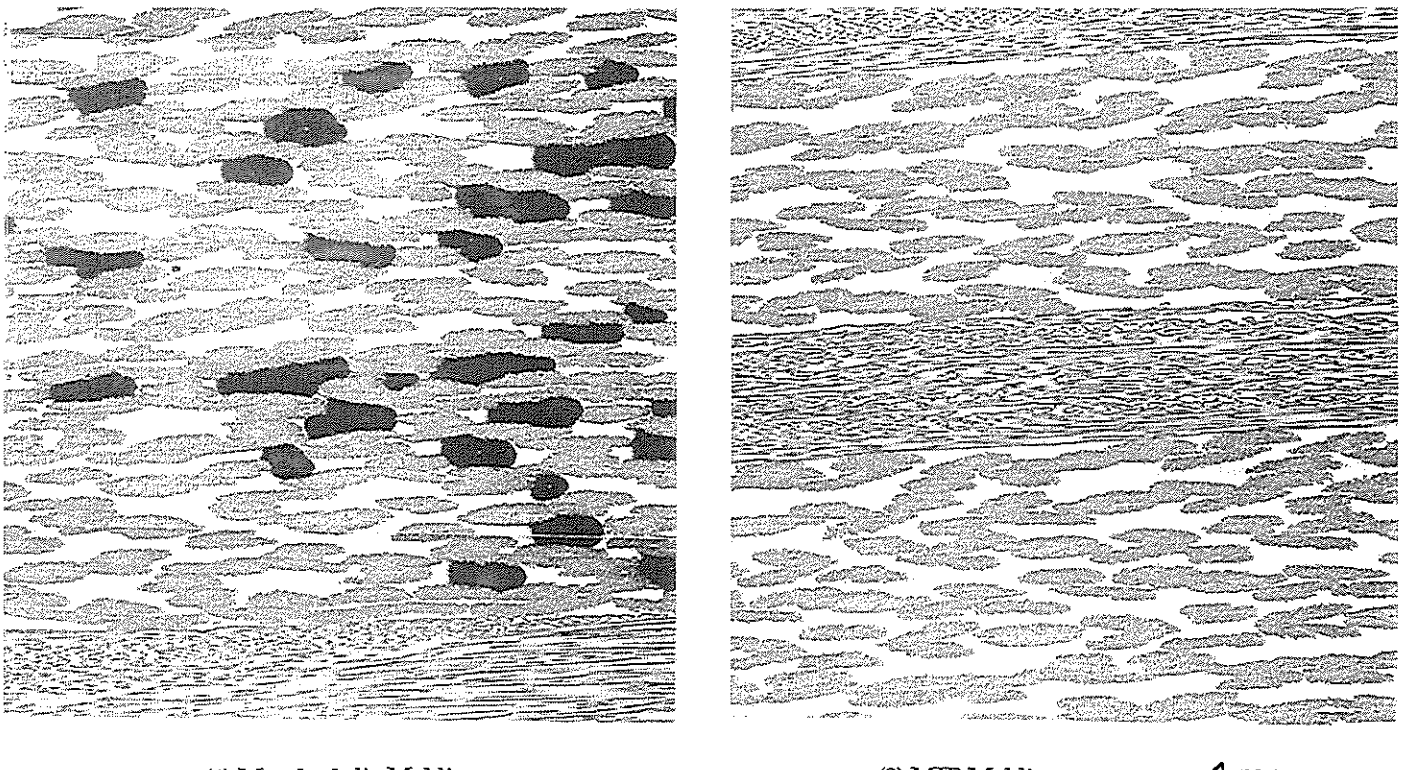
(3) Resin Transfer Molding (RTM)

This is a method that a dry fiber preform is set in a mold, and then resin is injected into the mold under pressure, so that both excellent dimensional accuracy and internal quality can be obtained. However, it is difficult to fabricate a preform for complicated shape and laminate patterns such as rotor hub components by an efficient way. Moreover, fiber disarrangement will occur while handling and/or injecting resin.

Therefore, in order to fabricate our bearingless rotor hub components with both excellent dimensional accuracy and internal quality, the development of a new molding process which had advantages of both matched-die molding and autoclave molding was required. In other words, a new process in which ordinary prepreg and a matched-die type mold were used and uniform pressure could be applied to the prepreg in the mold until the resin gelation occurs was required

Development of MIP Molding Process In such a situation we started to develop a new molding process named MIP(Matched-die Isostatic Pressing) before starting the development of production model. In the beginning, an element manufacturing test simulating a part of the hub plate was performed to understand basic process conditions, mold construction and so on, and then a sub-scale manufacturing test, using a mold which was modified from the mold for the torsion element of prototype model, was conducted to verify the effectiveness of MIP process (Fig.7 and 8). The material used in these tests was the same 180℃ cure type glass/epoxy prepreg as the production model.

The key point of the MIP process is that it makes



(1) Matched-die Molding (2) MIP Molding

Fig.9 Comparison of internal quality

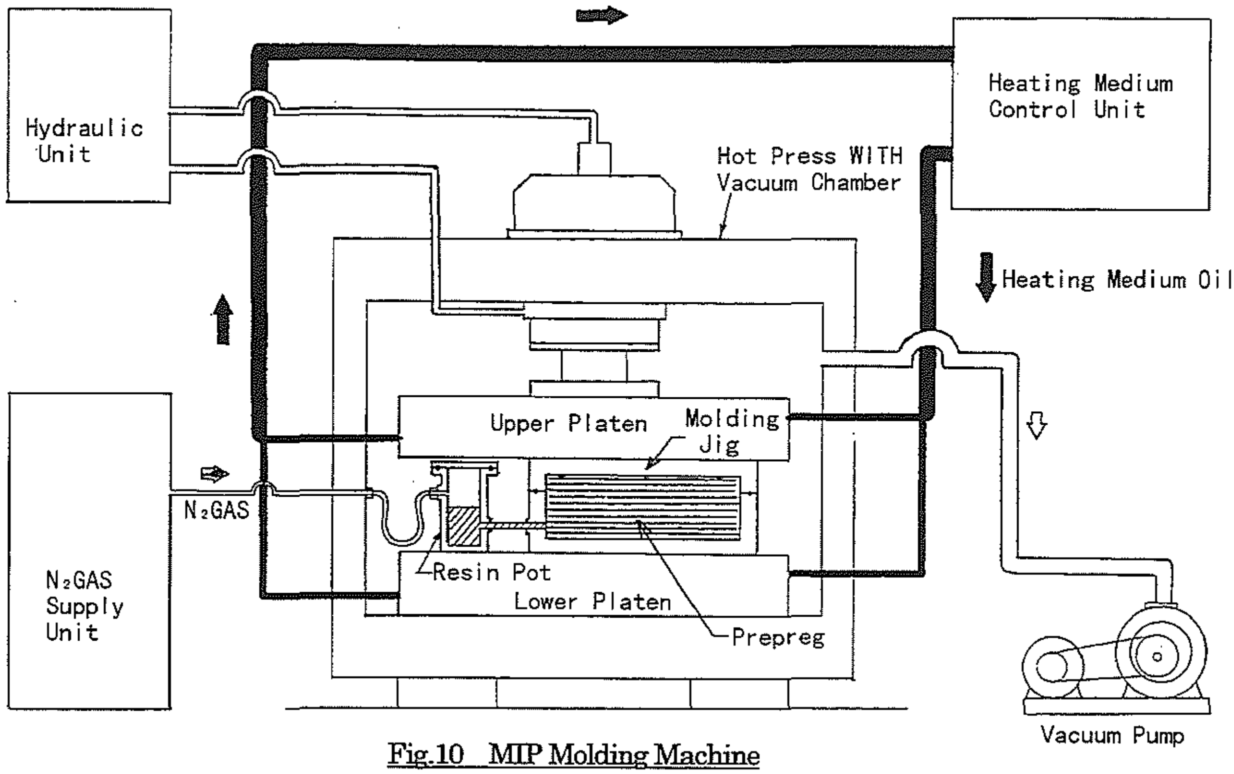


Fig.10 MIP Molding Machine

possible to apply isostatic pressure constantly to prepreg in a mold through pressurized liquid resin in resin pots, which are built in the mold or connected to the mold, by applying pressurized nitrogen gas into the resin pots. This isostatic pressure prevents voids caused by vaporization of volatile. In addition, even if an amount of lay-up is not enough to fill the mold, the injected resin from the resin pots makes up for the deficiency by infiltrating into the prepreg layers, consequently, no void laminate can be obtained. It means that the lower limit of an acceptable amount of lay-up becomes wider, so a cracking and/or fiber wrinkling caused by an excessive amount of lay-up can be prevented.

Fig.9 shows microscopic observation results of the element test specimens molded by an conventional matched-die process and by MIP process. It clearly shows that the MIP molded specimen is void free, while the matched-die molded specimen has a lot of voids. The result of the sub-scale manufacturing test of torsion element also showed very good quality and verified that our patented MIP process made it possible to mold thick and complex shaped composite parts with both excellent dimensional accuracy and internal quality.

MIP Molding Machine Based on the results of the above mentioned developmental tests, we developed the MIP molding machine for production use. Fig.10 shows a schematic view of the MIP molding machine. It consists of a 300tons hydraulic hot press surrounded by vacuum chamber (platen size:1.6m×1.6m), a hydraulic power unit, a vacuum pump, a heating medium oil control unit and a nitrogen gas supply unit. The control of heating, cooling, press stroke, pressure of nitrogen gas, vacuum and so on are fully automatic, so that complete unmanned operation is possible after setting a mold and resin pots.

Application of the New Manufacturing Processes

The manufacturing process of the composite bearingless rotor hub components by the above-mentioned new manufacturing processes is described in the following pages.

Material

In the hub plate and torsion element, glass/epoxy roving prepreg is used for main load-carrying members and glass/epoxy cloth prepreg used for skins and fillers. These prepregs are 180℃ cure type.

In order to apply pressure to prepreg in a mold until the resin gelation occurs, the gel timing of injection resin for the MIP process should be slower and the time for maintaining low viscosity should be longer than the prepreg resin. For this reason, we did not choose the same resin as the prepreg for injection, but choose a resin developed for RTM use which had the property as mentioned above.

Tooling

The bond tool is a very complex steel matched-die mold, which is designed in a three-dimensional CATIA surface model and NC machined. The tool consists of a upper die, a mid die, a lower die, removable mandrels to form the lugs, O-rings and so on. Besides, steel resin pots for the MIP process are connected to the mold through disposal copper pipes. The contour of the mold is modified taking account of a reduction of thickness after cure caused by resin shrinkage and a spring-in of lug. In order to evacuating air in the mold and resin pots before closing the mold, the upper die of the mold and lids of the resin pots are floated from O-rings by springs.

Fabrication

(1) Ply Cutting of Cloth Prepreg
Skin and filler plies are cut from cloth prepreg by GSI automatic cutter. Fillers are preplied and kitted into each lay-up group.

(2) Robotic Roving Placement
A mylar film and pins for wrap-around lay-ups are set on the lay-up table of the robotic roving placement machine shown in Fig.5 and roving lay-up sheets are laid-up automatically according to each lay-up pattern. In the case of the hub plate in production model, forty roving sheets are required and total roving length is about 18km. In some roving sheets, small diameter metallic wires are laid-up together for the NDI mentioned later.

(3) Lay-up
The skin plies, filler plies and roving sheets are laid-up in the mold by hand and compacted by vacuum periodically. Injection resin is prepared in the resin pots.

(4) MIP Molding
The mold and resin pots are set on the platen of the MIP molding machine shown in Fig.7. Once start button is pushed, automatic molding operation is carried out. Its sequence is shown as follows.

- Evacuate air in the vacuum chamber and remove air in the mold and resin pots.
- Heat the platen and close the mold gradually.
- Close the mold completely when the mold temperature reaches the temperature in which the viscosity of injection resin becomes low enough.
- Apply the adequate pressure to the resin pots by nitrogen gas, and apply isostatic pressure to the prepreg in the mold through the pressurized injection resin until the end of cure.
- Heat up to the appointed cure temperature, hold the temperature, and cool down.

(5) Non-destructive Inspection
After removal from the mold, the molded component is inspected using through-transmission ultrasonic and X-ray methods. In addition to voids and cracks, inspection of fiber wrinkles is very important to rotor hub components because fiber wrinkles give big impact to the strength. The absence of fiber wrinkles is verified by inspecting the disarrangement of metallic wires, laid-up together in some roving sheets, in X-ray films

In the result of fabricating the composite rotor hub components by the above mentioned manufacturing process, we confirmed that the components can go into the series production with stable good quality.

Conclusion

Before developing the production model of composite bearingless rotor system, we had studied about automated lay-up system and the improvement of molding quality of the rotor hub components, consequently, we developed a robotic roving placement system and a new molding process named MIP. By applying these new manufacturing methods, we established to fabricate very thick and complex shaped components such as the hub plate and the torsion element constantly with excellent quality and reasonable cost.

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