Mitsubishi Heavy Industries Technical Review Vol. 59 No. 4 (December 2022)

Approach to Advanced Composite Material Technology to Realize Weight Reduction of Future Aircraft toward Decarbonization of Air Transportation

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The phrase "flight shame" symbolically reflects the strong social demand for improving the environmental compatibility of aircraft. Under such circumstances, the aircraft of the future, which are to be fueled with sustainable aviation fuel (SAF) or hydrogen and are regarded as one of the most effective measures, have problems of high fuel costs and limited cruising ranges. As a means to promote decarbonization on the energy demand side toward achieving carbon neutrality, the weight reduction in airframe is getting increasingly important, because it will lead to a higher fuel efficiency and a longer cruising range. In the post-coronavirus society, on the other hand, there is growing demand for narrow-body aircraft. However, the application of composite material in narrow-body aircraft is hampered by the difficulty of reducing the weight and raising the production rate; there is, therefore, less progress being made than with wide-body aircraft in this regard. As an initiative to make a breakthrough in this situation, Mitsubishi Heavy Industries, Ltd. (MHI) has engaged in the research and development of advanced composite material technology that can realize weight reduction of future/narrow-body aircraft, under the sponsorship of the Green Innovation Fund Project by the New Energy and Industrial Technology Development Organization (NEDO)(1) *since 2021.*

1. Introduction

Just prior to the spread of COVID-19 across the world, the phrase "flight shame" had been heard mainly in Europe, raising serious concerns about CO_2 emissions from air transportation. The demand for air transportation then fell sharply because of the coronavirus pandemic, resulting in considerable reductions in CO_2 emissions in the air transportation sector. By 2024, however, it is expected to recover to the 2019 levels as a result of the high penetration of vaccinations and other reasons (**Figure 1**)(2), and the efforts to cut CO_2 emissions are now moving into top gear. In October 2021, the International Air Transport Association (IATA) approved a resolution to achieve (net-zero) CO_2 emissions for international aviation by 2050(3).

Although using green hydrogen as fuel in future aircraft is one of the most effective measures for the decarbonization of air transportation, the aircraft fueled with it have limited cruising ranges. This is because the total amount of fuel energy stored on board is limited owing to the low volumetric energy density of hydrogen. Therefore, this technology is considered to be primarily relevant to aircraft on short-haul routes, and the narrow-body aircraft market is expected to be introduced widely in the foreseeable future.

In the meanwhile, having suffered a blow owing to the coronavirus pandemic, airline companies are seeing the recovery first in sales for domestic flights. For the wide-body aircraft whose fixed costs are high, the old models have been retired from operational service earlier than planned and the introduction of new models has been postponed. What airline companies are prioritizing is the resumption of narrow-body aircraft operations. With the rise of low cost carriers

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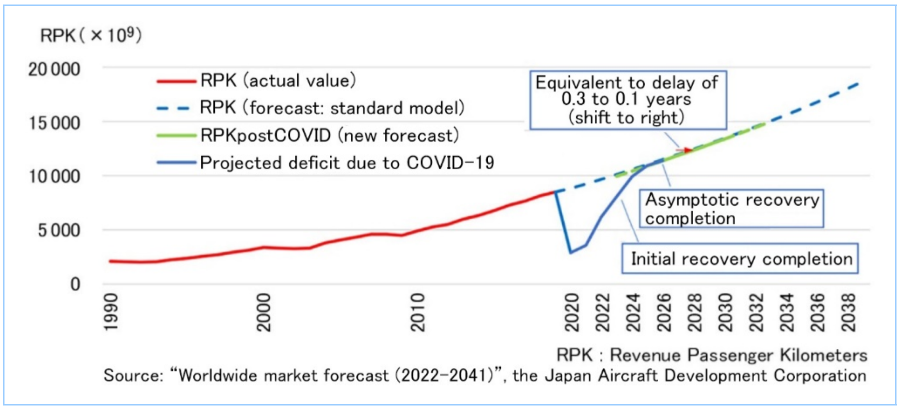
(LCCs), the demand for narrow-body aircraft is increasing although the momentum had already been picking up before the coronavirus pandemic. Despite such a shift in the aircraft market trend, the Japanese aircraft industry is still attaching too much importance to the wide-body aircraft Tier 1 business and has not yet been able to enter the market of producing major components for narrow-body aircraft.

Using our world-class composite material technology, which is the fruition of years of experience, we will be the first to successfully expand its application to the wings of future/narrow-body aircraft and utilize it for the benefit of society commercially. In this way, we aspire to build a new pillar for growth against such a business backdrop as described above.

This report focuses on the importance of aircraft weight reduction from a decarbonization point of view, and discusses the potential that narrow-body aircraft made of composite material have for the decarbonization of air transport as well as the challenges of composite material application for the realization of lightweight wing structures. Lastly, we will lay out the future directions of advanced composite material technology that will realize weight reduction in the wing structures of future/narrow-body aircraft.



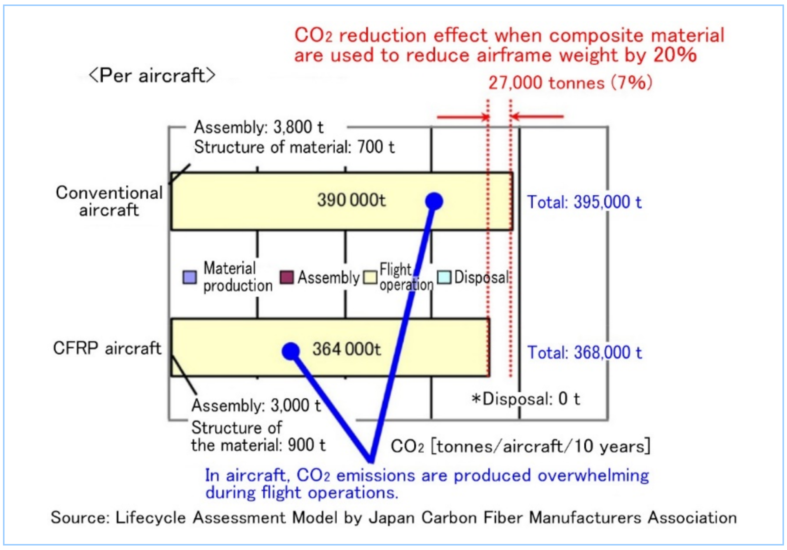
Source: "Worldwide market forecast (2022–2041)", the Japan Aircraft Development Corporation

Figure 1 Recovery of air transportation (RPK) after coronavirus pandemic

2. Importance of weight reduction of future/narrow-body aircraft

2.1 LCA model for aircraft

The life cycle assessment (LCA) is a method of evaluating the environmental impact of a product throughout its lifetime (from manufacturing to disposal). **Figure 2** compares the results of LCA between Boeing 767 domestic operations and the same aircraft, albeit with the weight reduced using composite material[(4)]. As shown in the figure, 99% of the total lifetime CO_2 emissions of the aircraft are produced during flight operations. Therefore, for the reduction of lifecycle CO_2 emissions, it is critical to improve the in-flight fuel efficiency, to which the degree of contribution from lightweight airframes with the use of composite material is significant.

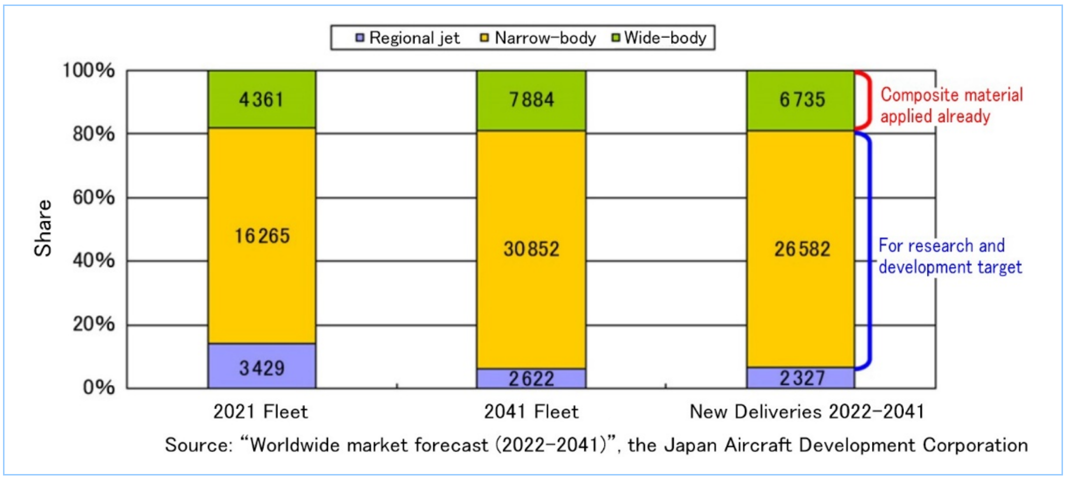


Source: Lifecycle Assessment Model by Japan Carbon Fiber Manufacturers Association

Figure 2 Example of aircraft CO_2 emissions throughout lifetime

2.2 Demand forecast by size of aircraft

As mentioned earlier, the demand for narrow-body aircraft has been growing in the post-coronavirus era. According to the long-term demand forecast for the next 20 years, the demand proportion of narrow-body aircraft will remain the same as the proportion obtained based on the number of aircraft in operation in 2021 (**Figure 3**)(2). Thus, it is believed such high demand will continue in the foreseeable future and the volume of the market will be large as well. However, the application of composite material in the major components of narrow-body aircraft has not progressed. If successful, the resulting reduction in the airframe weight of narrow-body aircraft has the potential to considerably contribute to decarbonizing the whole air transportation sector.

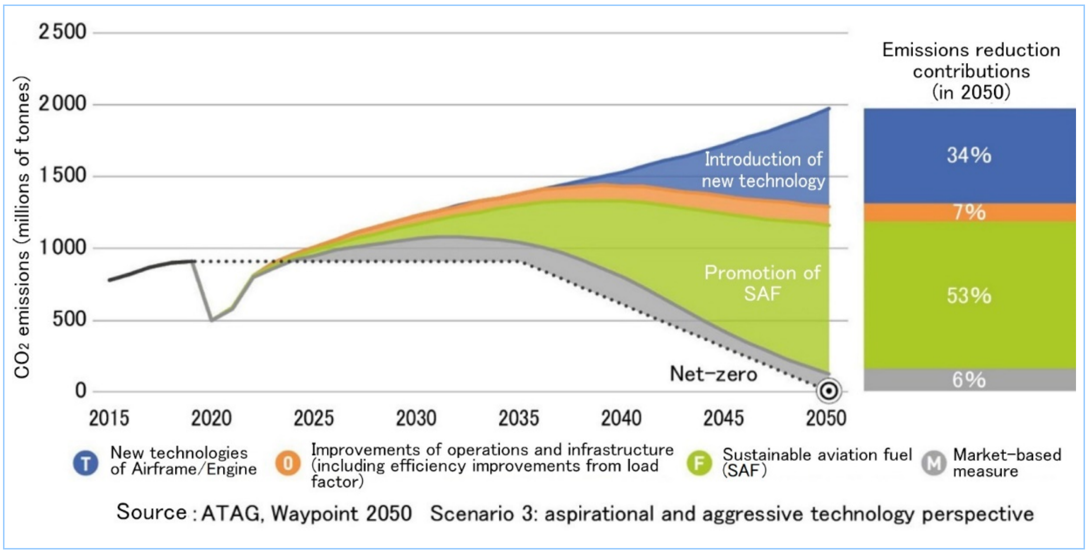


Source: "Worldwide market forecast (2022-2041)", the Japan Aircraft Development Corporation

Figure 3 Fleet and new deliveries forecast by size of aircraft

2.3 Goals to be aimed by air transportation industry for carbon neutral society

The Air Transport Action Group (ATAG) is a global air transportation industry coalition of companies such as major airframe and engine manufacturers and organizations such as IATA. Proposed in ATAG's report "Waypoint 2050"(5) are three scenarios for achieving net-zero CO_2 emissions for global air transportation by 2050. "Scenario 3", in particular, is based on an aspirational and aggressive technology perspective (**Figure 4**), which shows that 53% of the total CO_2 reduction will be realized by the use of SAF and 34% by the introduction of new technologies such as fueling of narrow-body-sized aircraft with hydrogen.

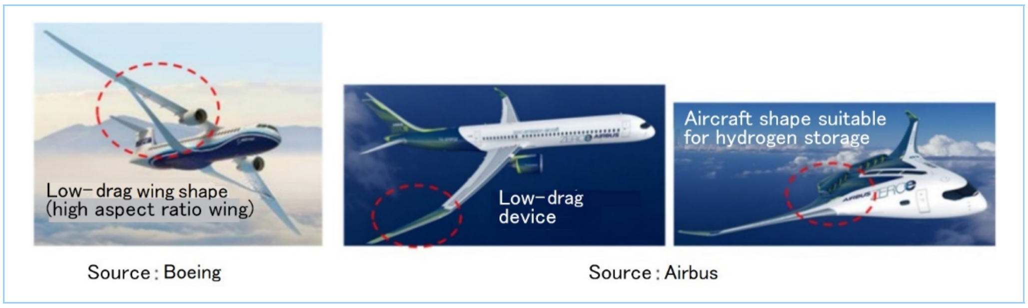


Source : ATAG, Waypoint 2050 Scenario 3: aspirational and aggressive technology perspective

Figure 4 Goals to be aimed by air transportation industry for carbon neutral society

As the future aircraft fueled with SAF or green hydrogen (**Figure 5**)(6)(7) will theoretically achieve zero (neutral) in-flight CO_2 emissions according to LCA, the reduction of airframe weight does not directly help with the decarbonization of air transportation. However, SAF and hydrogen have the problems of high fuel cost and limited cruising range. The realization of lightweight airframes, which will lead to higher fuel efficiency and longer cruising range, will greatly contribute to realizing the widespread adoption of airframes with new technologies. For the reasons of the preceding paragraph, the application of composite material in future aircraft is considered to play an indirect yet important role in the decarbonization of air transportation in terms of supporting the use of aircraft fueled with SAF or hydrogen.

Thus, the development of composite material technology for narrow-body aircraft and the consequent reduction in the airframe weight will support the widespread use of future aircraft and is also considered to be a significant step not only in the urgent mission of decarbonization, but also toward the carbon neutrality of air transportation by 2050.



Source : Boeing

Source : Airbus

Figure 5 High-efficiency future aircraft envisioned by airframe OEMs

3. Challenges in application of composite material for future/narrow-body aircraft wings

As described so far, although it is known that reducing the airframe weight of future/narrow-body aircraft by applying composite material can be an effective means of decarbonizing the air transportation sector, the practical application has not yet materialized in many aircraft models. Why this is the case is related to the two problems that are difficult to overcome with the conventional manufacturing method (i.e., prepreg and autoclave manufacturing), which will be described in the following sections.

3.1 Constraints on weight reduction by airframe shape requirements

This section addresses the constraints on weight reduction by the airframe shape requirements in the case of applying prepregs to the wings of future/narrow-body aircraft.

Prepregs are an intermediate material in which fibers such as carbon are pre-impregnated with thermoset resins and are prepared as adhesive sheets. This adhesion characteristically causes the sheets, once overlaid and bent, to be unable to absorb the circumferential differences because of the difficulty of sliding between sheets and have difficulty in adapting to the intended shape because fibers are taut and tight.

Because the airframe size of narrow-body aircraft is smaller than that of wide-body aircraft, the design requirements for strength often necessitate a steep change in the minimum plate thickness and a small radius of curvature in the wing shape. If forcibly applied to these parts, a multi-layer prepreg will be subject to defects (fiber wrinkles), leading to declining strength. To avoid the occurrence of such defects, the following measures, which increase the weight, are necessary.

- For the change of plate thickness, the rate of the change per unit length is slowed by allowing a thin part to have a thickness greater than that required for the strength.
- For a small radius of curvature, fiber wrinkling is prevented by cutting the fibers in the sheets where the fibers are likely to become taut and tight. The strength decreases due to cutting the fibers is compensated for by reinforcing with additional sheets.

As a result, the weight reduction effect of using composite material is more limited in narrow-body aircraft than in wide-body aircraft.

Having pursued improved fuel efficiency from the viewpoint of aerodynamic performance, it is expected that the shape of future aircraft airframes had to be more complex in the future (Figure 5). This will, as expected, make application of prepregs even harder to overcome the challenges that we are already facing with narrow-body aircraft.

3.2 Issues about production rate

As shown in Figure 3, because of the large market volume of narrow-body aircraft, a high production rate of at least 50 aircraft per month should be realized. However, the current composite wings of wide-body aircraft are manufactured by the prepreg-autoclave process and its monthly production rate is about 10 aircraft. If this manufacturing method (i.e., prepreg-autoclave processing) continues to be used and only the production rate is to be increased by a factor of five as needed by the narrow-body aircraft market, multiple production lines into which large facilities such as autoclaves are incorporated have to be ready for operation. However, this is not realistic because of the huge initial costs and maintenance costs as well as the need for large spaces. Therefore, a different approach is required to realize a high production rate in the application of composite material for narrow-body aircraft.

As mentioned about future aircraft in Chapter 1, their market is expected to be centered on the narrow-body aircraft market in the foreseeable future, and the demand for a higher production rate is expected to increase.

4. Future directions of advanced composite material technology

Through our past experience in establishing the technology for composite wings and tails, we have familiarized ourselves with the customer needs (long-time challenges and quality level) required for the development of composite aircraft structure.

As the first step, we will take advantage of this knowledge about customer needs so that we can be proactive and expand the technology for next-generation narrow-body aircraft wings. As described in Section 2.2, narrow-body aircraft are also the perfect frontier of composite material application from the viewpoint of carbon neutrality. Considering the affinity with our current composite material technology (wings and tails) mentioned above, we have concluded that narrow-body aircraft wings will be the best target for us. This makes it necessary to overcome the challenges particular to narrow-body aircraft wings, which were described in Chapter 3 and have a technology realizing weight reduction and the improvement of production rate.

The next step is to aim for a technology that can also handle complicated shapes, especially those that will be required by future aircraft, so that it will be a long-lasting technology applicable to future aircraft such as hydrogen-powered ones.

This chapter presents the details.

(1) Airframe weight reduction

To remove the constraints on weight reduction by the airframe shape requirements described in Chapter 3, we will first select a material with good formability (shape followability to forming die) and the manufacturing method, with the aim of securing an effect of 20% weight reduction from the metal airframe of narrow-body aircraft, which is the same reduction level as with wide-body aircraft. In addition, to make structural components thinner, allowable strain against the load on the aircraft structure, i.e., design strain will be improved. Our targets are a design strain improvement by 10% from the existing composite structure levels and a total of 30% weight reduction from the metal airframe.

The factors in determining the design strain of conventional composite structures are:

[1] Strength of the holes of fasteners used for parts assembly or installed as a fail-safe of bonded structures,

[2] Defects such as fiber wrinkles and voids in composite material and

[3] Allowable design strain that is set to be on the safe side based on a limited number of strength tests.

These issues need to be dealt with successfully for design strain improvement. Our approach is to combine design/verification technology with production technology (**Figure 6**).

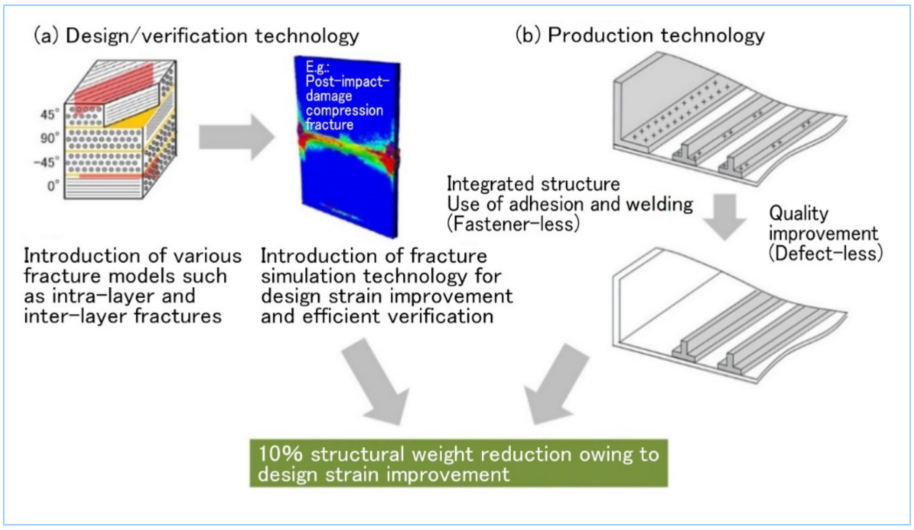


Figure 6 Integrated forming technology and design strain improvement for airframe weight reduction

The design/verification technology pertains to the method for performance/quality assurance of fastener-less structure (to improve [1]) and the strength verification aided by simulation in which fracture is predicted by numerical simulation based on the tests with various modes of fracture (to improve [3]). We will discuss this with aviation authorities and propose the verification method. With regard to the fracture simulation technology, research and development will be conducted under industry-academia collaboration, specifically with Tohoku University and the University of Tokyo, both of which have the world's most advanced technologies for composite material fracture analysis.

From the viewpoint of production technology, we will develop a composite parts manufacturing technology (integrated forming, adhesion and welding) to enable the integration of conventionally separated or mechanically jointed parts (to improve [1]), and a technology to lower the strength reduction factors such as wrinkles and voids (i.e., internal defects) by making full use of the material performance (to improve [2]).

(2) Increase of production rate

To achieve a higher production rate, the efficiency of each of the composite parts manufacturing processes should be improved (**Figure 7**). Each of these processes such as layup, forming, curing and inspection will be digitally transformed (i.e., mechanization or automation) with innovative ideas that are not limited within the bounds of past methods such as efficient provision of heat using additively manufactured (3D-printed) jigs and the use of AI inspection systems, thereby reducing the cycle time to 1/5 of the conventional level. In this research and development, we will set the facility specifications to realize a high production rate, which will be verified by simulation or according to the introduced equipment.

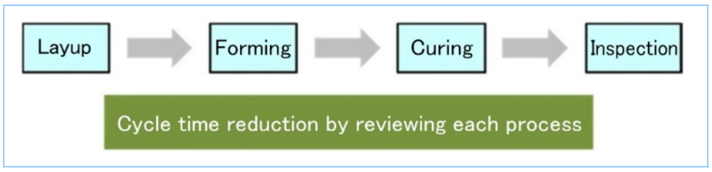


Figure 7 Increase of production rate for expanded application of composite materials

(3) Increased complexity of shape

To allow parts to take more complex shapes, it is necessary to have a manufacturing technology enabling the forming of parts with a small radius of curvature or twisted shape, without causing internal defects such as fiber wrinkles and voids. Using as the indicator the radius of curvature, which is a typical parameter of parts shapes, we set its target value to be at least 1/4 of the conventional level (**Figure 8**).

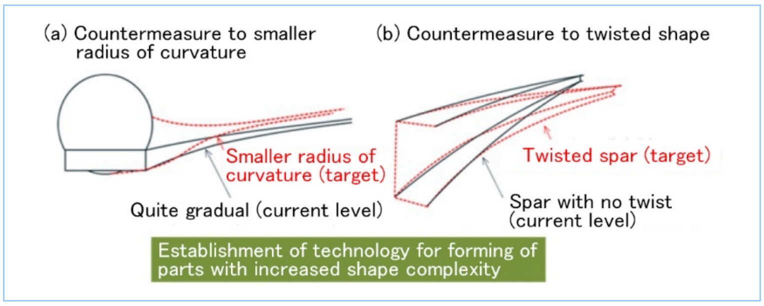


Figure 8 Increased shape complexity of parts required for future aircraft

To fulfill the three goals mentioned above, the process of manufacturing the large parts of wings (such as skins and spars) should not be the conventional method of layup highly adhesive resin-impregnated prepregs before thermoset using an autoclave for high-pressure heating. Instead, we adopt a resin transfer molding (RTM) manufacturing method in which less-adhesive dry fiber fabrics with good formability are laid up before being impregnated with resin, which is followed by heat thermoset under atmospheric pressure.

The main reasons for the adoption of RTM are summarized as follows.

[1] From viewpoint of aircraft weight reduction
  - Dry fiber fabrics are less adhesive than prepregs, and therefore have a large allowance for fiber displacement during three-dimensional shape forming. Their good formability makes it easier to adapt to a given shape. This is advantageous from both standpoints of parts integration and reduction of internal defects (fiber wrinkles).
  - Through our past development and in-house research projects, we have experience in working with authorities regarding the challenges in RTM technique and their measures, as well as the issues arising when fastener-less features are to be realized.

[2] From viewpoint of increasing production rate
  - Many of the suppliers of the RTM manufacturing process fiber/resin materials, equipment and processed products are also the suppliers of the conventional prepreg process materials, equipment and processed products. Therefore, it is possible to utilize the supply chain that we have established through the mass-production of wide-body aircraft wings, as well as our expertise in medium mass production. Their synergetic effects can facilitate the increase of monthly production rates and cost-cutting activities.
  - No autoclaves are needed, which means that the scale of the production facility is small and the degree of freedom is increased in terms of the cost and factory location. In raising the production rate, adding more production lines in parallel has high potential as a backup means to compensate for the cycle time.

[3] From viewpoint of shape complexity
  - Because of their good formability, dry fiber fabrics are advantageous in terms of having the capabilities to take a complex shape and reduce internal defects (fiber wrinkles) (able to be handled by expanding the parts integration technology of [1]).
  - The process/design method for minimizing defects in RTM curved parts has been established through our past development and in-house research on the development of composite structures. Based on this technology, we can proceed with the research and development of complex shape parts for high-efficiency future aircraft.

[4] Other reasons
  - In thermoplastic composite, the forming temperature is higher than it in thermoset composite. It is technically more difficult to form the thick plates required for large wing parts at high temperatures in a stable manner. Thermoplastics are also

prone to internal defects, and their permissible pressure/strain are low. Therefore, thermoset composite is more suitable for high strength parts such as wing skin panels.

On the other hand, complex shapes and high strength are relatively less needed in the other parts such as small wing parts (ribs and fixed leading and trailing edge structures). We will therefore work on the development of basic technologies with a view to applying parts integration technology in which high-speed thermoplastic composite material forming and welding are employed.

5. Conclusion

In this research and development, we aim to develop a new market by further expanding the world-class composite material technology that MHI has cultivated in the process of establishing the technology for composite wings and tails.

As described so far, in order to promote the decarbonization of air transportation, the use of composite material in future/narrow-body aircraft will be one of the most effective means. For the realization of composite wing structures, in particular, it is essential to become capable of handling a steep change in the shape specific to narrow-body aircraft and larger-scale production of aircraft. The expansion of technology is required in this regard, and by extension, further technological development will even enable composite material to be applicable to the aircraft of the generation after the next such as hydrogen-powered aircraft.

Going forward, under the sponsorship of NEDO's Green Innovation Fund Project and with help from Tohoku University and the University of Tokyo and their expertise in the latest analysis technology, we will continue to work on the research and development of advanced composite material technology for future/narrow-body aircraft wing structures. At the same time, we will approach the major overseas OEMs as appropriate with the aim of acquiring orders for next-generation narrow-body aircraft wing components toward its utilization for the benefit of society.

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