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ADVANCED-VARTM SYSTEM FOR AIRCRAFT STRUCTURES – MATERIAL TECHNOLOGIES

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SUMMARY

A toughened low viscosity epoxy resin system (TR-A37) and a non-crimp woven fabric (CZ8433DP) have been newly developed for A-VaRTM process. Test results show that the composites have excellent mechanical properties, also, no microcrack after thermal cycles. These results exhibit that the composites are adequate for aircraft primary structural elements.

Keywords: A-VaRTM, CFRP, epoxy, fabric, aircraft primary structural element

1. Introduction

Carbon fiber reinforced plastics (CFRP) consisting of carbon fibers (CF) and plastics such as an epoxy resin are lightweight and excellent in mechanical properties. Therefore, they have been used in wide applications including aircraft parts, automotive parts, building structures and sporting goods.

For fabricating CFRP, various processes can be selected. Among them, prepreg / autoclave process shown in Figure 1 (a) has been a major process to fabricate high performance CFRP adequate for aircraft structures. On the other hand, vacuum-assisted resin transfer molding (VaRTM) shown in Figure 1 (b) is an emerging process which has the advantage to fabricate CFRP of large scale and complex shape at lower cost. This is because it consists of less steps comparing to prepreg / autoclave process and it does not need an autoclave which is expensive. In fact, VaRTM process has been successfully used to fabricate large structures including truck parts and building structures as shown in Figure 2.

Toray Industries (Toray) and Mitsubishi Heavy Industries (MHI) have jointly developed Advanced-VaRTM (A-VaRTM) process, aiming to fabricate high performance CFRP [1, 2]. New material technologies and fabrication technologies have been developed for aircraft primary structural elements such as the vertical stabilizer of Japan's new regional jet aircraft “MRJ”.

This paper presents the material development for A-VaRTM process by Toray, including a toughened low viscosity epoxy resin system (TR-A37) and a non-crimp woven fabric (CZ8433DP).

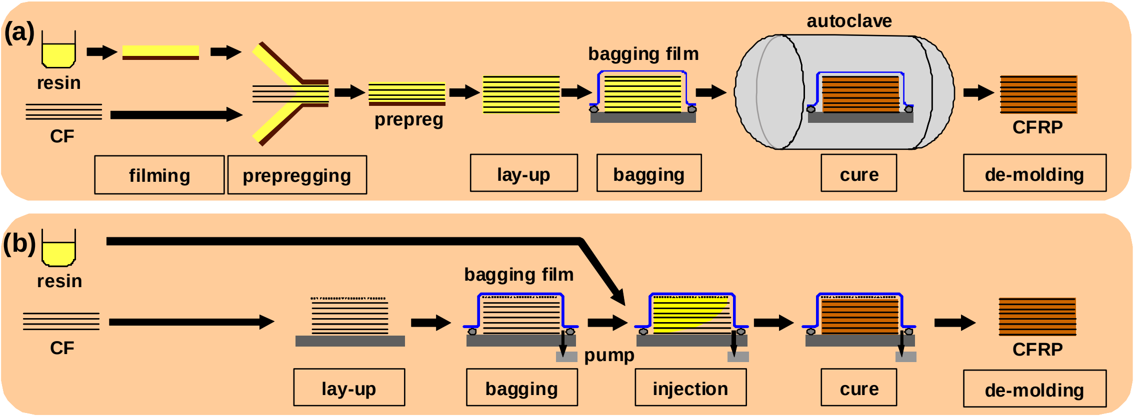


Figure 1 Schematic diagrams of CFRP fabrication processes:
(a) autoclave / prepreg process and (b) VaRTM process

Figure 2 Examples of applications of VaRTM process

2. Concept

The main targets in the material development for A-VaRTM process are as follows.

- High resin impregnation ability
- High 0° tensile strength
- High 0° compressive strength
- High compression after impact
- No microcrack after heat cycles

One of the important targets is the ability of resin impregnation. It is known that resin impregnation is explained by Darcy’s law:

$$u = -\frac{K}{\mu}\nabla P \qquad \text{(I)}$$

where u is fluid velocity (m/s), K is permeability (m^2), μ is fluid viscosity (Pa·s) and ∇P is pressure gradient (Pa/m). Therefore, we considered to develop a new fabric with higher permeability and a new resin with lower viscosity.

The other important targets are mechanical properties. It is known that fiber orientation is critical for composite mechanical properties, especially 0° tensile strength and 0° compressive strength. Therefore, we considered to develop a new fabric with less crimps. In addition, in order to improve compression after impact (CAI) and prevent microcracks, the concept shown in Figure 3 was applied. In this concept, interlaminar is selectively toughened by thermoplastic toughening particles (TP-particles), and intralaminar is selectively toughened by an epoxy resin with 'nano' toughener. The details are described in the latter section.

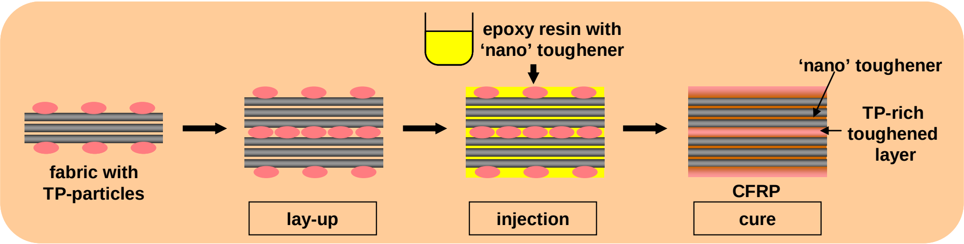


Figure 3 Schematic diagram of interlaminar and intralaminar toughening concept

3. Non-crimp Woven Fabric (CZ8433DP)

A new non-crimp woven fabric with TP-particles (CZ8433DP) has been developed. The intermediate modulus carbon fiber T800SC-24K-10E was used for the fabric. As shown in Figure 4, fine fibers were selected for auxiliary warps and weft to reduce crimps of CF warps. CZ8433DP was designed to have resin infusion paths between auxiliary warps and CF warps. In addition, TP-particles were applied onto the fabric in order to improve interlaminar fracture toughness.

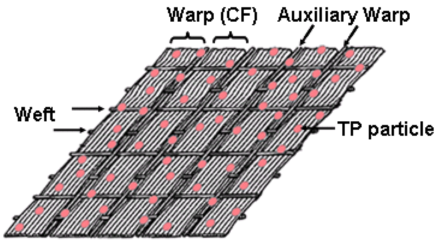


Figure 4 Schematic diagram of non-crimp woven fabric

4. Toughened Low Viscosity Epoxy Resin System (TR-A37)

A new 180 ºC cure two part epoxy resin system (TR-A37) has been developed. TR-A37 was designed to have relatively low cross-linking density, but have rigid structures, in order to improve fracture toughness without sacrificing Tg and modulus. Epoxy resins and hardeners with low viscosity were carefully selected to realize this concept. In addition, "nano" toughener was added into the resin to improve fracture toughness.

Several methods have been proposed to improve fracture toughness of resins. Addition of soft polymer particles is one of the options. It is pointed out that the toughness improvement depends on inter-particle distance, and the inter-particle distance depends on particle size as described with the following equation:

$$D = d\left\{\left(\frac{\pi}{6V_f}\right)^{1/3} - 1\right\} \qquad \text{(II)}$$

where D is surface-to-surface inter-particle distance, d is the diameter of polymer particles and V_f is the volume fraction of polymer particles [3]. From this equation, we expected that the soft polymer particles with smaller diameter had the advantage to reduce V_f, resulting in preventing viscosity increase. Therefore, we selected 'nano' toughener having the size of about 100 nm with adjusted surface to the resin for good dispersion. As shown in Figure 5, mode I fracture toughness (G_{IC}) of the cured resin by single-edge notched bending (SENB) tests was successfully improved without increasing resin viscosity by 'nano' toughener.

As a result, TR-A37 has low viscosity (120 mPa·s at 70 ºC), which allows fabrications of large and thick structures. Also, the cured resin has high Tg (187 ºC), high modulus (3.0 GPa), as well as high fracture toughness (122 J/m^2) as listed in Table 1.

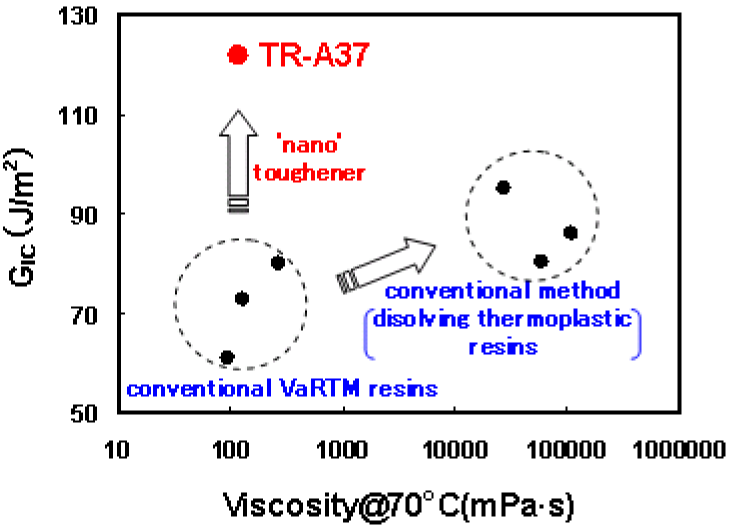


Figure 5 Relationship between viscosity
and mode I fracture toughness (G_{IC}) of cured resins

Table 1 Properties of TR-A37 comparing to prepreg resin

	TR-A37 A-VaRTM	#3631 Prepreg
Viscosity@70°C (mPa･s)	120	110,000
DMA Tg (°C)	187	200
Flexural modulus (GPa)	3.0	3.2
Fracture toughness G_{IC} (J/m²)	122	86
CTE (30-160 °C) (10^{-6}/K)	73	62

5. Composite fabrications

The CZ8433DP / TR-A37 composites for mechanical tests were fabricated by the following procedures. CZ8433DP plies were laid up on a tool plate, and a peel ply, a resin distribution layer (media) and a pressure plate were placed on the fabrics, then they were covered with a nylon bagging film as shown in Figure 6. TR-A37 was injected at 70 ºC for about 30 minutes. The composites were successfully fabricated after curing at 130 ºC for 2 hours followed by postcure at 180 ºC for 2 hours.

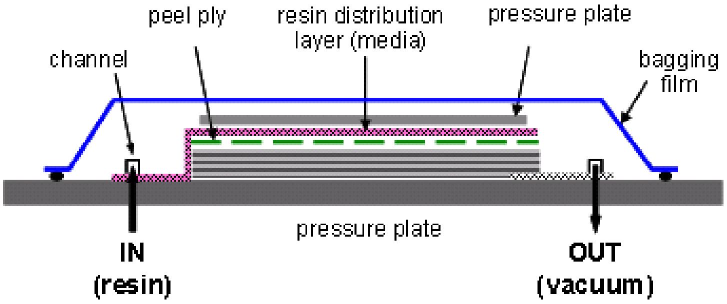


Figure 6 Setting for composite fabrication by VaRTM process

6. Composite Morphologies

The morphologies of resulting composites were observed by a scanning electron microscopy (SEM) and a transmission electron microscopy (TEM). The samples for SEM observations were prepared so that thermoplastic domains become visible separately. The samples for TEM observations were prepared by OsO_4 staining. SEM micrographs shown in Figure 7 (a) illustrate that thermoplastic rich toughened layer is selectively allocated in interlaminar. Also, TEM micrographs shown in Figure 7 (b) illustrate that intralaminar is toughened by ‘nano’ toughener which is well dispersed in the epoxy resin matrix.

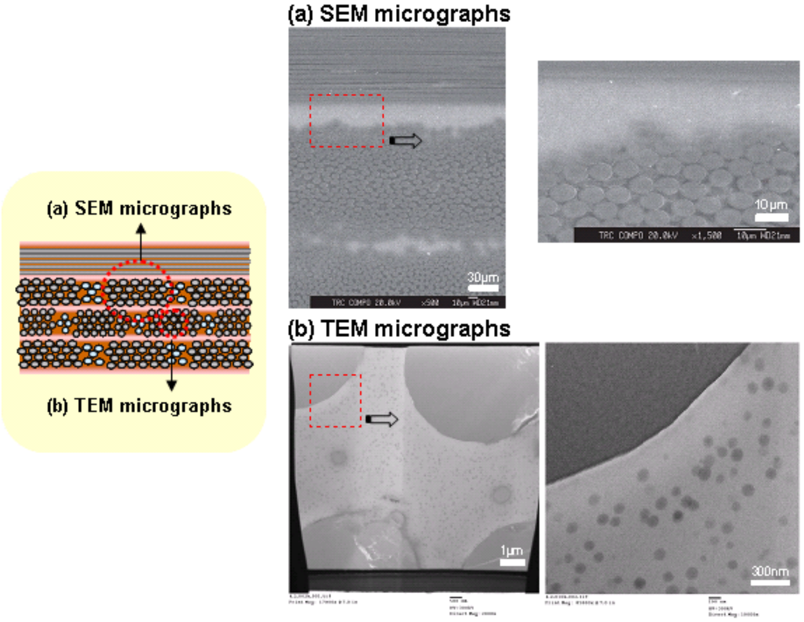


Figure 7 (a) SEM micrographs and (b) TEM micrographs of CZ8433DP / TR-A37 composites

7. Composite Mechanical Properties

The mechanical properties of CZ8433DP / TR-A37 composites including 0° tensile strength (0° TS), 0° compressive strength (0° CS), open hole compression (OHC), compression after impact (CAI) were measured. The results are shown in Figure 8. The results reveal that the composites have high 0° tensile strength, high 0° compressive strength, high OHC, as well as high CAI.

Also, microcrack tests were conducted. The composites were kept in an oven and heat cycles were repeated for 2,000 times. Then, optical microscopic observations of the composites were conducted to check microcracks. The results reveal that the composites do not have any microcracks as shown in Figure 9. This is one of the world's first VaRTM composites to achieve microcrackless. These results exhibit that the composites are adequate for aircraft primary structural elements.

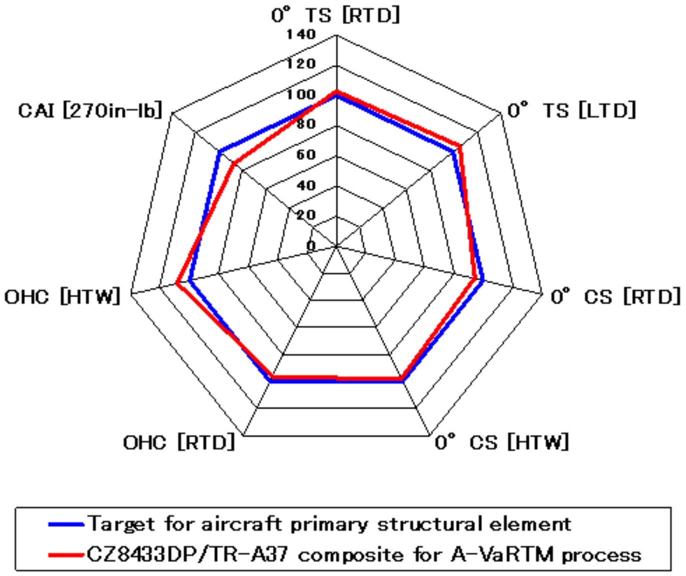
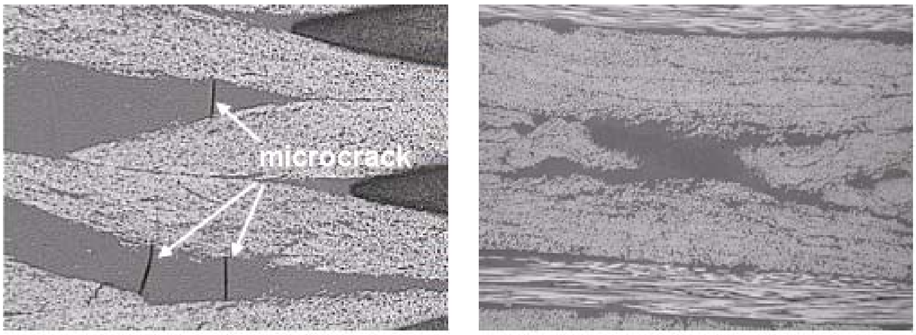


Figure 8 CZ8433DP / TR-A37 composite mechanical properties comparing to target for aircraft primary structural element (RTD: 23 ºC dry, LTD: -59 ºC dry, HTW: 82 ºC wet)



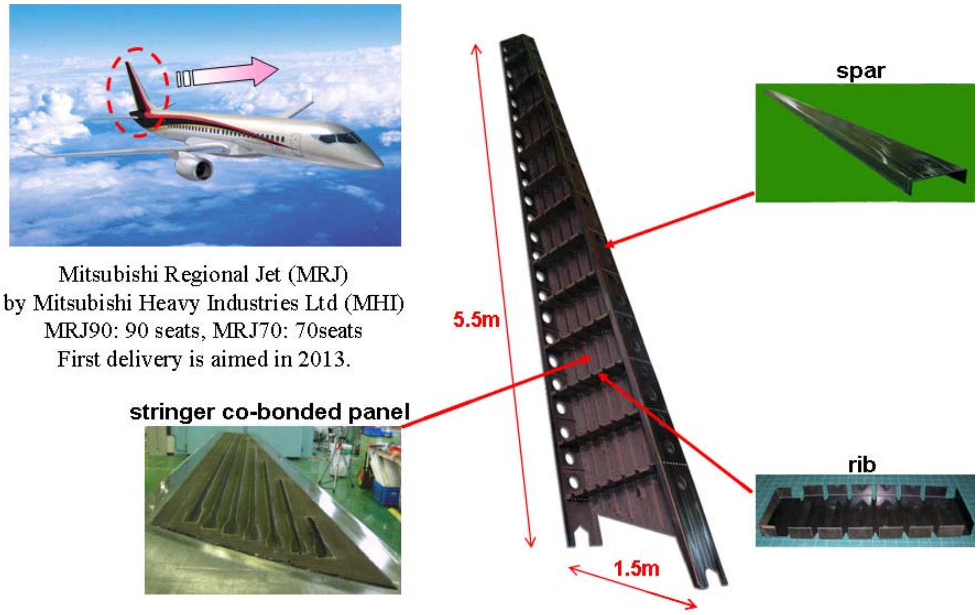
conventional composite

CZ8433DP / TR-A37 composite for A-VaRTM process

Figure 9 Optical micrographs of composites after heat cycles: (a) conventional composite [4] and (b) CZ8433DP / TR-A37 composite for A-VaRTM process

8. A-VaRTM Technologies for MRJ

We have developed the fabrication technologies for A-VaRTM process as well as the material technologies. Toray and MHI fabricated the full scale vertical stabilizer for MRJ to verify A-VaRTM process. It consists of stringers co-bonded panels, spars and ribs, having the size of about 5,500 mm ×1,500 mm × 380 mm and the maximum panel thickness of 10mm. The vertical stabilizer was successfully fabricated as shown in Figure 10. The fabrication of stringers demonstrates that the cost is reduced by 40 % comparing to conventional prepreg / autoclave process.



Mitsubishi Regional Jet (MRJ)
by Mitsubishi Heavy Industries Ltd (MHI)
MRJ90: 90 seats, MRJ70: 70seats
First delivery is aimed in 2013.

Figure 10 Vertical stabilizer for MRJ by A-VaRTM process

9. Future Works

We are conducting the material development for A-VaRTM process to improve mechanical properties, especially 0º compressive strength and CAI. Recently, we have developed next generation resin with higher modulus. The composites of CZ8433DP / next generation resin demonstrate that 0º compressive strength at room temperature and HTW (hot / wet) condition was improved significantly without sacrificing the other properties. We will continue the material development to contribute further weight reduction of aircrafts.

10. Conclusions

(1) Toray Industries and Mitsubishi Heavy Industries have jointly developed Advanced-VaRTM (A-VaRTM) process, aiming to fabricate high performance CFRP for aircraft primary structural elements.

(2) A new toughened low viscosity epoxy resin system (TR-A37) has been developed by optimizing the cross-linking structures and adding ‘nano’ toughener.

(3) A non-crimp woven fabric (CZ8433DP) has been developed by designing the woven structures to reduce crimps of CF warps and to have resin infusion paths for resin impregnation.

(4) The CZ8433DP / TR-A37 composites show excellent mechanical properties such as 0° tensile strength, 0° compressive strength, open hole compression and compression after impact. Also, no microcrack was observed after thermal cycles, exhibiting that the system is adequate for aircraft primary structural elements.

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