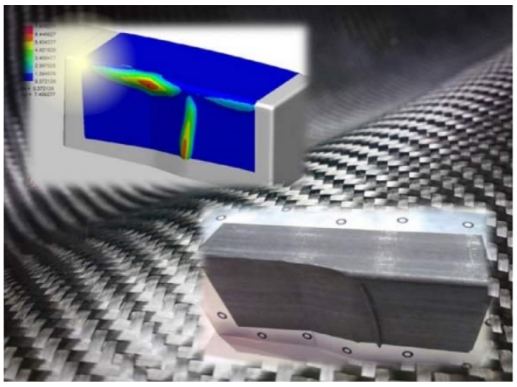
Low-cost and High-quality Drape Forming Technology for Complex Shape Composite Parts



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One of the forming methods for complex-shape composite parts such as spars and stringers of aircraft wings is to form multi-layer prepreg at once (drape forming), which is promising as a low-cost forming method with a short flow time. However, this method has the problem that if the deformation behavior of the prepreg is improper during forming into a part shape, manufacturing defects such as fiber wrinkling occurs in shape change areas of the part, causing a decrease in the strength of the composite part. Therefore, we have developed a low-cost, high-quality drape forming technology using forming simulation that can predict the deformation behavior of prepreg.

1. Introduction

In the field of aircraft, it is required to improve fuel efficiency by reducing the weight of aircraft. For this reason, composite materials with excellent specific strength and rigidity have been increasingly applied to aircraft parts and such materials account for about 50% of the aircraft weight in the case of the Boeing 787 and Airbus A350. Methods used for forming composite materials into aircraft structural parts include a hand lay-up method, a method of using AFP (Automated Fiber Placement), both methods laminate and form one ply of prepreg at a time, and a forming method of multi-layer prepreg laminated on a flat plate at once (drape forming).

Figure 1 shows the flow of drape forming. Drape forming is promising as a low-cost forming method because its flow time is short due to forming multi-layer prepreg at once. However, this method is likely to cause wrinkling during forming into complex shapes such as joggles. Since wrinkling of composite parts reduces the structural strength, reducing wrinkling is an important issue.

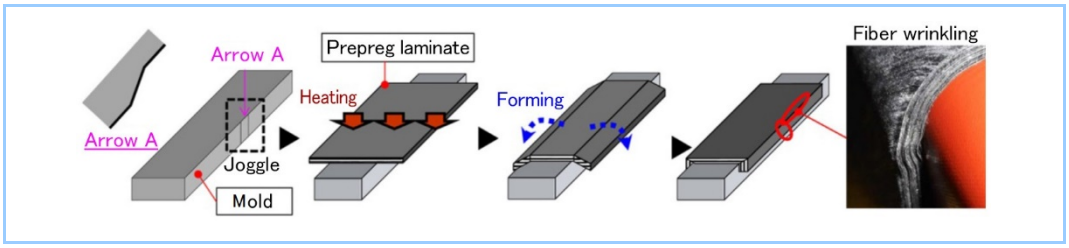

Figure 1 Flow of drape forming
In drape forming, prepreg laminated in advance is placed on a mold, heated to reduce its resin viscosity and formed into the mold shape using vacuum, etc. When the mold has shape change areas, wrinkling is likely to occur.

In order to solve this issue, we have been promoting the development of a new drape forming technology using forming simulation with the aim of elucidating the mechanism of wrinkling generation during forming and suppressing wrinkling[(1)]. This report presents the results of

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optimizing the prepreg forming process of C-shaped parts with joggles and verifying the wrinkling suppression effect.

2. Forming simulation of composite material

For the forming simulation, simulation software PAM-FORM (produced by ESI Group) of composite material was used[2]. This software enables simulation that considers the material anisotropy and temperature/speed dependence of prepreg and can predict the wrinkling generation process from the deformation behavior of prepreg during forming, so it is useful for optimizing forming conditions and the mold shape.

Figure 2 illustrates the outline of forming simulation. First, input the mechanical properties such as the tensile, bending, shearing strengths, etc., of the prepreg for each fiber orientation, the friction coefficient/tackiness between the layers, etc. and then set the forming conditions such as temperature, pressure, speed, etc. As a result of this simulation, the deformation behavior, fiber orientation, stress, strain, etc., of the prepreg during forming can be obtained. By analyzing these characteristics, the wrinkling generation process can be understood in detail.

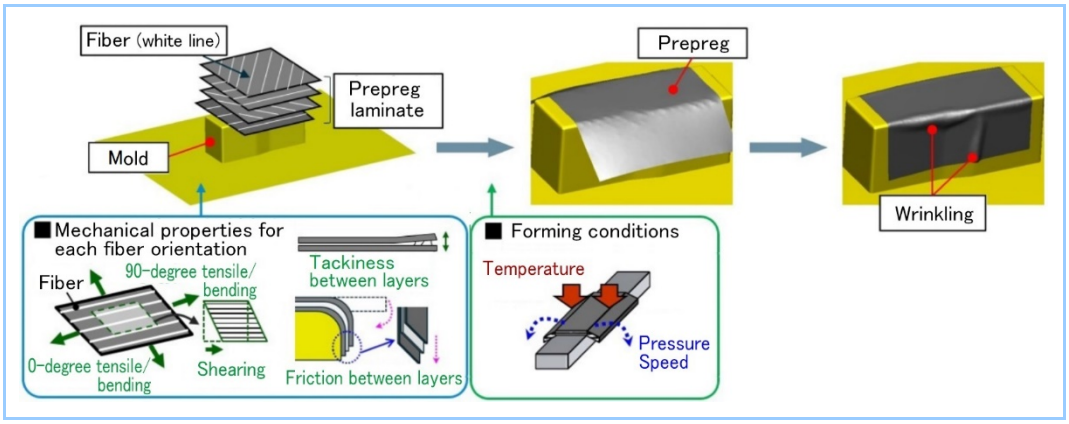

Figure 2 Outline of forming simulation
This figure shows the outline of forming simulation. When inputting the material properties and forming conditions and performing calculation, the resulting formed shape is output. By analyzing the deformation behavior during forming, the wrinkling generation process can be understood.

3. Verification of simulation accuracy

Figure 3 depicts mold shape and the simulation model. We verified a method of laminating prepreg on a mold, sealing the entirety with a flexible rubber sheet and vacuuming the inside of the rubber sheet to form the prepreg into the mold shape (vacuum bag drape forming method). The upper surface of the C-shaped cross section of the formed shape is called the web and the side surface the flange. As shown in Figure 3, in this verification, we formed a symmetrical model by 8-ply laminating unidirectional carbon fiber/epoxy prepreg (size: 500 mm x 230 mm) in a region of the mold containing one joggle. We also acquired the mechanical properties (tensile, bending and shear strength) of the prepreg for each fiber orientation and the friction coefficient between the prepreg layers at forming temperature and input them to the simulation. The mesh size of the prepreg was set to be finer in the order of at the corner R where the deformation was remarkable, on the flange and on the web as shown in **Figure 4**. The standoff block, which held the rubber sheet during vacuum and applied tension to the prepreg, was placed parallel to the mold. Finally, a rubber sheet was used to cover the entire surface and the same pressure as the vacuum pressure was applied in the direction perpendicular to the rubber sheet surface to simulate vacuum. The forming temperature was set to a temperature at which the flexural rigidity of the prepreg was reduced and sufficient slipperiness could be ensured.

Figure 5 gives the results of the simulation and the test. The simulation results indicate the distance from the surface of the mold to the outermost surface of the prepreg and the test results indicate the same measurement made with a 3D scanner. The red areas indicate that the prepreg deviates from the mold shape and wrinkling is generated. By comparing these results, it can be seen that the positions of the wrinkling generated at the corner R and the flange near the joggle almost agreed with each other. The simulation was also able to predict the height of each wrinkle to within

a margin of error of ±10%.

Based on the above results, this simulation method is determined to have a sufficient accuracy to simulate actual phenomena.

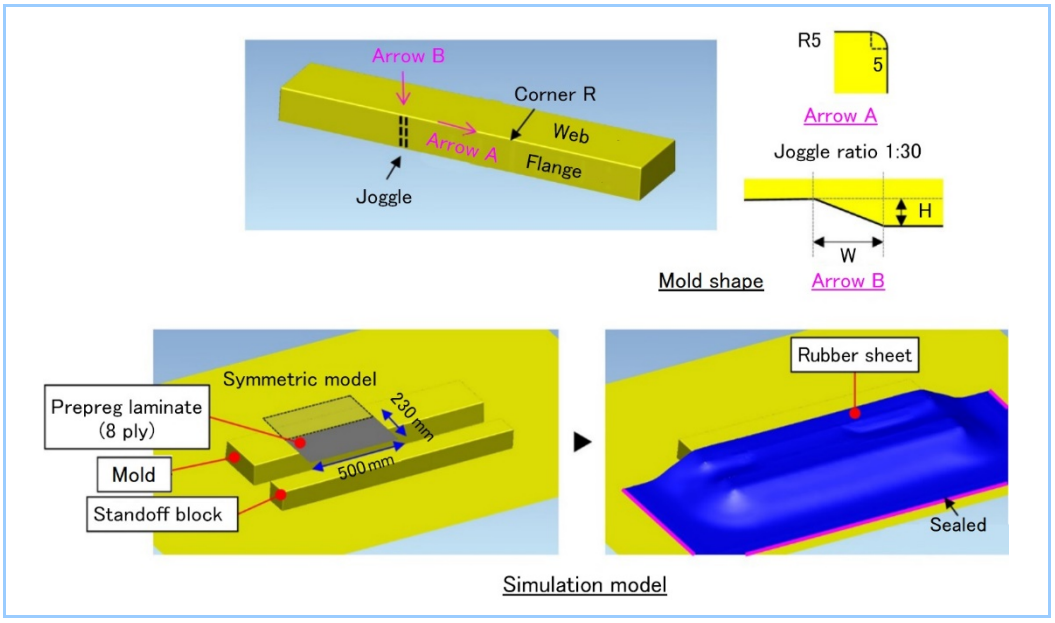

Figure 3 Forming simulation model
Forming simulation model for vacuum bag drape forming.

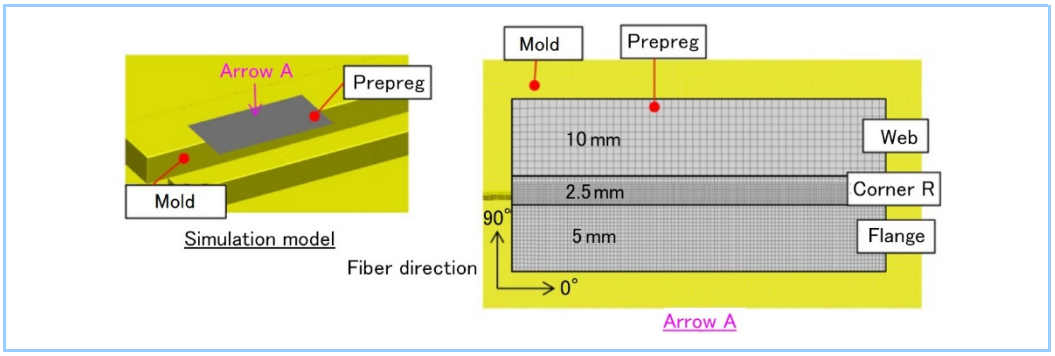

Figure 4 Mesh size of prepreg
The mesh size of prepreg was set according to mold shape and quality assessment priority.

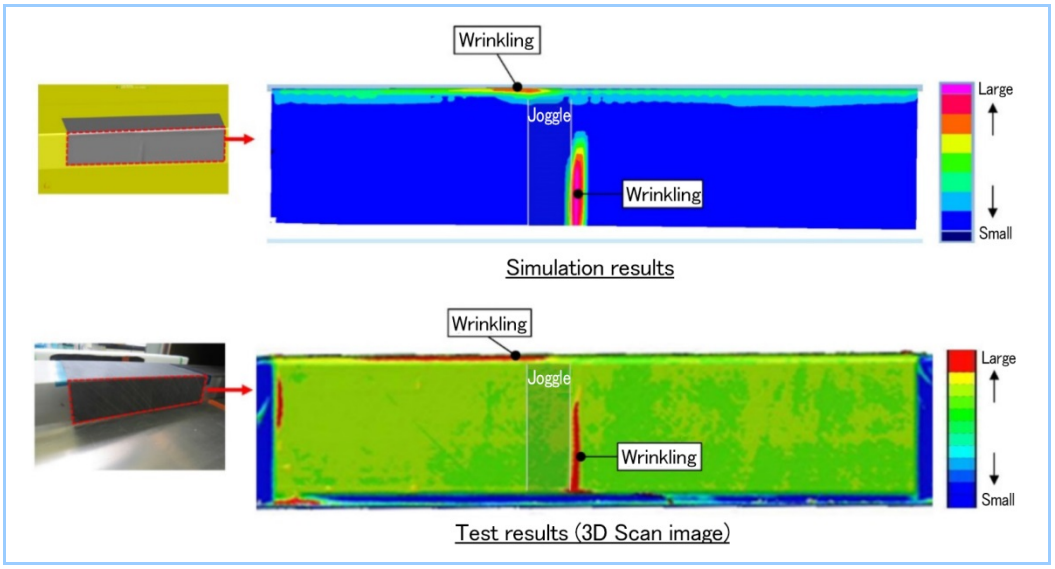

Figure 5 Comparison of simulation and test results
The upper shows the forming simulation results and the lower the test results of the 3D scan image. Both indicate the distance from the mold surface to the outermost surface of the prepreg.

4. Development of wrinkling suppression forming process

4.1 Wrinkling generation mechanism

Based on the simulation results described in Chapter 3, the wrinkling generation mechanism was clarified. **Figure 6** is a cross-sectional view of the position where the wrinkling at the corner R is maximized. The prepreg during forming easily deformed in the out-of-plane direction and came into contact with the mold at the flange before the prepreg at the corner R was completely formed. This is because the rigid carbon fiber is difficult to fit into the corner R shape of the joggle, while the prepreg at the flange is easily deformed by the pressure from the rubber sheet due to vacuum. When the prepreg at the flange comes into contact with the mold first, a clearance is created between the prepreg and the corner R of the mold. It is clarified that since the prepreg at the flange is restrained by the mold due to the subsequent vacuum, fiber is left behind at the corner R and remains as wrinkling when the forming is completed.

In addition, as shown in **Figure 7**, in the prepreg at the flange, the compression force is generated in the red line direction due to the joggle shape, and the prepreg buckles out in the out-of-plane direction. It is considered that remaining fiber generated at the flange is concentrated in the center direction of the compression force by the progress of vacuum, resulting in wrinkling.

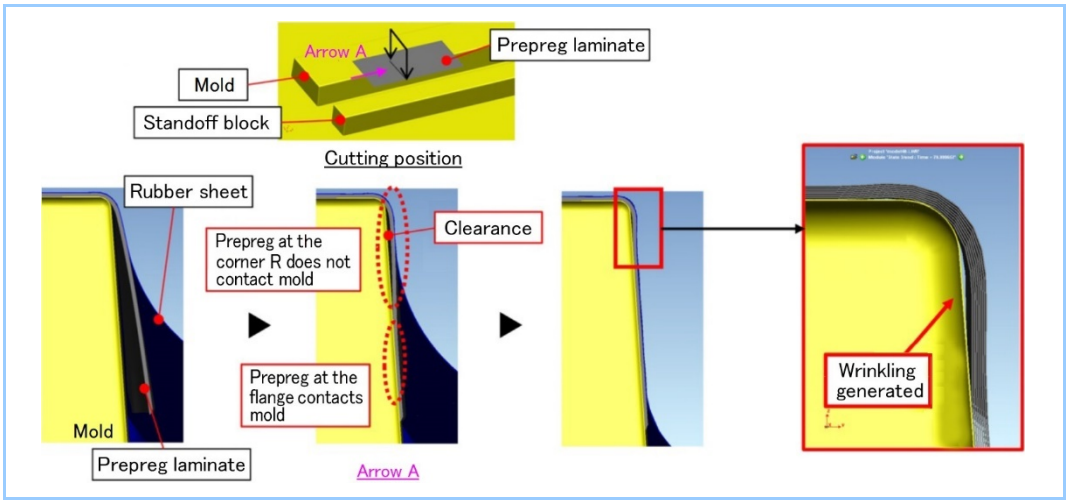

Figure 6 Wrinkling generation process at the corner R
The cross-sectional view shows the cutting position in the above figure viewed from Arrow A. Since the prepreg at the flange comes into contact with the mold first, remaining fiber was left at the corner R.

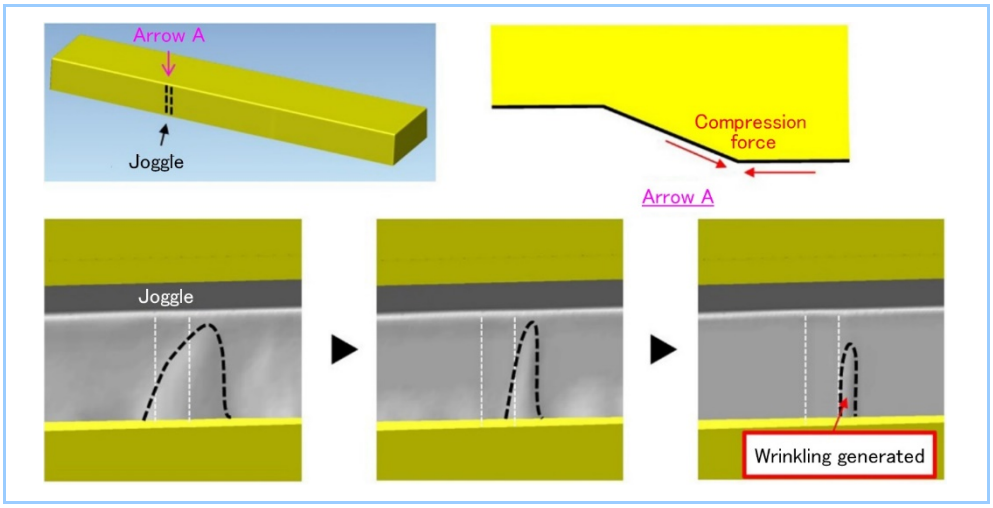

Figure 7 Wrinkling generation process at the flange
The prepreg at the flange deforms in the out-of-plane direction due to the compressive force due to the joggle shape, resulting in wrinkling generation.

4.2 Optimization of forming process

The results described in 4.1 indicate that in order to suppress wrinkling it is necessary to suppress out-of-plane deformation of the prepreg at the corner R during forming and to optimize the forming process so that the prepreg at the corner R is formed first and then the prepreg at the flange is formed. Therefore, in order to restrain the out-of-plane deformation of the prepreg, we devised a method of forming with the prepreg attached with an out-of-plane deformation control plate. This method can be realized simply by adding the procedures of manufacturing, attaching and removing the out-of-plane deformation control plate to the general vacuum bag drape forming method, and the wrinkling suppression effect can be expected without impairing the inherent low-cost advantage of a drape forming method.

Figure 8 is the simulation model. The out-of-plane deformation control plate was divided into three parts according to the joggle shape and attached to the prepreg at the flange.

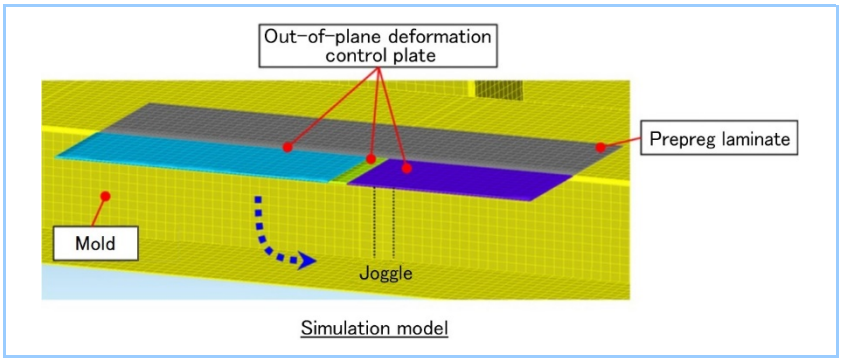

Figure 8 Application of out-of-plane deformation control plate
This figure shows a simulation model to which the out-of-plane deformation control plate is applied. The out-of-plane deformation control plate was divided into three parts according to the joggle shape and fixed to the prepreg.

Figure 9 gives the simulation results. The simulation indicates that the wrinkling height of the corner R is reduced by 30% or more by applying the out-of-plane deformation control plate and that the wrinkling of the flange disappears due to the suppression of the out-of-plane deformation of the flange. The cross-sectional view shown in **Figure 10** indicates that the prepreg is formed in the ideal order from the corner R to the flange. It is considered that remaining fiber at the corner R moves to the flange and the wrinkling at the corner R is reduced.

From the results described above, it was clarified that the developed method is effective for suppressing wrinkling, and we obtained the prospect of realizing a low-cost, high-quality drape forming technique for complex-shaped composite parts at the completion of the forming.

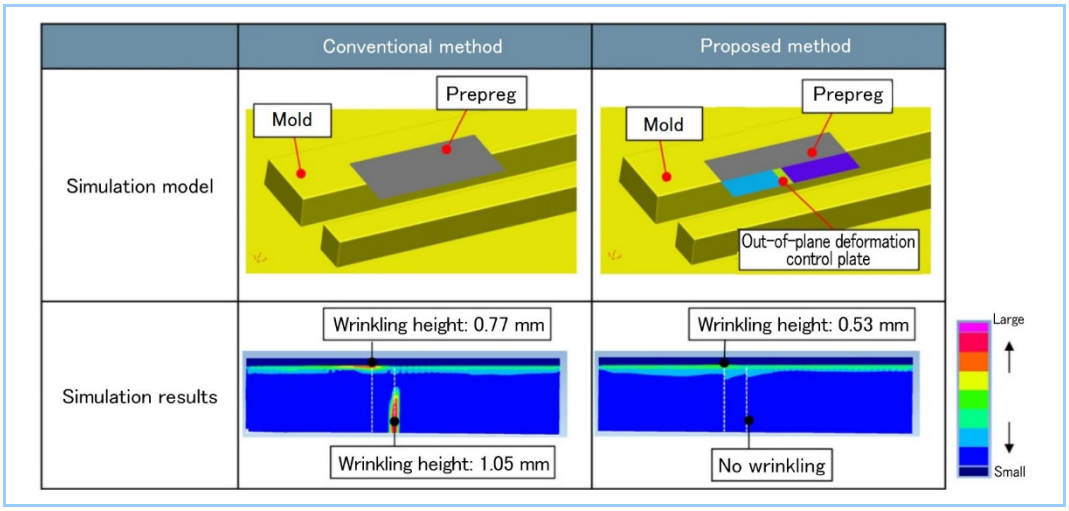

Figure 9 Simulation results
Applying the out-of-plane deformation control plate reduces the wrinkling at the corner R by 31% and eliminates the wrinkling at the flange.

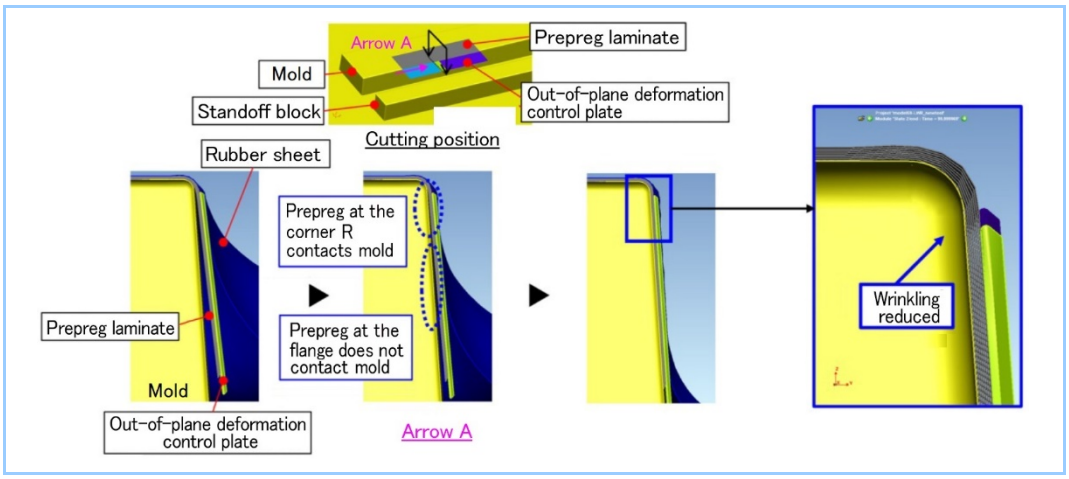

Figure 10 Suppression of wrinkling at the corner R due to out-of-plane deformation control plate

The cross-sectional view shows the cutting position in the above figure viewed from Arrow A. Since the prepreg at the corner R is formed first and then the prepreg at the flange is formed, the wrinkling at the corner R is reduced.

5. Conclusion

This report presented an elucidation of the wrinkling generation mechanism during drape forming of complex-shaped composite parts using forming simulation, and indicated that a wrinkling suppression effect was obtained by the forming process using an out-of-plane deformation control plate. As shown in **Figure 11**, by incorporating this simulation into the development flow, repeated forming tests using trial and error will be unnecessary, and test costs can be significantly reduced. Furthermore, since the simulation can be used to optimize the mold shape, it is expected that repeated forming tests and mold manufacturing will become unnecessary.

Moving forward, in order to make this forming process effective even for thicker and longer parts, we will optimize the shape, properties, application position, etc., of the out-of-plane deformation control plate to further improve the wrinkling suppression effect.

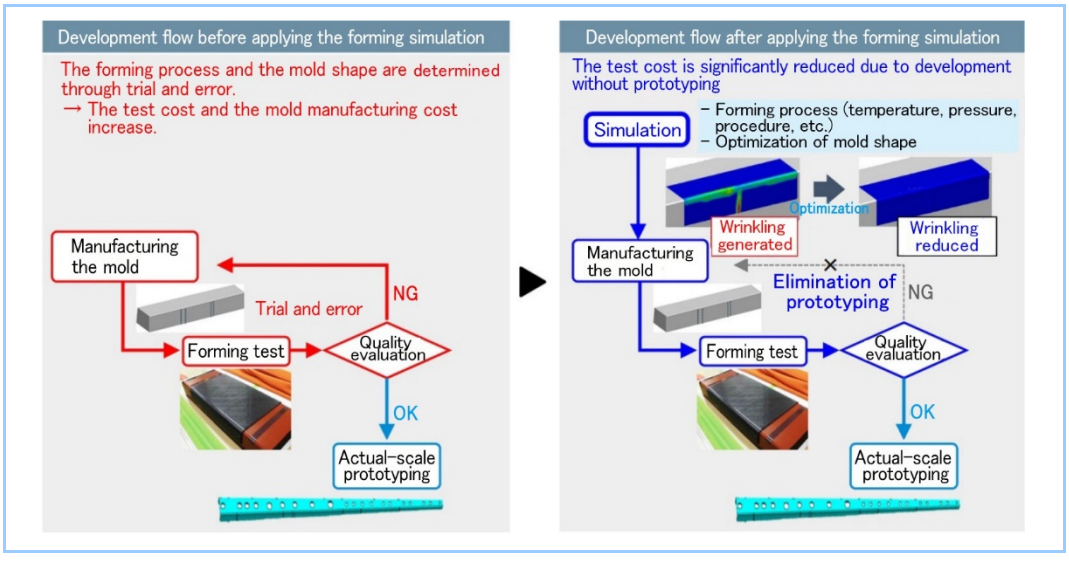

Figure 11 Development flow before and after applying the forming simulation

Applying the forming simulation to the development flow contributes to the elimination of prototyping and reduces the test cost significantly.

References

(1) Kondo, Y., et al., Development of Drape Forming Process for Composite Structure Using Forming Simulation, SE Conference 20 Amsterdam, (2020)
(2) ESI Group, https://jp.esi-group.com/