NIPPON STEEL TECHNICAL REPORT No. 122 NOVEMBER 2019

Technical Report

UDC 629 . 11 . 011 : 621 . 795 : 539 . 4 . 016 . 3

FEM Analysis for Thermal Distortion on Outer Panels

Koichi HAMADA*

Abstract

In the drying process in electrodeposition painting, the vehicle body is dried by hot air in the oven. In this process, the thermal distortion on the outer panel generates problems in the quality of the exterior. In this study, by considering the curing behavior of the structural filler and clarifying the deformation behavior of the body in the oven, we clarified the mechanism of thermal distortion and developed an FEM analysis method that can simulate and predict the thermal distortion.

1. Introduction

CO_2 emissions regulations applied to automobiles have become increasingly stringent in recent years. To improve the fuel economy, the application of high-tensile steel sheets to vehicle bodies has been expanded and the weight of bodies has been reduced, for example, by using thinner sheets for parts. The surface areas of outer panels such as a roof panel and door outers are large, so the effects of weight reduction are also large and thereby the needs for thinner panels are high. Some researchers have reported problems with exterior quality where when thinner outer panels are used, the surfaces of shells deform (hereinafter, referred to as thermal distortion) due to thermal strain in the painting and drying processes in addition to problems with the stamping performance.[1–4)]

The painting process of vehicle bodies consists of the washing process, electrodeposition process, sealing process, and finish coating process in this order as shown in **Fig. 1**. In the electrodeposition process, an automotive body is put into the electrocoating solution to form electrodeposited film. Then, the body undergoes the drying process where it is dried by hot air in a furnace to dry the electrocoating solution. Thermal distortion is often evaluated by the exterior check conducted for completed vehicles with various parts installed, so if such distortion is found, it takes many labor-hours for reworking and checks for multiple parts and across multiple manufacturing processes. **Figure 2** shows an example of thermal distortion on roof panels. Thermal distortion is often seen at the center and ends of panels as local deformation and the deformation volume is small at approximately 0.1 to 0.2 mm, so focal point check is performed to determine the extent of the deformation. In addition, after thermal distortion is found, the problem is handled through trial and error using actual parts, so drastic solutions are demanded.

This paper introduces a developed analysis technique that can predict in the design stage whether thermal distortion will occur. This technique was developed by clarifying the deformation behavior of bodies in the drying process and modelling the thermosetting characteristics of mastic sealers (hereinafter, structural fillers) that are applied to gaps between outer panels and reinforcements.[5)]

2. Thermosetting Characteristics of Structural Fillers

I worked to establish an analysis technique targeting roof panels. Fillers have been partially installed in the gap between a roof panel and roof reinforcement as shown in **Fig. 3** to secure the flare rigidity and rigidity against snow and to improve the noise vibration harshness (NVH) performance. Thermal distortion occurs at sections with fillers installed and it is often elastic deformation, in which when

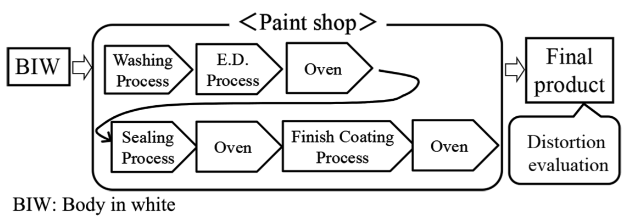

Fig. 1 Outline of painting process

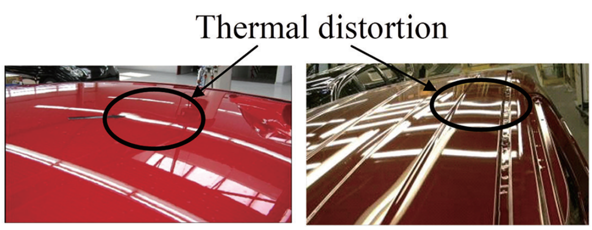

Fig. 2 Example of thermal distortion

* Senior Researcher, Integrated Steel-Solution Research Lab., Steel Research Laboratories
1-8 Fuso-cho, Amagasaki City, Hyogo Pref. 660-0891

hardened fillers are cut, the deformed sections return to the original states. Fillers possess a thermosetting property. To understand such thermosetting characteristics, the physical properties of general fillers were tested.

2.1 Tensile test

To extract the elastic moduli of fillers required to establish an analysis technique, a tensile test was carried out under conditions simulating the temperature conditions in a painting and drying furnace. **Table 1** shows the test conditions. Under the conditions simulating the heating process, a filler packed in the cast was thermal-cured to the test temperature and a dumbbell-shaped test piece was prepared. Then, the test piece was heated to the test temperature again and under that condition, a warm tensile test was performed. **Figure 4** shows the relationship between the elastic modulus and test temperature calculated from the stress-strain chart. When the test temperature was 120°C or lower, the filler did not harden, so no tensile test was performed. When the test temperature was 140°C or higher, the filler hardened. As the test temperature is higher, the elastic modulus is larger.

Under the conditions simulating the cooling process, a steel sheet was thermal-cured at a general baking temperature of 180°C to prepare a test piece and a warm tensile test was carried out from a test temperature of R.T. to 180°C. As the test temperature decreases, that is to say, while the cooling proceeds, the hardening also proceeds and thereby the elastic modulus becomes larger.

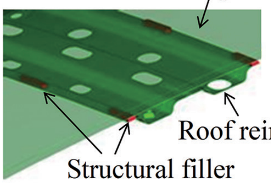

Fig. 3 Structural filler

Table 1 Test conditions

	Heat processing	Cool processing
Curing temperature	140–200°C × 20 min	180°C × 20 min
Test temperature	Same temperature as the curing temperature	180°C – R.T.
Tension speed	50 mm/min	50 mm/min

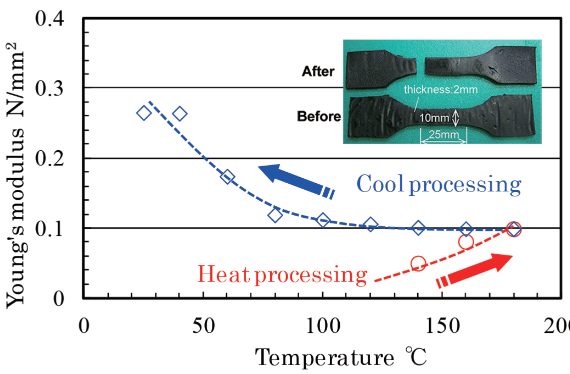

Fig. 4 Young's modulus of structural filler

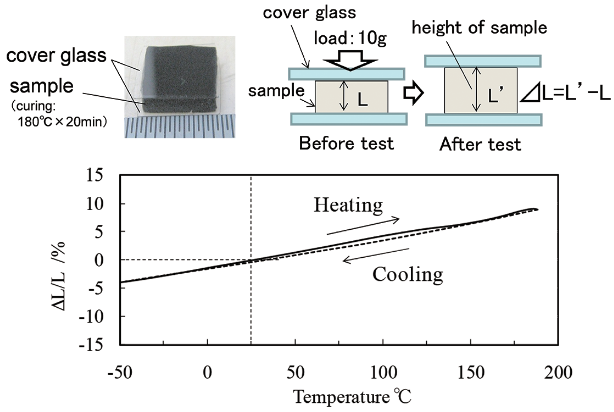

Fig. 5 Result of thermo mechanical analysis

2.2 Thermomechanical analysis test

Next, to understand changes in the volume of a filler before and after thermosetting, a thermomechanical analysis test (TMA) was carried out. As is the case with the tensile test, a sample cured at 180°C was placed between cover glasses. With a load of 10 g applied, the sample was heated and cooled to evaluate changes in the volume. **Figure 5** shows the test results. The figure shows that the influence of contraction and expansion of the volume of the filler as a result of the thermosetting is small.

The results above thus indicate that to simulate thermosetting characteristics of a filler in the drying process, the rigidity, in other words, the elastic modulus is to be set based on the body's thermal history.

3. Development of an Analysis Technique and Consideration of the Mechanism

3.1 Analysis technique

Although the analysis target is a roof panel, as the rigidity of the entire body may influence the drying process, a full-body model (half-sized model symmetrical in the horizontal direction (**Fig. 6**)) was used for analysis. The thickness of the roof panel is 0.7 mm. The model has three roof reinforcements. The thickness of reinforcement No. 2 connected from the B-pillar is 1.6 mm. The thickness of reinforcement No. 1 in front of the vehicle body and No. 3 in the rear is 0.55 mm. The fillers were modeled using beam elements. Each reinforcement has 10 fillers (five in the width direction and a total of two in front and in the rear) and five beam elements were used for each position to model a filler. **Figure 7** shows the body temperature history in the drying process. The vertical axis in Fig. 7 has been normalized with the set temperature of the drying furnace and the traverse axis has been normalized with the drying time. The body is heated to the set temperature, the temperature is held for a certain period of time, and cooled to room temperature. In this analysis model, the elastic modulus of the beam elements was set based on this thermal history.

3.2 Analysis results

Figure 8 shows the thermal distortion on the roof panel of an actual vehicle. The shape before and after the drying process was measured with a three-dimensional shape measuring instrument and this contour shows the amount of changes in the shape. Thermal distortion appears at the center in the width direction of the vehicle body as local deformation. On reinforcement Nos. 1 and 3, warps in a recessed shape remain at the sections with the fillers installed and on reinforcement No. 2, a convex warp remains at such section. **Figure 9** shows the analysis results as well. Local warps are seen at the same spots as those on the actual vehicle, correlating well with the actual results. These results show that using this technique can predict thermal distortion.

3.3 Mechanism of thermal distortion

This section studies the mechanism of thermal distortion. In the early stage of heating, the temperatures of shell materials such as the roof panel and side frame outers easily increase because they are thin, but the temperatures of inner plates and thick reinforcements do not increase sufficiently. Therefore, deformation restriction in the width direction of the vehicle body is strong and deformation of the roof panel is larger in the up and down direction of the body. Meanwhile, the deformation behavior of the reinforcements varies depending on the thickness. On thin reinforcement Nos. 1 and 3, the temperature increases are large because the thermal capacity is small and the deformation volume in the up and down direction is large as is the case with the roof outer. However, the temperature increase for thin reinforcement No. 2 is small because the thermal capacity is large and thereby the deformation volume is small. Therefore, when focusing on the behavior of the gap between the roof panel and reinforcements during heating (while the temperature is increasing), the gap of reinforcement Nos. 1 and 3 becomes smaller and that of reinforcement No. 2 becomes larger. With these states, as the temperature of the body increases, the fillers harden, so the gap between the roof panel and reinforcements changes before and after the drying process.

From these, changes in the gap between the roof panel and reinforcements may have the major effect of thermal distortion and warps remain according to the mechanism described below (**Fig. 10**).

(1) In the early stage of heating, the fillers have not hardened, so as the temperature increases, the roof panel and reinforcements deform due to the heat in the up and down direction of the vehicle body. At this time, when the roof reinforcements are thin, their temperatures easily increase and thereby the deformation

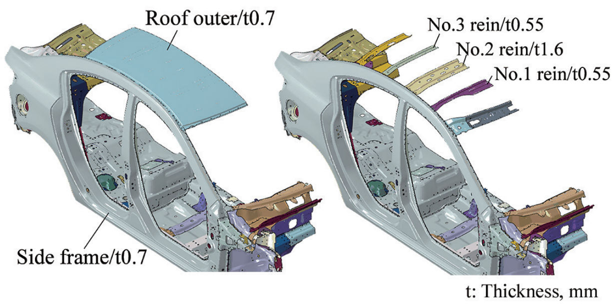

Fig. 6 CAE analysis model

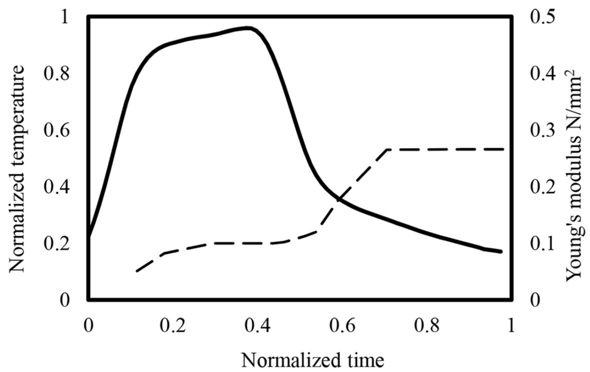

Fig. 7 Body temperature and Young's modulus of structural filler in oven

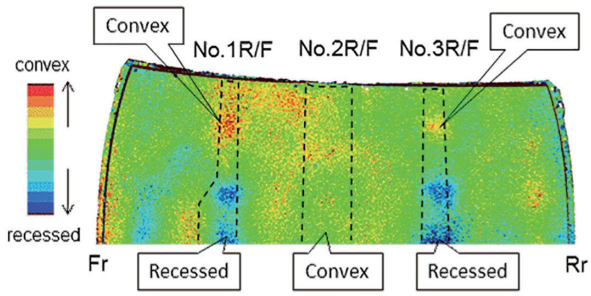

Fig. 8 Amount of thermal distortion (actual vehicle)

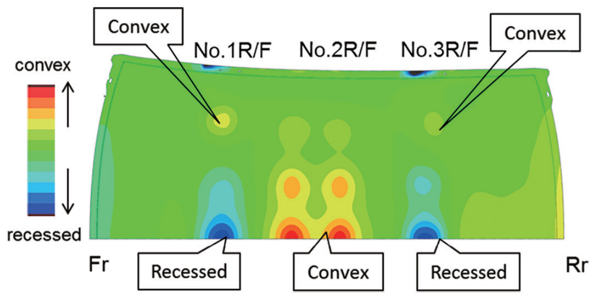

Fig. 9 CAE analysis result of thermal distortion

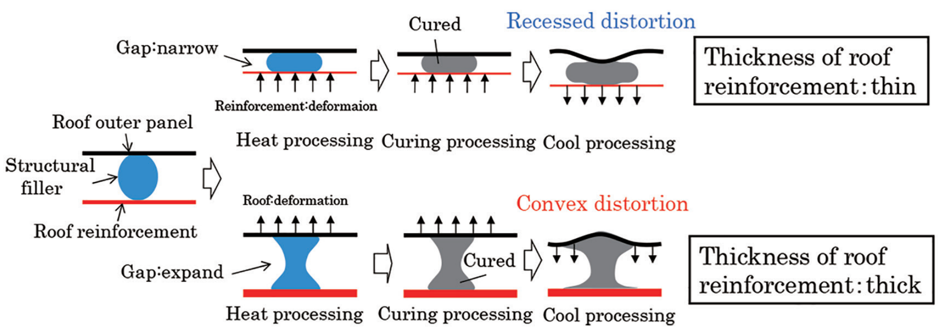

Fig. 10 Mechanism of thermal distortion

volume is larger, which reduces the gap between the roof panel and roof reinforcements. On the other hand, when the roof reinforcement is thick, its temperature does not increase easily and thereby the deformation volume on the roof panel side is larger, which increases the gap.

(2) In this state where the gap has been changed, the temperature of the entire body increases and the fillers harden due to heat.

(3) After cooling, the thermal deformation of the roof panel and reinforcements start returning, but the deformation of the hardened fillers returns only by the volume of the elastic deformation. Therefore, when the gap becomes smaller, convex warps remain and when the gap becomes larger, recessed warps remain on the roof panel side with lower plane rigidity.

4. Evaluation of Thermal Distortion on Door Units

The needs for thinner outer panels are high to reduce the weight of vehicle bodies. In this section, the analysis technique developed is used to evaluate how thinner door outer panels affect thermal distortion.

Figure 11 illustrates the analysis models of evaluated door units (door outer panels are not shown in the figure). Figure 11(a) is a conventional door structure. Fillers were used to partially bond the door outer panel with the door impact beam and dent reinforcement. The thickness of the door outer panel in the conventional structure is 0.65 mm, that of the door impact beam is 1.35 mm, and that of the dent reinforcement is 0.55 mm. The thermal distortion in a case where the door outer panel in the conventional structure was thinned to 0.4 mm was evaluated. Meanwhile, Fig. 11(b) illustrates the structure of a new lightweight steel door that Nippon Steel Corporation has developed (hereinafter, frame door structure).[6)]

As characteristics of this structure, multiple members with small rectangular closed cross sections (hereinafter, reinforced frame) have been arranged in a grid-like fashion along the inside of the door outer panel and it has no door impact beam that acts as the side impact prevention function in the conventional structure. A reinforced frame consists of hollow closed-sectional members made from 0.8-mm-thick thin steel sheets having a square or a rectangle that has the long side in the width direction of the vehicle to achieve both weight reduction and higher rigidity. In addition, a stronger 1 500-MPa hot-stamped material is used to take charge of the collision prevention function, which eliminates the door impact beam, and which has made significant weight reduction possible. Thermal distortion on the 0.4-mm-thick door outer panel in this structure was also evaluated.

Figure 12 shows the analysis results. Thermal distortion is caused by changes in the gaps at sections with the fillers installed as is the case with the roof panel. In the conventional door structure, differences in the thermal capacity between the door outer panel and door impact beam during heating and temperature rise enlarge the gap in front of the vehicle body and narrows it in the rear. After that, the fillers harden by heat, so a convex warp remains in front of the vehicle body and a recessed warp remains in the rear. When the thickness of the door outer panel is thinned down to 0.4 mm, changes in the gap are larger and thereby thermal distortion is also larger. On the other hand, in the frame door structure, the thermal capacity of the frame reinforcement is small, so changes in the gap with the door outer panel are also small. In addition, it has been confirmed that optimizing the locations of the fillers can suppress the thermal distortion to the same level as that of the current structure.

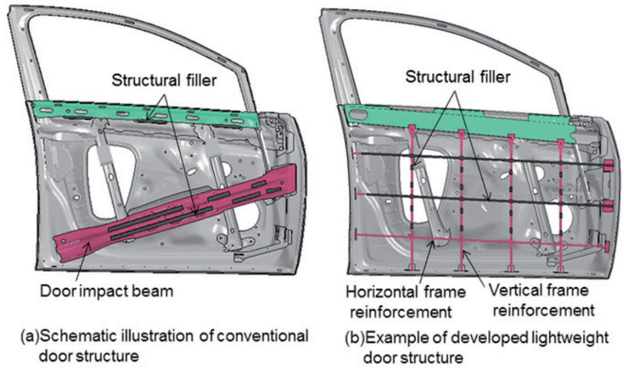

Fig. 11 CAE analysis model of door unit

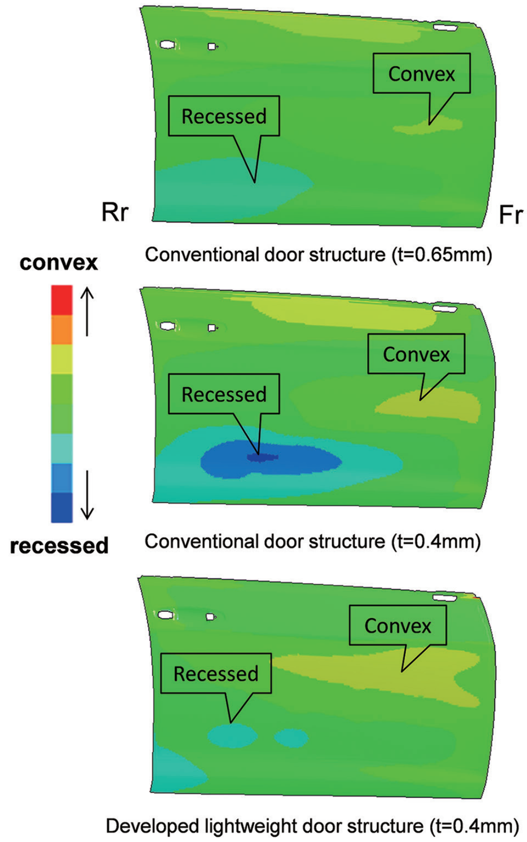

Fig. 12 CAE analysis result of door unit

5. Conclusions

This report introduced the developed analysis technique that can predict thermal distortion in the design stage that often occurs on outer panels of vehicle bodies. As the characteristics of this analysis model, thermosetting characteristics of structural fillers to be installed in the gaps between outer panels and reinforcements are set based on the temperatures of the bodies. This enables reproducing the behavior of the gap in the drying process and predicting in the design stage whether thermal distortion occurs with high accuracy. In addition, it has been confirmed that thermal distortion is suppressed in the new lightweight steel door structure developed by Nippon Steel.

References

1) Fukumoto, K. et al.: Proceedings, JSAE Annual Congress (Spring). No.72-05, 15–20 (2005)
2) Matsumura, Y. et al.: Mitsubishi Motors Technical Review. (16), 82–87 (2004)
3) Matsumura, Y. et al.: Mitsubishi Motors Technical Review. (18), 69–75 (2006)
4) Nakano, S. et al.: Mazda Technical Review. (31), 38–43 (2013)
5) Hamada, K. et al.: 2012 JSAE Annual Congress (Spring) Proceedings. 255-20125152, 2012
6) Suzuki, T. et al.: Nippon Seitetsu Giho. (412), 45–51 (2019)

Koichi HAMADA
Senior Researcher
Integrated Steel-Solution Research Lab.
Steel Research Laboratories
1-8 Fuso-cho, Amagasaki City, Hyogo Pref. 660-0891