

Integrated Simulation Technology for Design, Manufacturing, and Materials to Reduce Surface Distortion of Automotive Outer Panels

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ABSTRACT

When producing highly stylized exterior designs for automobiles, conventional manufacturing processes can cause surface distortions on the outer body panels, which require countermeasures in order to meet specifications. To address this issue, we have developed a new development-stage simulation technology. This technology integrates design, manufacturing, and materials factors to predict the potential for a design to be achieved without visible distortions.

We began by proposing a digital development concept that predicts distortions throughout all the plant manufacturing processes (stamp forming, spot welding, and paint curing) based on models made prior to the production of vehicle body design drawings. We then created a simulation technology to analyze the distortions that accumulate throughout all the manufacturing processes, and verified it on actual vehicles.

The technology was then integrated into the development operational rules for new models. This made it possible to reduce reworking due to distortions occurring in plants that had resisted resolution for many years, and thereby enable efficient production of stylized surface designs.

1. Introduction

In recent years, automobile development has increasingly focused on using digital development environments to shorten development times as well as initiatives to increase performance and quality⁽¹⁾. Within this scenario, in body development, design specifications from drawings are being turned into numerical requirements, and management baselines for manufacturing processes are being established. In terms of performance, CAE is being used for rigidity, crashworthiness, strength and durability, and NVH. In manufacturing processes as well, CAE is used for individual processes, including stamp forming, welding, and painting, and in body development, MBD and digital twin simulation analysis technologies are continuing to evolve.

However, the distortions that are detected in the quality control and inspection processes that determine the final style quality of outer body panels are the result of the accumulated deformations and distortions from the manufacturing processes that are based on design specifications. The sensitivity and interactions of the

influencing factors in each process are not well understood. In vehicle body design, as models evolve, exterior styling, light weight, safety, and functionality are being enhanced and specifications diversified. In manufacturing, there are advances in electric vehicle production technologies and the reduction of factory environmental impacts, while manufacturing conditions differ from one plant to the next. In terms of vehicle body materials, the use of high-strength, lightweight materials and recycled materials is on the increase, and materials specifications are diversifying. As a result of this growing diversification of requirements, factors impacting outer panel distortions are becoming more numerous and complex. Thus, conventional reporting⁽²⁾⁻⁽⁶⁾ and existing technologies are proving insufficient to address the issue.

In order to achieve highly stylized exterior designs for automobiles, therefore, we utilized a digital development environment to link factors relating to the design, manufacture, and materials of outer panels in automobile development, and developed CAE technology to predict surface distortions on outer panels.

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2. Development Goals

Our goal is to forecast and terminate, at the design stage, the occurrence of outer panel distortions by developing an integrated simulation technology that would encompass vehicle body materials, parts, and all manufacturing processes.

First, by developing CAE technology to analyze accumulated stresses and distortions from manufacturing processes based on design specifications (stamp forming, spot welding, and paint oven curing), it will be possible to predict changes in distortion over time in the actual processes.

Next, by conducting simulations within the baseline conditions and ranges of variation of the vehicle body materials, design specifications, and manufacturing processes, reasons for occurrence will be identified and specifications and conditions established that will not result in visible distortions.

3. Technology

3.1. Developing an Integrated Simulation Technology that Encompasses All the Vehicle Body Materials, Parts, and Manufacturing Processes

3.1.1. Approach to resolving outer panel surface distortions

(1) Influencing factors on outer panel surface distortions

Figure 1 illustrates the process leading to the detection of distortion in vehicle body panels. In vehicle body development, designers create a model layout that meets the required specifications and produce drawings. A prototype is then fabricated using manufacturing processes from stamp forming and spot welding to painting and assembly. From this, the manufacturing conditions that will become the baselines are determined. However, if distortions are visually detected in the exterior inspection process, manufacturing conditions need to be reset, and parts redesigned. In particular, distortions often occur at the surface of the T-intersection of the upper center pillars, on the lower sidesill, and the area around the roof panel arch. These are surfaces that tend to accumulate and concentrate stresses in response to external forces in the manufacturing processes, such as deformation of parts during processing, thermal stresses, or torsion. It is believed that when loads exceed the material's yield point, parts are subject to plastic deformation, which in turn causes outer panel surface distortion.

Although specifications that reflect countermeasures for past occurrences have been integrated into drawings, and verification performed on prototype vehicles, it has not been possible to predict occurrences in advance. The reasons for this are thought to be the application of unprecedented shape specifications in the pursuit of more advanced exterior styling for new models, and differences in production technologies and equipment between factories. There are

hundreds of factors that impact panel surface distortion on actual vehicle bodies, including panel gaps at welding points and residual stresses that cannot be measured except with CAE analysis can have a large impact, but are not checklist items in production engineering management for conventional manufacturing processes. These factors were therefore added as analysis items.

(2) Evaluating distortions accumulated throughout all processes

Figure 2 illustrates the distortion evaluation process. Depending on the model being developed, the design

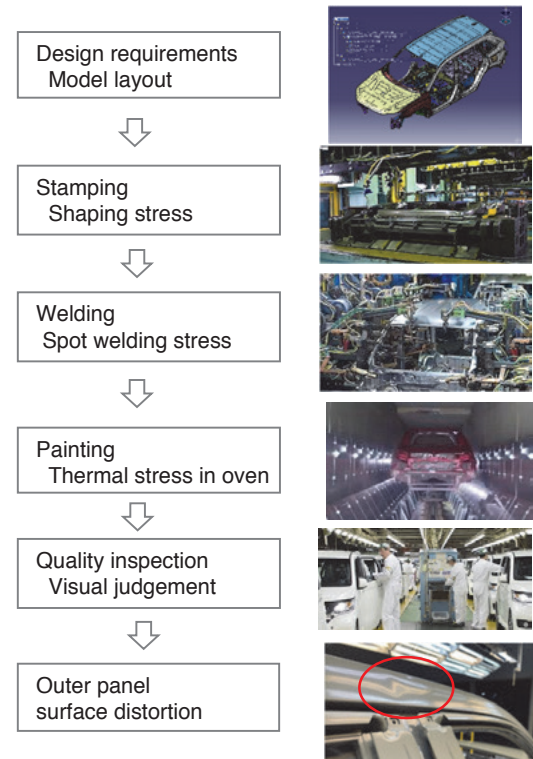


Fig. 1 Surface distortion in automotive body panel manufacturing

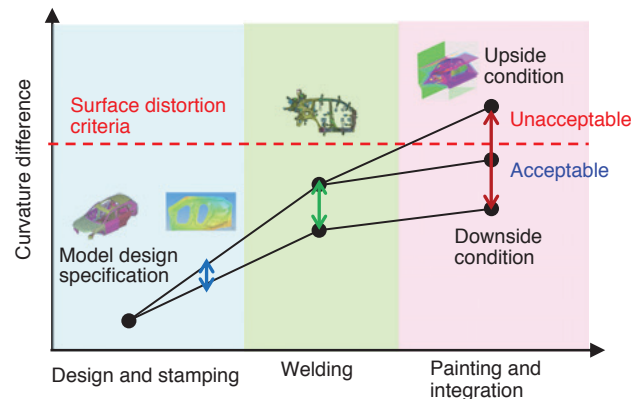


Fig. 2 Evaluation approach of surface distortion criteria for outer panels during development process

shape and size of the outer panels differ, as do the design specifications for the inner panels and the stiffeners between them. In addition, the equipment specifications and processing conditions vary from plant to plant. Within the production process, in the steps from delivered metal sheets to parts and vehicle body processing, the shape and dimensions of the outer panels change, and residual stress and distortions accumulate.

To predict these changes, simulation evaluations were performed based on baseline factors that affect distortion within each process and within ranges of variation. Next, the curvature distribution was determined for outer panels both with and without distortion, and the curvature difference between them was used as an index to evaluate the amount of distortion in the outer panels. The amount of distortion detectable by visual inspection has been accumulated as correlation data relative to the curvature difference⁽⁷⁾. Therefore, it was possible to compare the curvature difference of the distortion amount found in simulations to past data, which in turn enables the setting of specifications to mitigate distortion occurrence.

3.1.2. Developing an end-to-end integrated simulation method

Conventionally, CAE solvers specialized for each manufacturing process (stamp forming, welding, and paint curing) are used, and integrated analysis methods that link all processes have not been available. Here, a method was established to extract and transfer data that could accommodate differences in analysis settings (meshes, node data formats) between processes. Also, factors that impact outer panel surface distortion were reflected as input

data for the CAE analysis method. Figure 3 illustrates the manufacturing process steps and digital linking between processes using simulations. For factors against which distortions are especially sensitive, evaluations were performed from the baseline level to the ranges of variation in conditions at factories around the world, and the details are as follows.

(1) Target of analysis

As representative parts, the upper part of the center pillar, sidesill, and roof sections were chosen as targets for outer panel surface distortion analysis.

For the analysis, CAE models were needed that reflected past design know-how and design data from design requirements (baseline dimensions, curvature radius at baseline lines, step dimensions at gaps and offsets, bead surface rigidity, buckling strength, etc.). Here, the mesh sizes and joint modeling used in vehicle performance CAE analysis were repurposed, and analysis performed without the need for additional man-hours to create new models.

(2) Materials specifications

The materials constituting the outer panel parts and joints include steel sheets, aluminum sheets, joint bonding agents, sealers, and so on. The material properties that are entered into the analysis have varied stress-strain charts and temperature dependencies, according to the strength and composition of the base material. The analysis results also vary greatly according to the sheet thickness standard value and the upper and lower limits of tolerances. Therefore, an in-house materials database⁽⁸⁾ was used, based on accumulated and detailed measurements of material properties.

(3) Stamping process

In the outer panel stamp forming process, molding

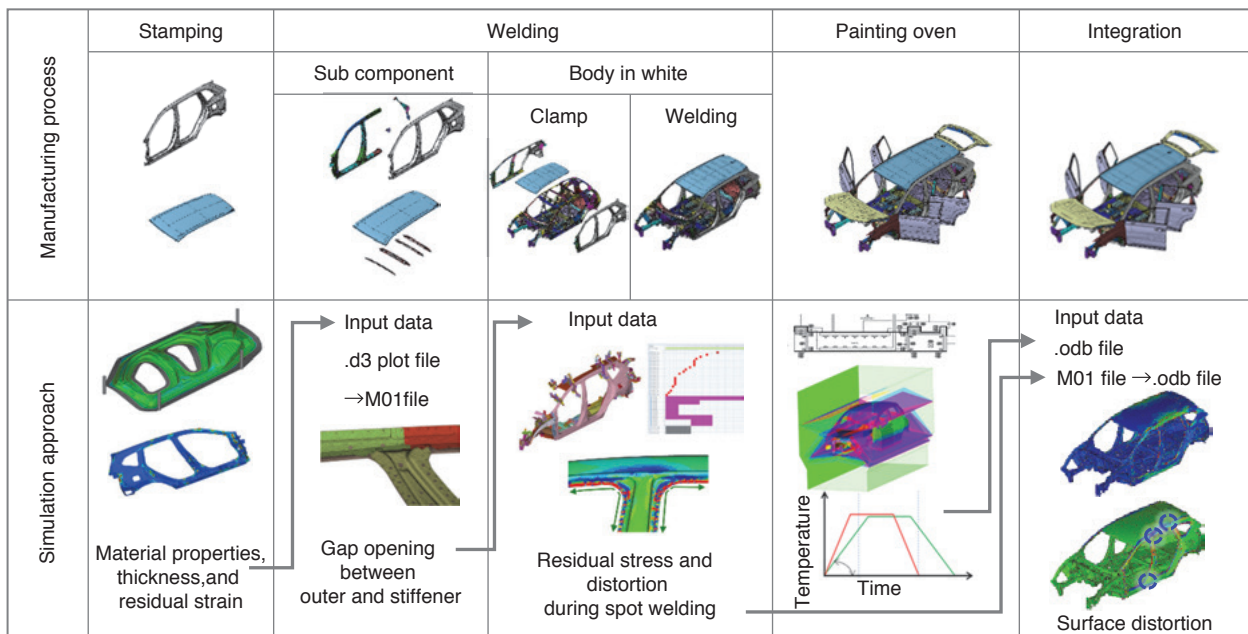


Fig. 3 Integrated simulation approach along manufacturing processes

processes such as draw-and-form molding have a larger impact on distortions than cutting and bending processes such as trimming, restriking, bending, piercing, and cutting. Here, JSOL Corporation's JSTAMP was used. As an explicit solver, the simulator was used to calculate plastic distortions and sheet thickness reduction ratios when drawing and forming flat sheets. Changes in steel sheet yield strength caused by plastic distortion are a key factor in outer panel surface distortions that occur due to compression stresses. Thus, the analysis reflected plastic distortions caused by process hardening. The impact of self-weight was also reflected, and the analysis results carried over to the analysis of the next process of welding.

(4) Welding process

The outer panel welding process specifications include a large number of conditional parameters, such as equipment specifications, welding specifications, clamp specifications, and so on. Factors among these that contribute to distortion are the position of fixing jigs, sheet gaps at spot-welding points, and the effect of residual stress propagation resulting from the spot weld order. These factors are as determined under production engineering requirements. Here, the implicit solver Visual-Assembly, produced by ESI Japan, was used and loaded with the welding clamp locations, spot welding order, and sheet gap parameters. The data for residual stress at the spot-welding points, distortions, and deformation shapes were carried over to the analysis of the next process, that of paint oven curing.

(5) Paint oven curing process

In the outer panel painting process, the vehicle upper body is suspended on a cart and moved over 100 m through a series of curing ovens (electrodeposition oven, intermediate coat oven, topcoat oven, and repair oven), the entire process requiring more than one hour. During this time, the temperature is increased up to about 200°C above the normal temperature to bake and cure the paint, before cooling again. The outer panels that directly face the high-temperature jets from the wall nozzles inside the curing ovens heat up first. The inner parts heat up more slowly as a result of the circulating hot air. The inconsistent thermal expansion caused by the heat difference between the outer and inner panel is a factor in distortion. However, performing thermal fluid analysis with CFD requires large amounts of computational time, making it impractical for the given development schedules. To shorten computation times, the heat transfer analysis solver THESEUS-FE from ARRK Engineering GmbH was used to model thermal fluid heat transfer coefficients and heat radiation. 3D models were first created that reflect the specifications of the different curing ovens at each plant, making it possible to recreate actual paint curing conditions and thereby grasp the spatial distribution and changes over time of the vehicle body temperature. From the analysis results, temperature profile data for each mesh node of the vehicle

body model were output and used in the next process as input load data for the final structural analysis of the vehicle body.

(6) Structural analysis reflecting manufacturing history

Since the distortions from the manufacturing processes discussed in (1) to (5) are cumulative, it is necessary for CAE analysis to carry over the history from each process. Therefore, a script was created that brought together the data formats from all the analysis files formats; namely, the .d3 plot file from the stamp process, the M01 file from the welding, and .odb files from the paint curing and final structural analysis. The implicit solver Abaqus, from Dassault Systèmes SE, was used for the stress analysis of the final vehicle body structure.

In this way, the accumulated distortions of the vehicle body design specification DPM, input materials properties, and manufacturing processes (stamp forming, spot welding, and paint curing) were linked as factors to create an integrated simulation that encompasses all development processes.

3.1.3. Verification approach and measurement method construction

On actual manufacturing lines or verification-purpose lines, a prototype vehicle was used to measure factors relating to distortion, and the results compared to the simulation for verification.

(1) Verification environment

The verification experiments were conducted at the Yorii Plant, which is a global baseline standard for plants. An SUV Type 1 model with a large outer panel surface area was used as the prototype vehicle to represent a model progressing through the line.

The Yorii Plant mass-production stamp equipment was used for the stamping process. The welding process was performed on the Yorii Plant verification prototyping line and was equivalent to mass-production welding. For the painting process, the vehicle was passed through the curing ovens on the mass-production line.

(2) Measuring conditions

In order to clarify the amount of distortion within and between the processes, the 3D forms, engineering strain (hereafter, "strain"), sheet gaps, and temperature changes were monitored over time, and the correlations between the timing and location of plastic distortion occurrences verified. Figure 4 shows the verification method. Non-contact 3D shape measurements were taken before and after each manufacturing process to determine the detailed deformation behavior of the actual vehicle. In the welding process, the gaps, and the changes in the gaps, between the outer and inner panels were measured with feeler gauges during clamping, welding, and unclamping. To ascertain the amount of distortion continuously over time between the welding and paint curing processes, three-dimensional deformations were measured from surface-distributed distortions

detected with optical fibers. In the paint curing process, thermocouples were placed on the outer and inner panels, as well as the stiffeners located between them, in order to evaluate the impact on distortion of temperature differences between the inner and outer panels. During these measurements, the optical fibers and thermocouple measuring instruments, and the data loggers were positioned inside specially fabricated heat-resistant boxes, enabling measurement of changes in temperature and distortions over time at approximately 200°C within the vehicle curing ovens.

3.1.4. Verification results by manufacturing process

(1) Stamp process

Side panel deformation during stamp forming was measured using a scribed circle as shown in Fig. 5 (the distortion was calculated from the changes in the long and short axes before and after deformation). The reduction ratio of the sheet thickness was also measured. Figure 6 shows a comparison of the results for the actual measured sheet thickness reduction ratio and the simulation of section 3.1.2.(3). The difference between reduction ratios was found to be less than 6.6%, indicating good correlation.

○ : Measured, — : Not measured

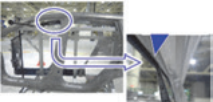
Verification test methods, measurement data	Process		
	Stamping	Welding	Painting
Optical 3D scan, 3D shape 	○	○	○
Feeler gauge and gap width 	—	○	—
Strain optical fiber, strain 	—	○	○
Thermocouple, temperature 	—	—	○

Fig. 4 Verification test methods for vehicles in factory



Fig. 5 Measurement method of stamping strain (scribed circle)

(2) Welding process

With regard to changes to strain due to the spot-welding order, which has a large impact on outer panel surface distortion, Fig. 7 shows a comparison of the results between the measurements from the optical fibers and the simulation described in section 3.1.2.(4). The welding spot timing and the changes in strain were found to correlate well at the roof, roof side, and sidesill evaluation locations.

(3) Paint oven curing process

For the painting process simulation described in

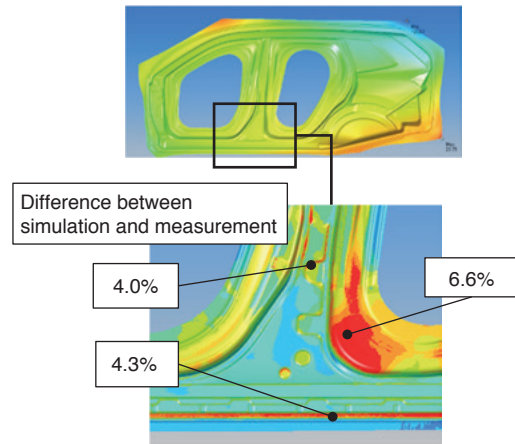


Fig. 6 Simulation of outer panel stamping and comparison of thickness results between simulation and measured reduction in sidesill area

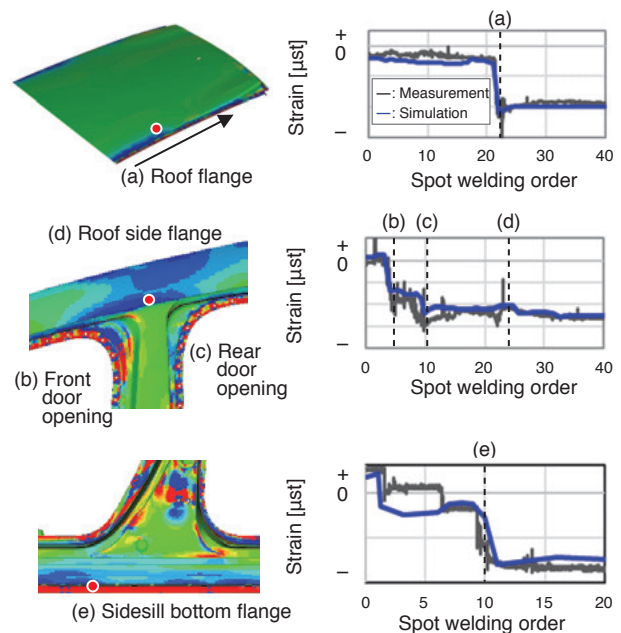


Fig. 7 Comparison of strain results between simulation and measurement along spot welding order

section 3.1.2.(5), Fig. 8 shows a comparison between the calculated and measured sidesill outer panel temperatures, under the temperature conditions and inlet flow rate of the electrodeposition curing process at the Yorii Plant. It was found that the temperature profiles correlated well. Figure 9 shows the difference in temperature between the sidesill outer panel and the stiffeners on the inner side at those locations, as well as the strain measurements made using optical fibers. It was shown that the maximum absolute value for strain variation coincided with the largest temperature difference. From this, it was inferred that plastic deformation occurs when the stress caused by thermal expansion differences during manufacturing exceeds the yield stress.

(4) Structural analysis verification reflecting manufacturing history

To verify the effectiveness of distortion analysis reflecting manufacturing history, the actual measured displacement from the initial sidesill design surface

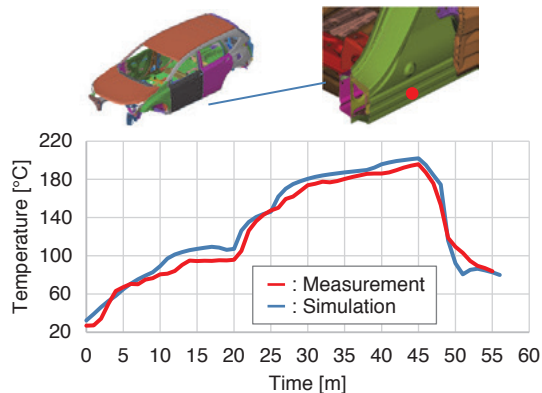


Fig. 8 Comparison of temperature results between simulation and measurement during paint oven process

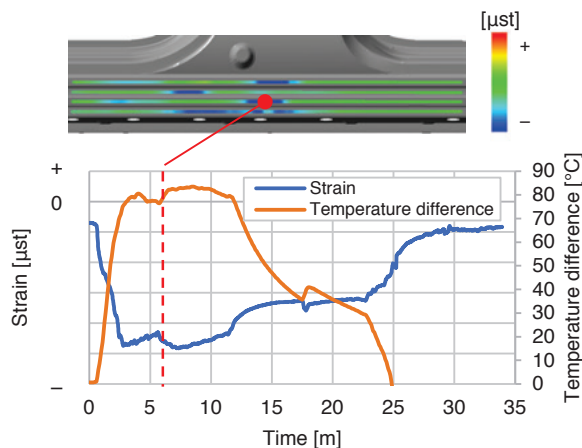


Fig. 9 Measurement results of strain on sidesill outer and temperature difference between sidesill outer and stiffeners

to the post-paint curing state was compared to the simulation results. This comparison is shown in Fig. 10. Compared to the actual measurement (a), simulation (b), which does not consider certain parts of the manufacturing history, showed much less deformation. On the other hand, in simulation (c), which considers the entire manufacturing history, the same deformation in the negative direction (indentation) was visible in the same location in both the measurements and simulation, indicating good correlation.

Next, Fig. 11 shows a comparison of the sidesill distortion amount over time, between the actual measurement taken using optical fibers during paint oven curing and the calculation. The stress value obtained by multiplying the measured strain value and the modulus of elasticity of the outer panel steel sheet material was plotted on the vertical axis, showing the region

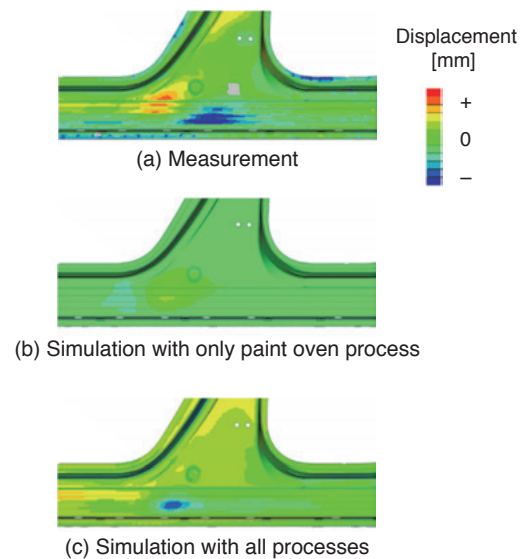


Fig. 10 Comparison of displacement results between measurement and simulation with processes on sidesill

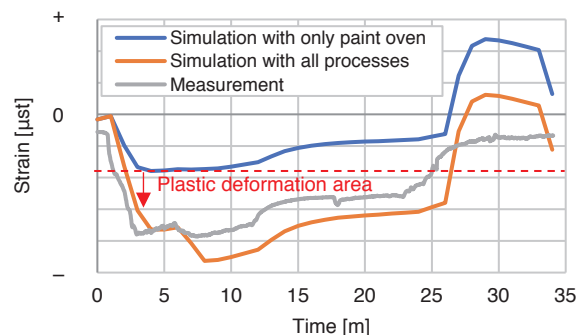


Fig. 11 Comparison of strain results on sidesill between measurement and simulation during paint oven process

where plastic deformation occurred as yield strength was exceeded. Distortion grew as heating began, and measurements showed that plastic deformation occurred after several minutes. In the simulation results, the simulation that did not consider the paint oven curing process showed that stress was within yield strength and no plastic deformation occurred. On the other hand, when the manufacturing history was taken into account, the results showed the same tendency as the measurements, where yield strength was exceeded and plastic deformation occurred.

As the above shows, this simulation method, which integrates the manufacturing processes, was able to predict both the timing of plastic deformation and the amount of distortion that is shown in the measurements, thereby confirming its utility.

3.2. Predicting Feasibility Using Integrated Simulations to Establish Specifications to Suppress Outer Panel Surface Distortion

Simulations were run for specifications aimed at suppressing strain that occurs under various conditions that impact outer panel surface strain distortion of the roof, sidesill, and upper center pillar of a vehicle model. In order to determine the feasibility of specifications, base conditions and variation ranges were compared for panel thickness and outer panel surface curvature in the design specification, differing thickness reduction ratios in the stamp forming process, panel gaps at welding spots during the welding process, and heating rate in the paint curing process. Figure 12 shows that for the sidesill, the impact of sheet thinning during stamp forming and panel gaps during welding was relatively minor. However, when comparing the base condition with the upper-limit condition for heating rate during paint curing, a significant difference was observed. Here, when measurements were made on actual panels, the results showed that under the

baseline heating rate for paint curing, the same as used in the simulation, no distortions occurred. On the other hand, when the upper-limit condition was exceeded, the distortion exceeded the criteria, correlating with the simulation results.

At the same time, Fig. 13 shows that a comparison of the simulation results (a) with the measurement results (b) showed a similar distribution trend in the curvature differences of the distortion. From these results, it was possible to reassess the range of variation and apply the optimal heating rate to the manufacturing conditions.

Next, we performed simulations for the roof panel. Figure 14 shows that under the baseline conditions, distortion increased during welding, but the effect of the paint curing process was relatively small. Also, an analysis of the upper-limit of welding condition variation showed that distortions increase, but that even adding paint curing conditions at the upper-limit of the range had only a small impact. This indicated that the welding process had the greater impact on distortion.

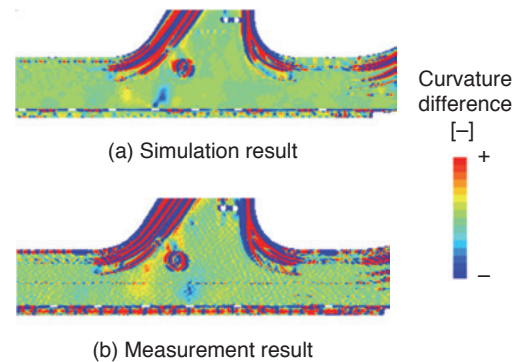


Fig. 13 Simulation and measurement results of curvature difference with all processes on sidesill

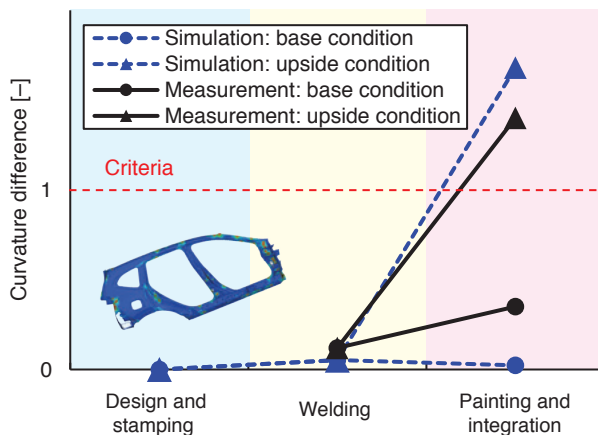


Fig. 12 Comparison of curvature difference results on sidesill

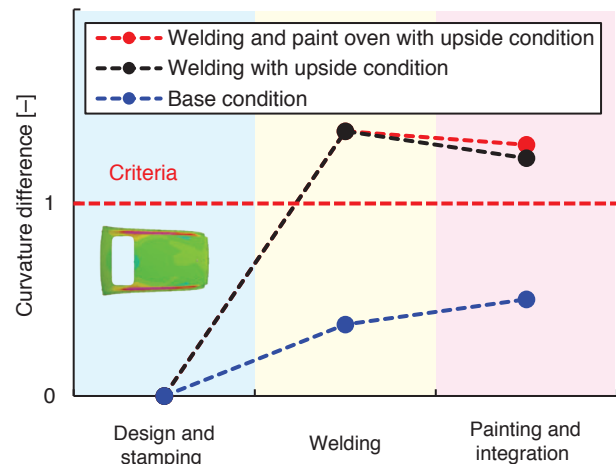


Fig. 14 Simulation comparison results of curvature difference on roof panel

As shown in Fig. 15, the larger the gap between panels at the spot-welding points, the greater the deformation of the rectangular structure. It is thought that this causes excess stress on the roof surface and thus distortion to occur. By modifying the welding conditions and reflecting the optimized manufacturing condition, it was possible to suppress these outer panel surface distortions.

It was also found that the dominant factors that cause outer panel surface distortions vary depending on the parts involved.

From the above, it was possible to predict the feasibility of specifications by referencing the design specifications for the outer panels of a vehicle and taking into account the accumulated distortion from each manufacturing process. It also became clear that the sensitivity to and interactions of influencing factors differ depending on the component or part, and an end-to-end integrated simulation method is effective for suppressing occurrences of distortion among the complex conditions of an entire vehicle.

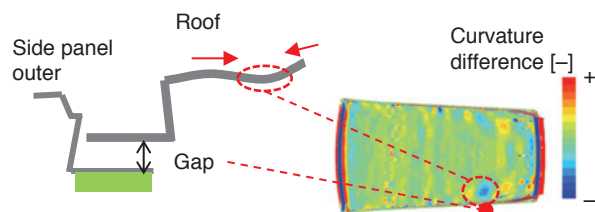


Fig. 15 Simulation result of curvature difference due to gap on roof panel

4. Conclusion

In order to achieve highly stylized exterior designs for automobiles, we developed a simulation to predict, at the design stage, the occurrence criteria for outer panel surface distortion. By incorporating this technology into the development management steps for new models, we were able to end the need for reworking in response to outer panel surface distortion occurring at plants around the world, and thereby increase design development efficiency.

- (1) We developed a CAE technology that carries over accumulated distortion and stress data, enabling end-to-end evaluations of vehicle body materials, design specifications, and manufacturing processes (stamp forming, spot welding, and paint curing).

The results of verifications on actual vehicles enabled us to predict the occurrence timing of plastic deformation.

- (2) Using the integrated simulation method that we developed, we were able to understand the mechanisms under which different factors have large impacts on distortion, depending on the outer panel part. By optimizing design specifications and manufacturing conditions that constitute these factors, we were able to suppress the occurrence of distortion.

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