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Development of Hot Stamping Technology for High-performance Automotive Parts

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Abstract

Application of the hot stamping method is expanding as a method of forming high-strength parts suitable for weight saving of automotive parts. At present, hot-stamped parts using a steel strength of 1500 MPa are in general use, and development of stronger and more highly functional parts are desired. Since a decline in productivity by the heating and cooling process is also a problem in hot stamping, interest in techniques for high productivity adapted to complicated thermal processes is rising. Therefore, experimental results of hot stamping by a partially heated tool as one of the tailored property methods and of hot stamping with the direct water quench system for high productivity with a short quench time are presented. Furthermore, an example of the phase transformation CAE method developed for design and estimation of high-performance automotive parts is used as reference.

1. Introduction

Hot stamping technology can achieve both high strength and shape fixability of steel parts at the same time. This technology has been increasingly used as a means to reduce the weight of automotive parts since around 2000. **Figure 1** illustrates an outline of the hot stamping process. Generally, to make a steel sheet stronger through quenching, it is heated in a heating furnace above the austenitization temperature (Ac3) and it is then transferred to a press machine. The steel sheet is stamped before the start of quenching. Then, it is rapidly cooled by transferring the heat to a tool.[1] Currently, mainly 1500-MPa steel sheets for hot stamping are widely used, and the application of stronger 1800-MPa steel sheets to actual automotive parts has been promoted.[2] With the development of forming technologies for high-strength steel sheets, the strength of hot-stamped parts may also be further enhanced in hot stamping in the future.

However, the performance of automotive parts is not determined only by the strength of materials. Technologies for the design of parts structure based on the performance required have also been advancing. A typical example is the application of tailor-welded blanks in cold forming. This enables high-performance parts to be formed by the combination of different materials and different thicknesses. Hot stamping processes have flexibility of heat treatment in the heating and cooling processes. Therefore, certain technologies for manufacturing parts consisting of some sections with different strengths by various heat treatments have been proposed. A group of these technologies called tailored property methods includes combinations with the application of different materials and different thicknesses.[3]

Meanwhile, the productivity of hot stamping is lower than that of cold stamping because of thermal processes that restrict the heating time, transfer time, and cooling time. As a solution to this problem, reduction of cooling time in the stamping process used to be generally adopted. However, in the tailored property methods, the cooling speed of some sections is lower than in the common hot stamping method. Therefore, productivity is still a fundamental

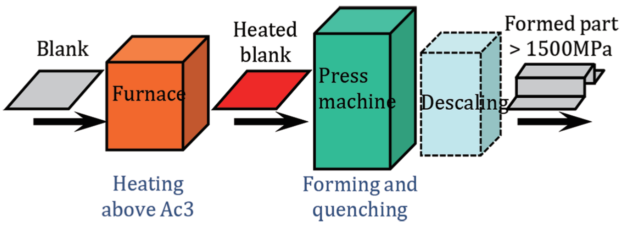

Fig. 1 Outline of hot stamping process

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problem. In addition, problems in mass production may need to be solved, for example, accuracy of the shape of parts, which is influenced by temperature distribution and material properties after stamping.

As described above, in order to enhance the functionality of hot-stamped parts mainly by the tailored property methods in the future, technologies for improving productivity and shape accuracy may be important. Regarding improvement of the functionality in hot stamping, this paper describes the results of a forming test using a partially heated die, which is one of the tailored property methods. This paper also describes the results of another forming test by direct water quenching on improvement of productivity. In addition, this paper introduces case studies of the phase transformation CAE method that was developed to estimate the final shape and functions when these technologies are applied to actual parts.

2. Trial for Higher Functionality (Tailored Property Methods)

2.1 Test procedure

Among various tailored property methods to improve the functionality of hot-stamped parts, the method of providing strength differences only by heat treatment using partially heated dies was selected as a subject of the test and the effects were examined. **Figure 2** illustrates the test equipment. The test equipment consists of a press machine, heated die (upper punch), and heater control unit. The test die for forming hat-shaped parts was 80 mm wide, 60 mm high, and 700 mm long. The upper punch had cartridge heaters and thermocouples in its cross section. Insulators were provided between the three blocks divided in the longitudinal direction of the punch to enable partial heating of each block. The wires for controlling the heater and other parts were connected to the control unit through the rearside of the die. As the material of the die, SKD61, which is generally used for hot stamping tools, was used.

As the test material, a 1500-MPa galvanized sheet for hot stamping with a thickness of 1.6 mm was used. The blank was 226 mm wide and 700 mm long such that the flange width after forming was 15 mm.

As temperature conditions for partial heating, to increase the quantity of retained austenite during quenching to form a softened section, the die in the center block was heated to 280°C before forming and the blank was held within the tool for 30 seconds. In addition, to compare the shape and hardness of parts, some trials were performed by the usual hot stamping method in which the die was not heated and the blank was held for 15 seconds. The temperature of the die during the test was measured with the thermocouples installed in the die. The temperatures of the surface of the die and formed parts were measured with a thermographic camera installed at the side of the press machine.

2.2 Test results

The blank was heated to 950°C in a heating furnace and transferred to the press machine. Then, it was stamped at approximately 700°C and held in the partially heated die. **Figure 3** shows the temperature distribution on the formed part immediately after being released from the die. The vertical wall of the heated die section is approximately 200 to 250°C and the temperature condition is clearly different from that of the non-heated die section.

Figure 4 shows the hardness profile at the center of the vertical wall in the longitudinal direction. When the die was not heated, the hardness was 450 HV, which is the general hardness in hot stamping of 1500-MPa materials, almost evenly. On the other hand, when the part was held in the heated die in the center block, the hardness at the center was approximately 350 HV, showing clear characteristic differences by holding the part at a high temperature. The hardness transition range at the boundary between the heated and non-heated sections is approximately 50 mm from the boundary toward the non-heated block.

The shape of the formed parts was measured to compare differences from the design shape. **Figure 5** shows the results. The upper row (a) shows the results for the part that was quenched in the non-heated tool (held in the die for 15 seconds). The lower row (b) shows the results for the part that was held for 30 seconds in the partially heated tool. The figure shows the results for the plane sur-

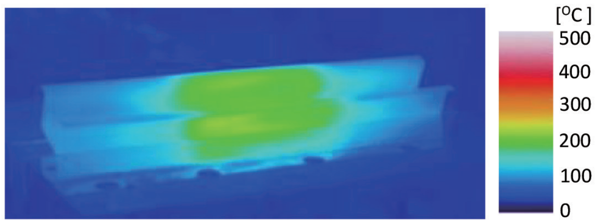

Fig. 3 Temperature distribution after holding

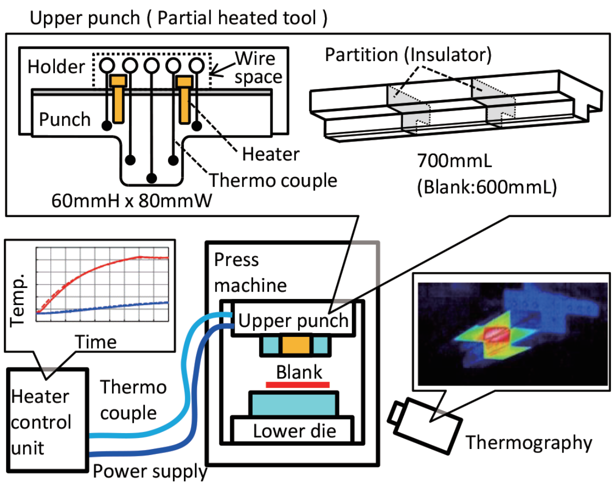

Fig. 2 Partial heating tool for tailored property parts

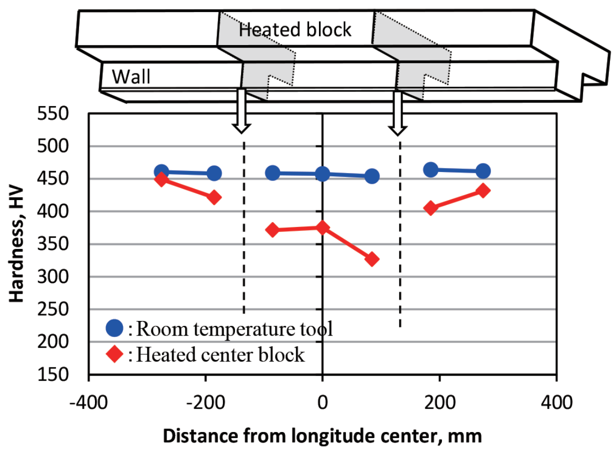

Fig. 4 Hardness profile on the wall of parts

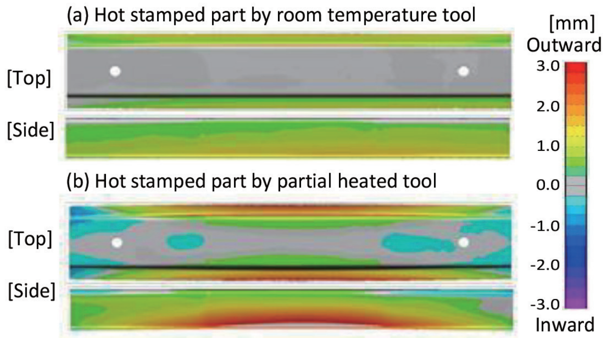

Fig. 5 Difference between formed and designed shape

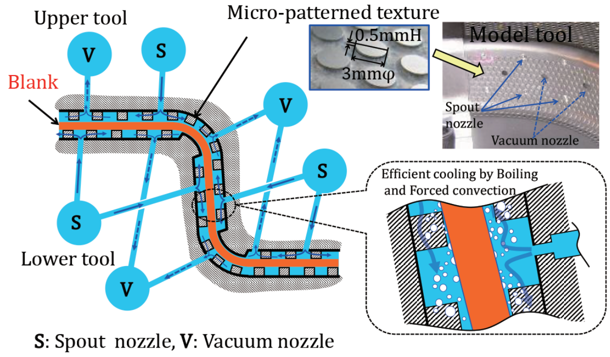

Fig. 6 Outline of direct water quench system

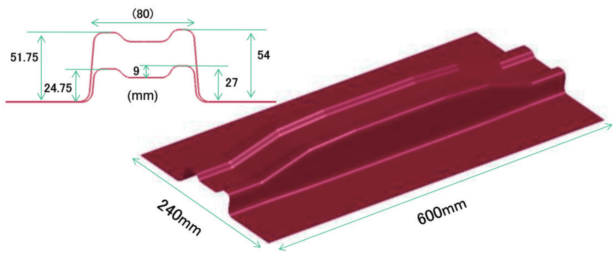

Fig. 7 Direct water quench tool for a model part with actual design elements

faces (top plate and flange side) and the side (vertical wall surface) for each type of part. When the die was not heated, errors in the design shape were roughly within 0 to 0.5 mm. On the other hand, when the die was heated, the center of the vertical wall was swollen. In the lower section of the wall that was the most swollen, in particular, the error was approximately 3 mm. In addition, both ends of the top plate and flange sagged. From these results, to secure the accuracy of part shape with a method in which the temperature histories partially vary, it may be essential to establish technologies for estimating changes in shape due to temperature distribution and cooling histories as well as technologies for designing the structure of parts and dies.

3. Evaluation of High-productivity Technologies (Direct Water Quenching)

3.1 Direct water quenching system

In-die quenching, which is characteristic of the hot stamping method, depends on the contact heat transfer between the surface of a hot-formed part and the surface of the die whose interior is water-cooled. However, in automotive parts consisting of complicated planes, contact is unstable because there are various gaps between the die and the part due to the influence of the thickness distribution in a part and varying accuracy of fabricated dies. At a section with a definite gap, the air space works to insulate heat, which reduces the cooling speed as compared with a section with good contact. Therefore, the quenching time becomes longer, which increases the time of the stamping process. To solve this problem, the direct water quenching method conceived as a cooling method using heat transfer by coolant, in addition to the contact heat transfer method, is introduced. In the direct water quenching method, cooling water is ejected directly from the die to cool a formed part.[4)]

Figure 6 illustrates the die structure that is characteristic of the method. The figure shows the point at which a hot blank is put between the upper and the lower tools. The prime characteristic is that the contact surfaces of the die have projections and depressions called a micro-patterned (MP) texture, and even when the die is closed, a passage for the coolant is secured. In addition, spout nozzles that send cooling water from the inside of the die to the MP surfaces and vacuum nozzles that release steam generated by water cooling and excess cooling water from the MP surfaces are provided in an appropriate way, thus forming a cooling water network that covers most of the surface of the part.

As the cooling performance, when a 1.4-mm-thick steel sheet is cooled, it takes approximately 10 seconds to complete quenching (below 200°C) in conventional die cooling. On the other hand, in direct water quenching, it takes only 2.5 seconds to cool the sheet to the normal temperature (near the water temperature).[5)] This high-productivity hot stamping method has been applied to mass-produced parts. However, this method has some restrictions: restrictions in the range in which the MP can be processed due to the shape of the planes of the dies and restrictions in the processing locations of the spout and vacuum nozzles due to the die structure. Therefore, rapid cooling is possible, but temperature history and temperature distribution are not always even. This may affect the shape accuracy,[6)] so, in order to make the temperature distribution even, adjustments are required in some cases to allow the cooling performance to match that of the low cooling rate.

For parts with different thicknesses and different strengths, the cooling speed needs to be adjusted in a more complicated way. To examine cooling design conditions appropriate for such parts and check the appropriate cooling characteristics and shape control, a direct water quenching die was fabricated for thick materials for which cooling in a short period of time was difficult.

3.2 Test procedure

Figure 7 illustrates the shape of a die for a model part. The die has an asymmetric cross section in the shape of an “M” and a section where the height and width gradually change as is typical of the cross-sectional shape of bumpers and pillars. As the MP on the cooling surface, circular contact surfaces of 3 mm in diameter were left and 0.5-mm-deep depressions were etched. For the raised ridgeline sections, no MP was applied in order to avoid wear and galling. Spout nozzles and vacuum nozzles were provided on the surface of the MP in a grid-like fashion at intervals of 30 mm where the spout and vacuum nozzles were shifted by half the interval. The test material was a 2.6-mm-thick 1500-MPa galvanized sheet for hot stamping. The rectangular blank was 235 mm wide and 495 mm long. The blank was heated in a furnace whose temperature was 950°C for 5 minutes. The temperature at the start of forming was approximately 750°C, the forming speed was 40 mm/s, and the forming load was

3000 kN. Coolant was ejected when the blank arrived at the bottom end of the forming stroke and the flow was maintained when the blank was held at the bottom end of the forming stroke.

3.3 Test results

3.3.1 Temperature distribution and cooling performance

Figure 8 shows temperature distribution at the time of release from the tools under various test conditions. In die quenching with a holding time of 5 seconds, a wide hot area of approximately 300°C remains on the top plate. In direct water quenching with the same holding time, the temperature satisfies the general temperature of hot stamping (below 200°C). In single-sided direct water quenching (lower side) shown in the bottommost row of the figure, hot areas remain at the ridgelines of the letter “M.” Only spout nozzles are provided in these sections due to the die structure and thereby no vacuum nozzles are provided in the vicinity, so it is possible that the hot areas remain due to the residual coolant. The flow rates affect the spread of the initial cooled areas from the temperature distribution in double-sided direct water quenching with a holding time of 2 seconds. The calculated time during which the coolant fills the MP passage after the spout is 0.05 seconds. However, it may take time for the cooled area to expand because steam may stay in the high-temperature area.

Figure 9 shows the relationship between the temperatures and holding time at the maximum- and minimum-temperature sections at the time of release. Figure 9 (a) compares die quenching and double-sided direct water quenching. Although the high-temperature range in direct water quenching overlaps with the low-temperature range in die quenching in some temperature ranges, the temperature of the high-temperature section decreases to below 200°C and the temperature of the low-temperature section decreases to room temperature within 3 seconds for a test sheet with a thickness of 2.6 mm. These results show the effect of rapid cooling by direct water quenching. Figure 9 (b) compares the flow rate conditions in double-sided direct water quenching. In the low-temperature sections, the histories are similar regardless of the flow rate. In the high-temperature sections, the cooling start is delayed when the flow rate is lower. These results show that local heat transfer in direct water quenching is affected by the arrival range of the cooling water and the cooling time after arrival. As the arrival range of cooling water correlates with the flow rate of the spout, the average temperature of specific areas on the surface of a part can be estimated by simulation in which the flow rate of the spout is linked with the heat transfer coefficient.[6] However, these results suggest that, when thick sheets are cooled where time differences in arrival of cooling water clearly occur, transitional diffusion of cooling water needs to be taken into account in simulation.

3.3.2 Shape accuracy

Figure 10 shows the measurement results of the shape of formed parts held for 5 seconds in each cooling method. For the die quenching in the upper row in the figure and the double-sided direct water quenching in the second and third rows from the top, although a

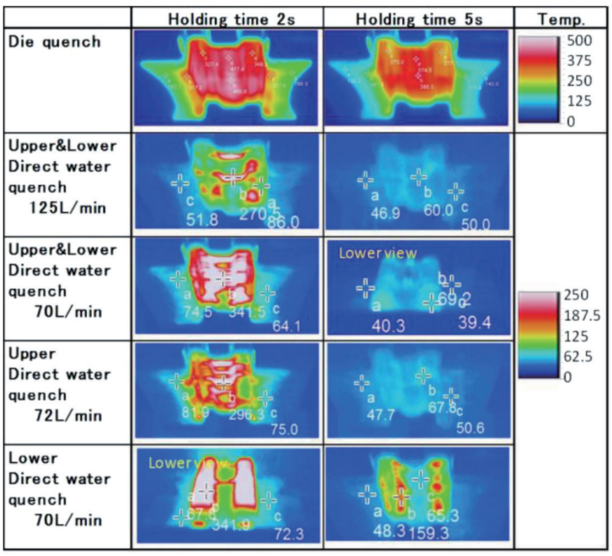

Fig. 8 Temperature distribution of formed parts with direct water quench tool

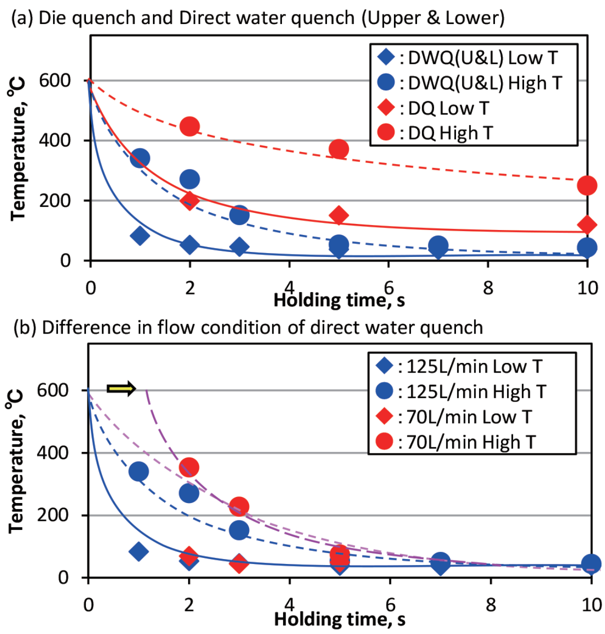

Fig. 9 Relationship between holding time and max. and min. temperature of parts

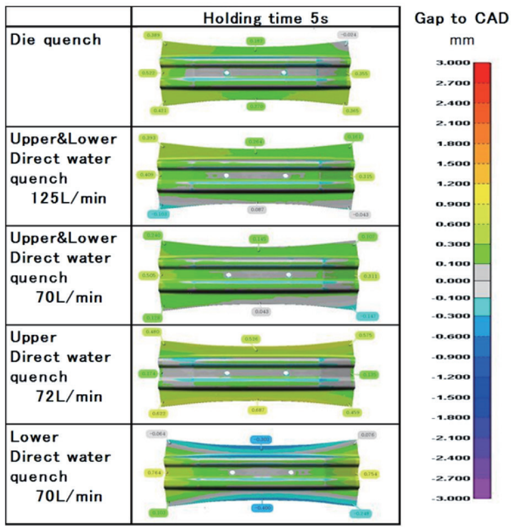

Fig. 10 Result of trial on shape change by spout system

bending trend is seen at the top plates, the errors are within ±0.5 mm from the CAD shape. For the single-sided direct water quenching (upper side) in the fourth row from the top, the flange clearly tends to bend upwards. For the single-sided direct water quenching (lower side) in the bottommost row, the flange clearly tends to sag. The errors increase to approximately ±0.5 to 1 mm deviation from the CAD shape. The starting points of these shape changes are on the ridgelines on the cross sections of the parts and no bends are seen on the wall sections. Therefore, differences in the temperature histories between the ridgeline section and the flat plate section originated in the MP areas that vary between the upper and the lower faces may affect the shape. Therefore, double-sided direct water quenching is superior from the viewpoint of shape accuracy, because the method reduces differences in temperature histories.

In the future, CAE technologies for designing the shape of thick parts in rapid cooling, for estimating the shape of a part with varying thicknesses after partial direct water quenching, and for designing dies for those complicated parts are potentially required. In those CAE technologies, thermal contraction and phase transformation behavior due to differences in temperature histories should be considered. The same technologies can also be used to estimate the shape of parts manufactured by the aforementioned tailored property methods.

4. Study of the Application of Phase Transformation CAE Techniques

4.1 Hot stamping method and CAE technologies

In the hot stamping method in which parts are processed at high temperature, forming loads are low. However, the formability is not always good because of the influence of the temperature distribution of parts due to contact with tools during forming.[7] Therefore, a forming CAE technique in which heat transfer is coupled with forming has been studied and such functions for hot stamping forming simulation have been implemented for general-purpose analysis solvers.[8] In addition, regarding the performance after quenching, general-purpose analysis tools for estimating hardness based on a CCT diagram and calculation of phase transformation have been used in practice.[9]

However, estimation of shape accuracy has not been extensively studied in the hot stamping method that has spread because of its good shape fixability. In actual hot-stamped parts, shape accuracy varies due to differences in the temperature histories from the forming process to the cooling process.[6] Moreover, the aforementioned tailored property methods and direct water quenching method produce extreme differences in temperature histories. Therefore, CAE techniques considering phase transformation need to be established to estimate shape accuracy. For that purpose, the authors obtained data on detailed material properties in phase transformation through experiments and have developed an original analysis technique with a material model that shows such properties accurately. Study to estimate shape accuracy after hot forming has been conducted using this technique.[10]

Figure 11 shows an outline of the hot stamping phase transformation CAE. In conventional hot forming CAE, only properties of strain and stress in the austenite phase and temperature were coupled in calculation. To add coupling with metallographic structural changes to conventional CAE and consider phase transformation behavior with high accuracy, Nippon Steel Corporation developed a subroutine of structural material "umat" and a subroutine of thermophysical property "thumat". These are implemented for the general-purpose solver LS-DYNA. In "umat", density, volume changes, and transformation plasticity strain as a result of phase transformation are considered in order to simulate the stress and strain of the materials. In "thumat", changes in the heat generation and thermophysical properties as a result of phase transformation are considered based on the thermophysical property of each phase.

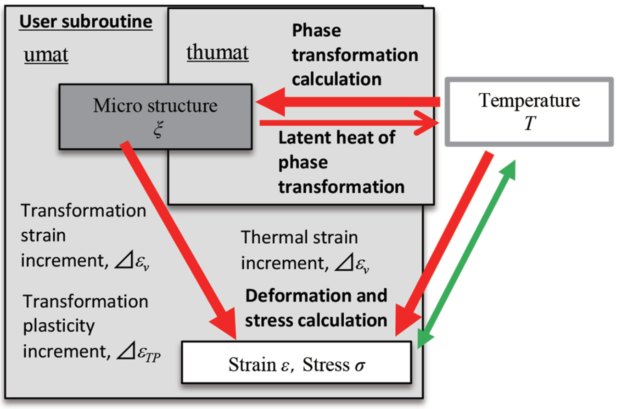

Fig. 11 Outline of phase transformation CAE

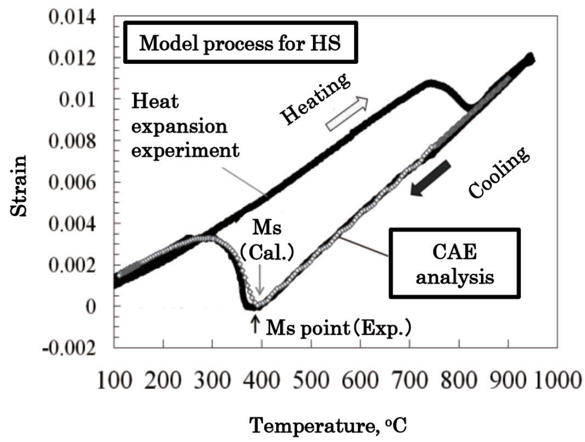

Fig. 12 Comparison of temperature-strain relation of experiment and analysis

Figure 12 shows example results of the study of the accuracy of phase transformation estimation. Measured temperature changes in experiments were given as thermal boundary conditions and changes in the strain due to the temperature changes were simulated. Changes of strain and Ms temperature almost match the experimental values. It shows that the new CAE technique can accurately estimate phase transformation behavior in hot stamping.

4.2 Trial for part analysis

It has been confirmed that actual phenomena in hot stamping can be simulated through the study of estimation of the shape for U-bending tests using the aforementioned phase transformation simulation method.[10] The thermal histories of hot-stamped parts are complicated as a result of their higher functionality. Therefore, the simulation was applied to such actual parts and problems of accuracy of calculation and its application were extracted.

As the subject of simulation, a hat-shaped part processed with a partially heated die by the tailored property method mentioned in Section 2 was selected. **Figure 13** shows the simulation model. The

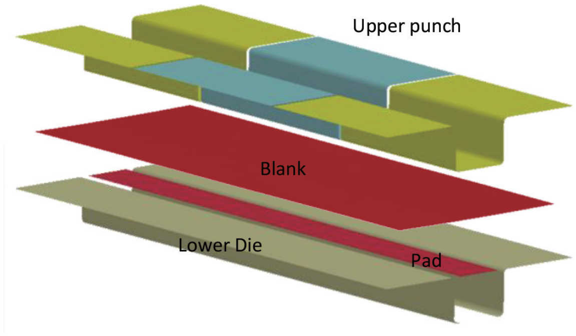

Fig. 13 Simulation model for tailored property HS

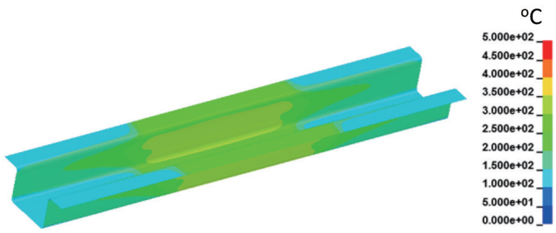

Fig. 14 Temperature distribution after holding with quenching and heating by CAE

model consists of a divided upper tool (punch), rectangular blank, pad, and lower tool (die). A general model for hot stamping forming simulation where deformable shell elements were applied to the blank and rigid shell elements were applied the tool was employed.

For the temperature conditions, based on the temperatures actually measured in the test, the initial temperature of the blank was set to 700°C, the temperature of the heated section at the center of the punch was fixed at 330°C, the initial temperature of the non-heated sections on both sides was set to 120°C, and that of the lower die was set to 60°C. The simulation was performed in the three processes of forming, holding and air cooling. In the forming process, the forming speed was set to 40 mm/s and the forming time was 1.5 seconds. In the process of holding, the die was closed and held for 30 seconds. Then, the blank was cooled by air to 20°C. Simulation of the air cooling process was performed considering phase transformation and the final shape was obtained by springback calculation without considering temperature.

Figure 14 shows simulated temperature distribution after the holding. By the heat transfer settings based on knowledge from conventional forming analysis, the temperature distribution almost matches the test results in Fig. 3. **Figure 15** shows the hardness profile of the vertical wall by the subroutine for phase transfer. It has been confirmed that the simulation results for hardness of the non-heated and heated sections of the punch show good agreement with the experiment results. However, temperature and hardness changes near the boundary between the die blocks are complicated, so application is under study. In simulation of thermal boundaries like this case, it seems that the balance between tools, as well as the heat transfer within a blank and the heat loss from the tool system, has a large influence. The setting of heat transfer characteristics and heat transfer boundary conditions in CAE may need to be further improved.

As mentioned in Section 2, when tailored property methods are applied, the shape accuracy varies due to thermal strain and other

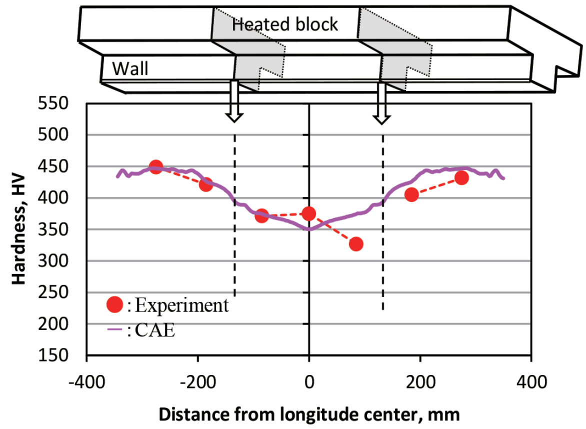

Fig. 15 Comparison of hardness on wall portion between experiment and CAE

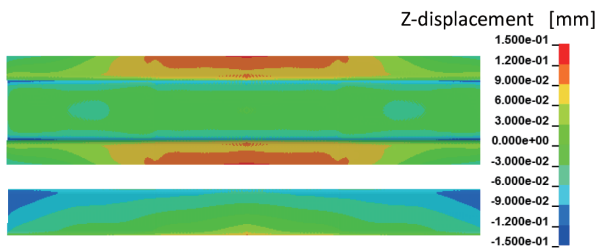

Fig. 16 Example of simulation result of final shape

factors. This phase transformation CAE technique can potentially be used effectively to estimate such accuracy. **Figure 16** shows the simulation results of the final shape. It shows the characteristics (opening and closing in the cross section and bends in the top plate and flange) well. Through this CAE application trial, it has been found that, to simulate deformation accurately, it is essential to consider the balance between the influence of phase transformation from the forming process to the holding process and the influence of thermal contraction after phase transformation is complete. The temperature of dies in the scale of actual parts, detailed temperature distribution on various sections of a part, and differences in temperature histories are not well understood. Therefore, improvement of the method of reproducing accurate temperature histories by optimizing these simulation conditions will be promoted in the future.

5. Conclusions

To reduce the weight of automobiles and secure safety in the future, the functions of hot-stamped parts must be enhanced and thereby the application of tailored property methods and other application technologies will likely further spread. In addition, high-productivity technologies need to be developed to allow such methods to be widely applied to mass production, so this development needs to be promoted based on various application patterns. For phase transformation CAE technology that supports such development and design, it is probable that the material model and components of simulation techniques are almost complete. However, to reproduce phenomena in complicated hot stamping processes, technologies for application and evaluation need to be established by obtaining more practical data.

The authors would like to establish technologies for analyzing, evaluating, designing, and prototyping hot-stamped parts with higher functionality speedily in the future to flexibly respond to the advancement of automobile bodies.

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