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Improvement of Crashworthiness in Hat-shaped Components Made of High-strength Steel Sheet

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Abstract

In order to realize the improvement of collision safety and weight reduction of automobiles, the application of high strength steel sheets to car bodies is expanding. However, to exhibit performance such as crashworthiness of a component using a high strength steel sheet, it is necessary to suppress weld fracture. In this report, we conducted resistance-spotwelding with post heat for tempering, arc-spot welding that can control the characteristics of weld metal by using welding material, and a combination of spot welding and other welding methods to improve welding strength. As a result, these means are effective for preventing the fracture of the weld, and showed a higher crashworthiness as compared with a component welded under a conventional spot-welding condition. That is, by improving the reliability of the weld, high performance of a component using the high strength steel sheet was demonstrated.

1. Introduction

In order to meet both the strengthened requirements of automotive collision safety regulations and needs to reduce weight for the purpose of fuel consumption improvement, the application of high strength steel sheets to vehicle bodies is increasing.^{1, 2)} Since high strength steel sheets used for a vehicle body are press-formed to become a product (component), it is necessary to have excellent workability in addition to strength. Strength and workability contradict each other. In order to balance between the two properties, the amounts of additives such as C, Mn, and Si should be adjusted, while controlling the steel structure during the production process. At the same time, the use of hot-stamped steel is growing as well as for the purpose of obtaining high strength steel that has higher shape fixability and requires smaller force applied when pressing. The addition of C, Mn, etc., to such hot-stamped steel is also necessary to secure strength and hardenability. However, the addition of alloy elements adversely affects the weldability. For example, the lowered weldability may weaken a joint that is assembled by resistance spot welding, the most popular welding method in the field of vehicle body assembly,^{3,4)} causing a problem. Welded areas that are easily broken mean unstable collision safety performance of the vehicle

body. For this reason, various measures to improve weld strength have been proposed to date.

This paper describes the results of the examination on methods to prevent a welded area from fracturing by designing the welding process in bending tests of modelled components made from high strength steel sheets. Specifically, the fracturing prevention effect for welded areas of the full use of arc spot welding, ^{5, 6)} an improvement of the resistance spot welding current inputting pattern (for tempering after applying currents in a full-fledged manner), and the combined use between spot welding and other welding methods. Through such a reliability improvement of welds, we investigated the possibility of high strength steel components exerting high crashworthiness.

2. Crashworthiness Improvement through the Use of Arc Spot Welding and Designed Spot Welding Current Inputting Pattern

2.1 Test method

In the test of this section, we used a 1.4 mm-thick S45C steel sheet. (Since medium carbon steel like this is advantageous in terms of environmental load and costs, the use for automotive parts is ex-

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pected in the future.) **Table 1** shows the chemical composition. The tested steel contains carbon at 0.44 mass%. After leaving the specimen at 1193 K in the nitrogen atmosphere furnace for 300 s, it was taken out of the furnace to be immediately hardened with a die. At the same time, it was formed into a hat shape as shown in **Fig. 1**. The length of the component was determined to be 800 mm. Then, it was annealed at 633 K for 12.6 ks so that the strength of the component would be at the level of 1180 MPa. The same heat treatment was performed for a strip specimen.

Next, the strip specimen was placed on the hat shaped specimen aligning the strip specimen with the flange of the hat shaped specimen. The overlapping area was both resistance spot (RS) welded and arc spot (AS) welded. For RS welding, welding conditions were adjusted so that the diameter of the nugget on the face where the two steel sheets overlapped would be $3.0\sqrt{t}$ (where t is the steel sheet thickness; It is 1.4 mm in this case), $4.0\sqrt{t}$, and $5.0\sqrt{t}$. The RS welding pitch was determined to be 40 mm. With the nugget diameter of $5.0\sqrt{t}$, application of currents was started for tempering after the nugget formation to also evaluate the influence of annealing the nugget on the crashworthiness of the component.

For AS welding, a cold metal transfer (CMT) power source was used for the welding machine. In order to obtain stable penetration, a 4 mm-diameter hole was formed before welding at the welding area on the hat shaped specimen flange. The target of the wire when welding was the hole center, using stationary arc. When using a CMT power source, the voltage and currents are automatically determined to obtain the feeding speed of the set weld wire (equivalent to heat input). For welding, a weld wire with a diameter of 1.2 mm and strength class of 490 MP was used. Table 2 shows the chemical composition of the weld wire. As shown in the table, a weld wire with lower strength than the strength of the specimens used in the test was selected. Mixing the specimen steel and the weld wire constituents during welding can lower the hardness of the weld metal. We thought that the reduction of hardness would improve the toughness of the weld metal, resulting in an improvement of the joint strength. During AS welding, the diameter of the weld metal was changed by varying the weld wire feeding speed. The diameter of

 Table 1 Mechanical properties and chemical compositions of the steel used

Thickness	Grade	С	Si	Mn	
(mm)	(MPa)	(mass%)			
1.4	1180	0.44	0.21	0.78	



Fig. 1 Schematic of the hat-shaped component

the weld metal on the face where the two steel sheets overlapped was $1.7\sqrt{t}$, $5.3\sqrt{t}$, and $5.8\sqrt{t}$. The weld pitch was determined to be 40 mm, which was the same as that of spot welding.

In order to inspect the shape of the weld metal, the cross-section of the center of the welded area was mirror polished, and was observed after being corroded using a picric acid solution. In addition, the Vickers hardness distribution at each welded area was measured for each welding method: for spot welding, the distribution was measured when the nugget diameter was $5.0\sqrt{t}$, and under the conditions under which currents were input for tempering at the nugget diameter $5.0\sqrt{t}$; for AS welding, the measurement was conducted at the weld metal diameter of $5.8\sqrt{t}$. Hardness was measured with a measurement load of 9.8 N and measurement pitch of 0.2 mm at the position 0.2 mm away from the surface of the upper steel sheet overlapping the lower sheet.

A dynamic three-point bending was conducted for the component manufactured. **Figure 2** shows a schematic view of the setup of the test. The component was placed on two 30 mm-radius supporting rolls arranged 700 mm apart. Then the component was crashed into a 50 mm-radius impactor installed above the component at the speed of 2 m/s. The load was measured with a load cell installed on the impactor. In this test, the component was arranged with the strip specimen placed on top of the hat shaped specimen to crash the strip specimen into the impactor. The reason for this is that the crash of the strip specimen into the impactor would cause higher load to act on the weld than the crash of the hat shaped specimen, thus clarifying the weld quality.

2.2 Test results and consideration

2.2.1 Cross-sectional observation results of welded area and hardness measurement results

Figure 3(a) shows an image of the cross-section of the spotwelded area with the $5.0\sqrt{t}$ - diameter nugget. The RS welded area was subject to the pressurization and heat input by electrode during welding, forming a concave cross-section. Figure 3(b)(c) show images of the structure of the base metal and weld metal (nugget). Tempered martensite was observed in the base metal. Such a structure was formed as a result of the above-described heat treatment

Table 2 Mechanical properties and chemical compositions of the welding consumable used

Diameter	Grade	С	Si	Mn
(mm)	(MPa)	(mass%)		
1.2	490	0.07	0.7	1.4
Unit: mm		R50	Sec	tion A–A
			s	$A \rightarrow$
R30		700		A → I 30
		800		

Fig. 2 Setup for three-point bending test



(a) Cross-section of resistance spot weld



(b) Microstructure of base metal



(c) Microstructure of weld metal

Fig. 3 Cross-section and microstructure of resistance-spot-weld

consisting of quenching and tempering. Although martensite was formed in the weld metal and adjacent heat affected zone (HAZ), almost no carbide was observed. This is because cooling speed at the welded area was high enough to prevent auto-tempering after quenching (tempering that occurs in the cooling process after quenching).

Figure 4 shows images of the cross-section and structure of the AS welded area with the weld metal diameter of $5.3\sqrt{t}$. The AS welding constituted penetration welding unlike the RS welding, forming an excess metal on the front and back faces of the welded area. The main phase of the weld metal at the AS welded area was ferrite, with most of the remaining part occupied by pearlite. In the HAZ, ferrite and pearlite were observed in addition to martensite. The reason for structures differing in different areas in the AS welded area is mixing (dilution) of constituents of the base metal and the weld wire.

In addition, the HAZ structures at the RS welded area and AS welded area were different. We consider that this was caused by the difference of the cooling speed (slower in the AS welding) after welding.

Figure 5 shows a chart plotting the comparison result of Vickers hardness distribution at the welded area between the two welding methods. The nugget Vickers hardness of the RS welded area reached HV 700. This value is equivalent to the martensite hardness estimated from the amount of carbon, and agrees with the structure observation result described above. At the RS welded area where current inputting for tempering was performed after the nugget formation, the hardness of the nugget edge and adjacent HAZ was reduced to HV 400. The reason for the softening was that martensite formed in these areas was tempered by current inputting for tempering.



(a) Cross-section of arc spot weld



(b) Microstructure of weld metal



(c) Microstructure of HAZ

Fig. 4 Cross-section and microstructure of arc-spot-weld



The hardness of the weld metal at the AS welded area with the weld metal diameter of $5.8\sqrt{t}$ was HV 250, which was lower than the hardness obtained from the RS welded area. Similarly, the highest hardness of the HAZ was lower in the case of the AS welded area. As described above, this is because a comparatively soft structure was formed. At the area apart from the AS welded area and $5\sqrt{t}$ RS welded area, the so-called HAZ softened area in which the base metal was further tempered and softened was found. The width of this softened area was narrower than the RS welded area. The rea-

son for this is that the input heat was lower in the RS welding, narrowing the region that reached the temperature range that would cause tempering (significant softening occurs in the range from 773 to 1000 K).

2.2.2 Three-point bending test results

2.2.2.1 Resistance spot-welded (RS) component

Figure 6 shows a chart plotting the relationship between displacement (component push-in quantity) of the impactor and the load obtained from the three-point bending test for the RS welded component. It shows that as the nugget diameter increased, the load level gradually increased, and that the load under the $5.0\sqrt{t}$ condition conducting current inputting for tempering was higher than the load under other conditions. As described later, the estimated causes for these results are: (1) The number of welded areas broken during the three-point bending test decreased due to an increase of the nugget diameter and the current inputting for tempering; (2) As a result, high rigidity of the component was maintained even if displacement was 20 mm or more.

2.2.2.2 Arc spot (AS) welded component

Figure 7 shows a chart plotting the relationship between the displacement and the load obtained from the three-point bending test of the AS welded component. The load level increased along with the increase in the weld metal diameter. The reason for this is that similar to the case of the RS welded component, the number of broken welded areas decreased during the bending test along with the increase in the weld metal diameter, retaining the component rigidity.

Next, the crashworthiness was compared between the RS welded component and AS weld component. From all the test conditions, we selected some conditions with the most excellent crashworthiness for comparison. Specifically, for the RS welding, we selected the conditions of the nugget diameter of $5.0\sqrt{t}$ and current inputting for tempering when the diameter was $5.0\sqrt{t}$; For the AS welding, we selected the condition of weld metal diameter of $5.8\sqrt{t}$. Figure 8 shows a chart plotting the relationship between the displacement and the load under the selected conditions. The figure explains that the load on the AS welded component was higher in the entire displacement range than the load on the RS welded component with the nugget diameter of $5.0\sqrt{t}$. It also explains that the load on the AS welded component was higher by the displacement range of 25 mm or less than the load on the RS welded component current inputting for tempering when the diameter was $5.0\sqrt{t}$.



Fig. 6 Load-displacement curves obtained for the three-point bending test for spot-welded components

The absorbed energy (AE) was defined using the load integrated by the displacement in the range from 0 to 100 mm. **Figure 9** shows a bar chart comparing the AE (average of the two samples) under all conditions. The figure shows that the AE of both welded components increased along with the increase in the weld diameter. Also, the AE of the RS welded component with the nugget diameter of $5.0\sqrt{t}$ improved by 26% as a result of current inputting for tempering. When compared under the conditions with the weld metal diameter of $5.0\sqrt{t}$, the AE of the AS welded component was higher by 25% than the value of the RS welded component that did not undergo the current inputting for tempering when the weld metal diameter was $5.0\sqrt{t}$. Assuming that the AE had linear relations with the weld metal diameter, the AE of the AS weld component with the weld metal diameter of $5.0\sqrt{t}$ was obtained using the AE when the weld metal diameter was $1.7\sqrt{t}$ and $5.3\sqrt{t}$.

2.2.2.3 Crushing behavior of the components

Figure 10 shows images of the appearance of components under several conditions taken after the three-point bending tests. In the case of the RS welded component with the nugget diameter of $3.0\sqrt{t}$, all welds were broken and separated during the bending tests. When the nugget diameter was increased to $5.0\sqrt{t}$, the number of broken welded areas decreased. When the current inputting



Fig. 7 Load-displacement curves obtained for the three-point bending test for arc-spot-welded components



Fig. 8 Comparison of load-displacement curves obtained in the threepoint bending test between the resistance-spot-welded- and arcspot-welded-components

for tempering was additionally performed, the fracturing at welds was suppressed. When the weld metal diameter of the AS welded component was grown to $5.8\sqrt{t}$, the fracturing of welds was suppressed as well.

Figure 11 shows a chart that compares the number of broken welded areas (average of the two samples) between the RS welding and AS welding under all conditions in the three-point bending test. Welded areas that were separated into two parts were counted as the "broken welded areas." The figure shows that the number of broken welds decreased in the AS welded component along with the increase of the weld metal diameter. For the AS welding, even with the weld metal diameter of $1.7\sqrt{t}$, the number of broken welded areas was 6. In view of the fact that all welds of the RS welded component with the nugget diameter of $3.0\sqrt{t}$ were broken, the AS welded areas were better in strength and (or) toughness than the RS welded areas. This tendency was reinforced by the result in which the cross tensile strength of the AS welded joint was higher than that of the RS welded joint.⁵

Figure 12 shows images of the crushing behavior of the components taken while undergoing the three-point bending tests. From all conditions, the images of the RS welded areas are those under the conditions of the nugget diameter of $3.0\sqrt{t}$, $5.0\sqrt{t}$, and the current



Fig. 9 Comparison of average absorbed energy between resistancespot-welded- and arc-spot-welded-components



Fig. 10 Appearance of the components after the three-point bending tests

inputting for tempering with the nugget diameter of $5.0\sqrt{t}$. The images of the AS welded areas are those under the condition of the weld metal diameter of $5.8\sqrt{t}$. In the images, the longitudinal center of the component, i.e., the parts that crashed into the impactor are enlarged. For the RS welded component with the nugget diameter of $3.0\sqrt{t}$, the welded area was broken when the displacement was approx. 10 mm. At the same time, "distortion" (deformation involving falling inward) was observed on the wall of the hat shaped component. These fractures of welded areas were likely to have been caused by an increase in the load acting on the welded areas along with the deformation of the hat shaped component. The load level is considered to have decreased as shown in Fig. 6 as a result of the acceleration in the deformation of the component vertical wall after the displacement exceeded 10 mm.

When the nugget diameter was $5.0\sqrt{t}$, no cross-section collapse was observed in the hat shaped component with displacement of 15 mm or less. Fracturing of a welded area was found when the displacement was 20 mm. When the displacement was 40 mm, a collapse was observed in the hat shaped component cross-section. It appears that this cross-section collapse caused the decrease in the load on the component after the displacement reached 20 mm shown in Fig. 6.

Under the condition in which currents were input for tempering when the nugget diameter was $5.0\sqrt{t}$, fracturing of the weld did not



Fig. 11 Number of fractured welds of each component during the three-point bending test



Fig. 12 Crash behavior around the center of the components during the three-point bending test

occur during the test. The hat shaped component and the rectangle steel sheet were integrally deformed, while the two components suppressed the deformation of each other, keeping the rigidity of the components high. This is likely to be the reason for the load kept high during the bending test as shown in Fig. 6.

Looking at the images of the crushing behavior of the AS welded component with the weld metal diameter of $5.8\sqrt{t}$ in Fig. 12, the welded area under this condition was not broken during the bending test. The images show that when the displacement was 10 mm, the excess metal of the weld metal located 20 mm to the left from the component center crashed into the impactor in the position indicated with a broken line rectangle. In other words, the impactor contacted at least two locations: the excess metal and component center. We think that the area that bore the stress increased in the component through such a contact status with the impactor different from the contact statuses under other conditions, suppressing the initial cross-section collapse.

As shown in Fig. 8, in the vicinity (15 mm) of the displacement, the load of the AS welded component with the weld metal diameter of $5.8\sqrt{t}$ was higher than the value of the RS welded component that underwent the current inputting for tempering with the nugget diameter of $5.0\sqrt{t}$. It is likely that this high load on the AS weld component was caused by "the delay in cross-section collapse" of the AS welded component in comparison with the RS welded component. However, as shown in Fig. 8, the loads of these components were generally equivalent to the displacement of 25 mm or more. Therefore, we think that after the collapse of the component rigidity became equivalent).

Figure 13 shows images of the welded area cross-sections of the RS welded component with the nugget diameter of $5.0\sqrt{t}$ and the AS welded component with the weld metal diameter of $5.3\sqrt{t}$ broken in the bending test. In the case of the RS welded component, fracturing at the welded area progressed either in the direction of the interface between the two steel sheets or in the thickness direction. The two fracturing directions were found from the AS welded component as well. Before the cross-section observation, the weld fracture cross-section observation was conducted using a scanning electron microscope (SEM). Figure 13 shows fracture cross-section images as well. At the RS welded area broken at the interface between



Fig. 13 Cross-sections and SEM micrographs of fractured welds during the three-point bending test

two steel sheets, an intergranular fracture surface was observed. Considering the size for each fracture, it appears that the grain boundary of dendrite was exposed on the fracture surface. In the case of the RS welded area broken in the thickness direction, we think that the former austenite grain boundary in the HAZ was exposed on the fracture surface.

Figure 13 shows images of the fracture surface of the AS weld component taken using SEM as well. Even after the welded area was broken at the interface between the two steel sheets, the fracture surface was in the shape of inclined dimples. This implies that the welded area underwent shear fracturing.

Dimples were also observed on the fracture surface of the weld broken in the thickness direction. As described above, an obvious difference was found on the fracture surfaces of the RS welded area and the AS welded area. This fracture surface difference as well indicates that the AS welded area exceeded the RS welded area in terms of toughness. Based on such superiority of the AS welded area, the crashworthiness of the AS weld component is better than that of the RS weld component.

3. Crashworthiness Improvement by Combining Use of Welding Methods

3.1 Welded area fracture prediction using finite element method (FEM) analysis

The previous chapter described the examination of the means for suppressing welded area fracturing for the hat shaped component, by increasing the nugget diameter and performing current inputting for tempering for all welded points in the case of the RS welding, and by replacing the RS welding with the AS welding for all weld-ing points. However, FEM analysis allows for predicting how much load will act on a welded point of the component and whether there is a risk of fracturing. Examining such prediction results makes it possible to selectively take countermeasures only for welding points with considerable risk of fracturing, improving the component manufacture efficiency. The following section shows an example of the use of the fracture prediction software for spot-welded areas (NSafeTM-SPOT) for reinforcing welded areas that required countermeasures using a combination of welding methods, which led to an improvement of crashworthiness.

3.2 Effect of crashworthiness improvement using combined welding methods

The three-point bending test results were analyzed using NSafeTM-SPOT to obtain the load that acted on each welded area and the fracture risk rate caused by the load. The component shape and welding pitch were the same as that shown in Fig. 1. The nugget diameter of all welded points was determined to be $3\sqrt{t}$. The steel strength was at the 1470 MPa level, assuming the strength of 1470 MPa-class hot stamped steel (1.4 mm-thick) with a carbon content of approx. 0.2%. The constraints and boundary conditions for the components were defined such that the test in Fig. 2 was reproduced. The analysis result showed that the welded area in the center of the component crashing with the impactor was predicted to fracture due to shear force. In addition, the fracture was predicted to involve a sharp increase in peel force at the adjacent welded areas, resulting in fracture of the adjacent ones as well. From this result, it is considered that an increase of the nugget diameter would be effective for preventing fracture for welds in the center of the component. This is because an increase in the nugget diameter (joint surface area) is highly effective for improving the shear strength of a welded area. To prevent the fracture of adjacent welds, continuous joining



Fig. 14 Schematic diagram of components with weld-fracture-countermeasures



Fig. 15 Absorbed energy of component with each weld-fracture-countermeasures at 100 mm stroke

was considered to be effective in preventing large peel force from being generated.

Figure 14 shows a schematic view of the specific measures. The measures are: Condition D involving an increase of the nugget diameter in the center of the component (an increase to $6\sqrt{t}$); condition DP involving an increase of the nugget diameter + an increase of welding points; condition DL involving an increase of the nugget diameter + laser beam welding; and condition DB involving an increase of nugget diameter + a structural adhesive. Figure 15 shows a bar chart plotting the verification results of the effects of these measures. The figure shows that the absorption energy with any measure was higher than the absorption energy under the comparative condition ($3\sqrt{t}$ for all) with no measure.

The AE improvement was 7% for D, around 20% for DP and DL, and 30% for DB. This indicates that any combination of an increase of the nugget diameter of the center welded area plus a reinforcement of the adjacent welded area was excellent in the improvement of AE. As shown in **Fig. 16** with images of the appearance of components after the test, D failed to prevent welded area fracture. It is likely that the center welded area and welded areas located on the side external to the center fractured caused by the fracture of an adjacent weld. Under DP, DL, and DB, by almost completely preventing fracturing in the center and neighboring welds where the acting load was high, the fracture of welds located external to them was able to be suppressed, showing high crashworthiness. Furthermore, it is considered that since the deformation restraint effect was



Fig. 16 Appearance of the components with weld-fracture-countermeasures after the three-point bending test

added by surface bonding, the maximum AE was shown under DB.

The examination on the effective countermeasures for weld fracture in high strength steel components using analysis was described above. We consider that such a method is effective for not only the model component described in this paper, but also for vehicle bodies.

4. Conclusion

In order to lighten vehicle body weight and improve collision safety, the practical use of inexpensive medium and high carbon steel also prospective in environmental load reduction is expected, in addition to the high strength steel developed so far. To make these high strength steel sheets exert high performance, highly reliable joining methods capable of suppressing weld fracture need to be proposed, for example, the multi-stage current inputting spot welding, arc spot welding, and the combined use of multiple welding methods to deal with the load at each welded area, as described in this paper. In addition to them, designing the component cross-section structure that reduces the load acting on each welded area can be effective.

Together with the material development, the engineering innovation for used technologies needs to be continuously pursued to meet the needs that are becoming increasingly sophisticated. Our initiatives described here are expected to constitute the foundation that supports the automotive industry.

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