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Arc Welding Technologies for High-strength Steel Sheets for Automotive Chassis Members

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Abstract

This paper examines the latest results of studies on arc welding of high-strength steel sheets to improve the fatigue strength and corrosion resistance of automotive chassis parts. First, the effects of weld metal hardness and bead shape on the fatigue strength of weld joints are described; selection of the welding material and welding condition is important. Second, the effects of shield gas composition on weld bead shape, and the arrangement of stiffening beads to mitigate stress concentration are outlined. Third, the electrodeposition coating properties of weld joints are studied from the viewpoint of enhancing corrosion resistance; the coating properties depend on the ease of peeling and the coatability of weld slag, and coating defects increase depending on the chemical composition of the steel material to be welded and that of welding wire. Fourth, shot blasting is proposed as an effective measure to improve the fatigue strength and corrosion resistance of weld joints.

1. Introduction

Weight reduction of car bodies is a pressing issue in consideration of energy saving and environmental conservation, and as a consequence, needs are increasing to reduce the thickness of steel sheets used for car parts by increasing the steel strength. Chassis members are made of comparatively thick steel sheets, and arc welding is widely employed for their manufacture[1)] due to advantages such as the method being a continuous welding process suitable for securing high strength and stiffness of the products, viable by one-side access adequate for forming closed-section pieces, and working flexibility with respect to gaps between material sheets. However, since arc weld joints are located inevitably at positions where stress tends to concentrate structurally, and chassis parts are subject to repetitive loads during running, fatigue cracks are likely to develop from weld joints. In addition, on salty terrains, weld joints, when poorly coated, are prone to corrosion, leading to the loss of material thickness in the long run.

In consideration of the above, the steel sheets used for automotive chassis parts are mainly those of 440 and 590 MPa strength, and the use of 780 MPa class sheets is gradually increasing. Thus, in contrast to current wide use of 1.2 GPa class cold-rolled sheets and 1.5 GPa class sheets for hot stamping applications for body frame parts,[2)] the strength level of the steel sheets for chassis parts is markedly lower. Chassis members are critical safety-related parts, and to expand the use of ultra-high-strength steel sheets for them, it is necessary to improve the reliability of weld joints to a greater degree than they have been conventionally, and to this end, it is important to establish a welding method by which the fluctuation of joint quality is minimized. Against this background, the present paper describes the latest studies on improvement of the fatigue strength of arc weld joints of automobile chassis parts and enhancement of their corrosion resistance.

2. Fatigue Strength of Arc Weld Joints

The methods for improving the fatigue strength of weld joints were developed, first, in the fields of bridge construction and shipbuilding, and consequently, ultrasonic impact treatment (UIT),[3)] by which compressive residual stress is imposed on the joints, and welding materials of low transformation temperature[4)] were developed and practically applied for steel structures of heavy steel plates. For arc welding of thin steel sheets, on the other hand, studies are being conducted aggressively in view of the increasing need

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for use of high-strength thin steel sheets for welded products; such studies include a report on the effects of steel chemistry on the shape of weld toes,[5] another on the advantages of high-strength welding wires,[6] and yet another on the improvement of weld bead shape through the change of shield gas composition.[7] In addition, to obtain flat weld beads, new welding processes such as the plasma arc hybrid welding[8] and the MX-MIG process[9] have been proposed.

In field practice, however, the fatigue strength of weld joints tends to fluctuate, and it is not always possible to obtain intended results stably through improvement measures. In consideration of the above and for better understanding of the fatigue strength of arc weld joints of thin steel sheets, we studied the effects of the strength of weld metal and the shape of weld toes on the fatigue strength of weld joints. We also studied the appropriate shield gas composition for minimizing bead shape fluctuation, and the effects of reinforcing beads for decreasing structural stress concentration. This paper presents the findings obtained through these studies.

2.1 Governing factors of fatigue strength of fillet weld lap joints of thin steel sheets

Various measures are taken to enhance the fatigue strength of arc weld joints; such include lowering of the stress concentration factor through improvement of weld toe shape, and strengthening of the weld metal by use of high-strength welding wires, but there have been few studies on the quantitative evaluation of the effects of such measures applied to thin sheets.[10] In view of the situation and with the aim of clarifying the factors that govern the fatigue strength of fillet arc weld lap joints of thin sheets, we studied through tests the relationship between the stress concentration factor and the material hardness at positions where cracks are likely to develop.

Test pieces of fillet weld lap joints of hot-rolled steel sheets of a 980 MPa class were prepared by arc welding using welding wires of different strengths and under different welding conditions, and their fatigue strength was measured. **Figure 1** shows sectional macro photographs of typical specimens; the radii of the weld toes measured on the photos are given therein for reference. The beads of both conditions A and B are those of 2.9-mm thick sheets, but their shapes are different as a result of different positioning of the welding wire and the currents. The bead of condition C, on the other hand, is that of 2.3-mm thick sheets welded under a standard welding condition; the bead is flatter and smoother than the other two.

Four types of welding wires were used for the test pieces: a 490 MPa class mild steel wire, 780 and 980 MPa high-strength steel wires, and a high-strength trial wire with a high carbon content. It has to be noted here that there were cases where low-temperature cracks appeared at the weld metal roots of some specimens for which the high-C trial wire was used. This indicates that the high-C wire is inadequate for the commercial production of welded parts without special measures. In spite of this, the specimen joints prepared using all these wires were evaluated to clarify the factors that affected the fatigue strength of weld toes.

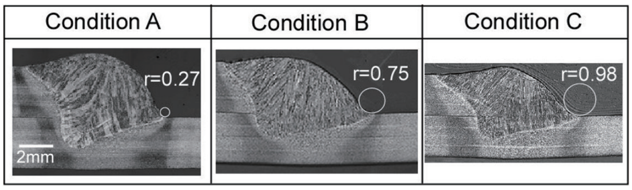

Fig. 1 Sectional macro photographs of arc weld joints formed under different conditions

Figure 2 shows the hardness distribution of some specimen joints. The graph shows that the hardness of the weld metal increases with the increase in strength of the welding wire. It is also clear that, with the wire of mild steel and the 780 MPa steel, the hardness of the heat affected zones (HAZ) adjacent to the fusion line is higher than that of the weld metal, but it is lower in the case of the high-C trial wire.

Figure 3 shows the fatigue test results of the specimens. Here, the specimens underwent reverse bending, and in 2 million cycles of bending, the stress amplitude at which the bending torque decreased by 40% without fracture was defined as the fatigue limit. To prevent opening of the roots during the fatigue test, an arresting weld bead was provided on the back side of the bead to be tested.[6]

The graph indicates that, while fatigue strength of the joint tends to increase with the increase in welding wire strength, it fluctuates even with the same welding wire depending on the welding condition: for example, the fatigue limit of the joint welded with the mild steel wire under condition A was 130 MPa, but it increased 1.6 times to 210 MPa under condition C.

To estimate the fatigue strength of weld joints of heavy steel plates, the modified Goodman's diagram was used.[4] Because it is believed possible using the diagram to estimate fatigue strength in a simplified manner from the tensile strength of the cracked portion and the stress concentration factor, we applied the method to the weld joints of thin steel sheets. By this method, the estimation equation is as follows:

$$\sigma fw = \alpha TSw/Kt. \quad (1)$$

Here, σfw is the fatigue limit when the stress ratio R is −1, α the fatigue limit ratio, TSw the tensile strength of the portion where a crack occurred, and Kt the stress concentration factor; it is assumed here that the ratio TSw/Kt was proportional to the fatigue strength

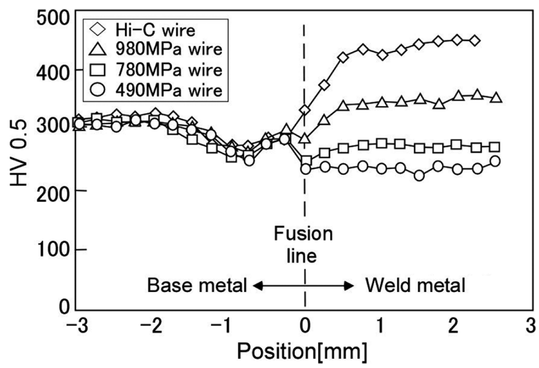

Fig. 2 Vickers hardness of joints welded using different wires

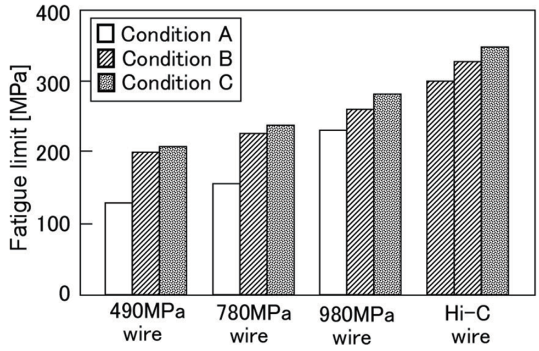

Fig. 3 Fatigue strengths of fillet weld lap joints

of the weld joint. Note that residual stress was not taken into consideration in the present test, as the residual stress of the test pieces was as low as ±50 MPa, approximately.

Empirically, the tensile strength (in MPa) of steel is roughly three times its Vickers harness value, and for this reason, TSw was assumed to be three times the hardness value of the weld metal near the bead top. The value of Kt was obtained using the following approximation formula based on Kinebuchi's analysis result[11]:

$$Kt = 6.24x^6 - 30.8x^5 + 60.8x^4 - 60.8x^3 + 32.6x^2 - 9.33x + 2.37, \quad (2)$$

where x is the ratio (r/t) of the curvature radius r of the weld toe to the sheet thickness t.

Figure 4 shows the relationship between the fatigue strength of the weld joints and HV/Kt, (HV being Vickers hardness). It is clear from the graph that the fatigue limit increases nearly in proportion to HV/Kt, from which it is possible to presume that the bending fatigue strength of fillet weld lap joints of thin steel sheets can be estimated in a simple manner from the hardness of the weld metal and the curvature radius of the weld toe (stress concentration factor).

Here, fatigue strength was calculated from the stress concentration factor, which was estimated based on the macroscopic weld bead shape, generally understood as the weld toe shape. However, there are uneven wave patterns called ripples on the weld metal surface, and the fatigue cracks are likely to start from such ripples.[12] For in-depth understanding of the fatigue behavior of weld joints, more microscopic analysis is essential.

2.2 Improvement of weld joint shape by changing shield gas composition

It has been reported that smooth weld beads are formed and higher fatigue strength is obtained by changing the shield gas composition from 100% CO_2 to an argon-rich composition such as Ar+ 5%CO_2.[7] On the other hand, weld bead shape changes depending not only on the shield gas composition but also on the wire aiming position and the welding current. In consideration of this and with the aim of clarifying the effects of shield gas composition on weld toe shape, we measured the shape of weld toes formed under different conditions.

Specimens of fillet weld lap joints were prepared using shield gases of Ar+20%CO_2 and Ar+5%CO_2, changing the welding voltage (V) by ±2 V from the standard, and the wire aiming position (x) by ±1 mm from the standard position; note here that, the standard wire aiming position was defined as 0.5 mm away from the edge of the upper sheet, and the wire aiming was shifted horizontally by 1 mm either towards the upper sheet (positive side) or away from it (negative side).

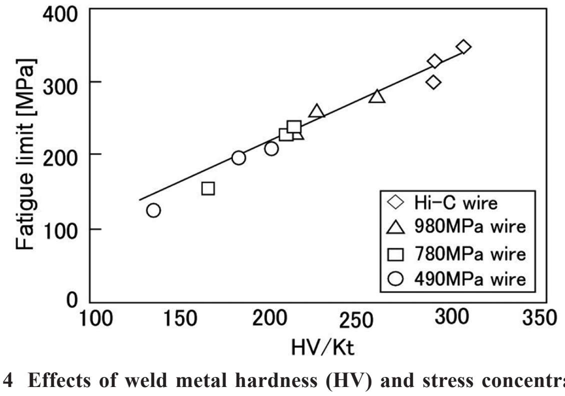

Fig. 4 Effects of weld metal hardness (HV) and stress concentration factor (Kt) on fatigue strength of weld joints

Figure 5 shows sectional macro photographs of some specimen joints. The photos indicate that flat and smooth beads are obtained when the CO_2 concentration of the shield gas is decreased, the welding voltage increased, and the wire aiming position adequately shifted. The decrease in the CO_2 content and the increase in the welding voltage presumably expanded the area covered by the arc, and as a result, the base metals were heated in a wider area, which made the bead flatter and smoother. On the other hand, when the wire aiming position was shifted away from the upper sheet, the heat input to the lower sheet increased, and the weld metal presumably covered a wider area by wetting.

Figure 6 shows the relationship between the welding condition and the stress concentration factor of the joints; the stress concentration factor was calculated from the curvature radius of the weld toe measured on sectional photographs and using equation (2). As is understood from the sectional observation of the weld joints, the stress concentration factor decreases as the wire aiming position is shifted away from the upper sheet and the welding voltage is increased. The graph also shows that, when the CO_2 content of the shield gas is decreased, the maximum of the stress concentration factor lowers, and the range of its change becomes narrower: whereas the highest Kt value with the Ar+20%CO_2 gas was 1.73, the same with the Ar+ 5%CO_2 gas was 1.44, which means that an improvement in fatigue

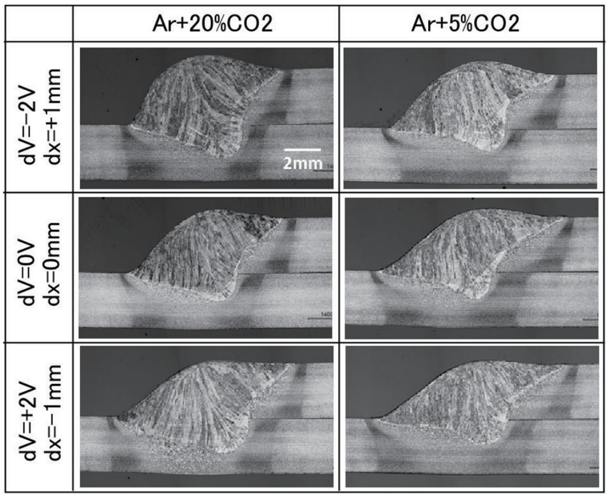

Fig. 5 Sectional macro photographs of arc weld joints with shield gas of different compositions

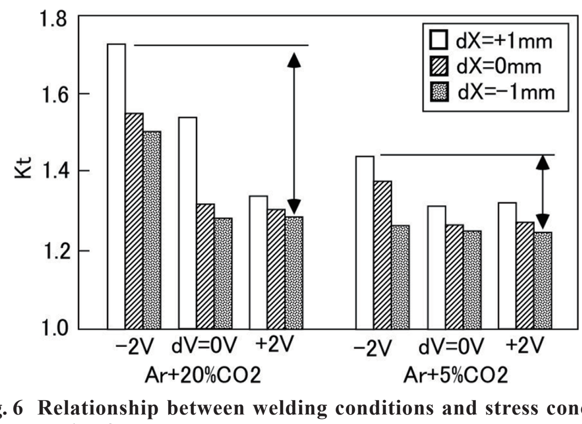

Fig. 6 Relationship between welding conditions and stress concentration factor at weld toe

strength roughly by 20% is expected. The above results seem to indicate that a decrease in the CO_2 content of the shield gas is effective at mitigating stress concentration especially under welding conditions where the bead tends to be peaked, such as the wire aiming position shifted towards the upper sheet and a low welding voltage.

2.3 Improvement of fatigue life of weld joints with stiffening beads

As a fundamental study on the fatigue strength of weld joints, the previous sub-section 2.2 dealt with the case where cracks started from weld toes. Automotive chassis parts are generally so designed as to prevent fatigue cracks from developing from weld roots. Most conventional studies on the fatigue strength of weld joints are related to measures against crack development from the top of beads. However, since most chassis parts have complicated shapes, loads are likely to concentrate at weld roots for structural reasons. In addition, to respond to the increasing need for wider use of stronger and thinner steel sheets, it is necessary to develop measures to improve the fatigue strength of weld joints including the roots.[13)]

Figure 7 shows the stress distribution and deformation of fillet arc weld lap joints under axial loads; here, the displacement in the thickness direction is enlarged for easy understanding. Rotational deformation is seen to occur at the weld joints under load application. When there is a gap between the two sheets, the deformation is greater, and the increase in the stress concentration factor is pronounced especially at the root.

With structures of thin steel sheets, the fatigue strength of weld joints is adversely affected by rotational deformation under loads. Facing such a situation, we proposed a measure to improve the stiffness of weld joints by providing stiffening beads, which are weld beads not for joining materials together but for suppressing the deformation of welded structures.[14)]

As an example, we studied the fatigue life of a structure of a flat base plate and a bracket. Test pieces as shown in **Fig. 8** were prepared by welding a channel-section bracket onto the upper surface of a hat-section base plate to form T-shaped fillet weld beads around the bracket. As it had been found in preliminary tests that fatigue cracks were likely to develop at the weld joints at the ends and the corners of the bracket, stiffening beads were provided at those positions. Fatigue life was evaluated using a type of specimen having a stiffening bead as an extension from a bracket end, a second type having a stiffening bead as an extension from an end and another running at right angles to the former at the same end, and a third type having a stiffening bead running in the normal direction from a bracket corner.

At the fatigue test, cyclic loads were applied to the upper part of the bracket, and the occurrence of a crack was detected using strain gauges attached around the weld joints. **Figure 9** shows the fatigue life extension effects of the stiffening beads. Whereas cracks began to develop at the bracket ends and corners after 0.3×10^5 and 1.0×10^5 cycles of loading, respectively, without stiffening beads, the fatigue life was increased to 0.8×10^5 cycles with an extension stiffening bead at bracket ends, and it was further increased to 1.6×10^5 cycles, a fatigue life extension of roughly five times, with an additional one in right angles at each end. Regarding the bracket corner, with a stiffing bead running in the normal direction, no cracking was detected even after 4.0×10^5 load cycles, a life extension of more than four times.

As explained above, by adequately providing stiffening beads at critical positions, local stress concentration at weld joints is mitigated, and the fatigue life of the structure is expected to increase. The measure proposed herein consists simply of forming weld beads, each some tens of millimeters in length, at positions where cracks are likely to develop in ordinary welded structures; it is an effective fatigue life improvement measure requiring only minimum additional costs. In commercial practice, however, the positions of the stiffening beads may be restricted, or a stiffening bead may cause a change in the stress distribution of the product, and trial and error is required to find an optimum solution. In consideration of this, we intend to systematize part design procedures so as to include the measure as a standard step.

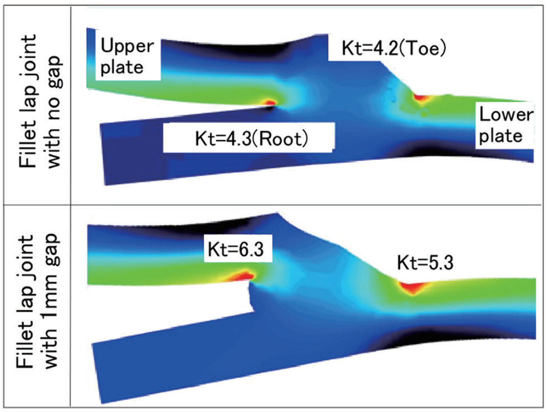

Fig. 7 Stress distribution of fillet lap joints in loading direction

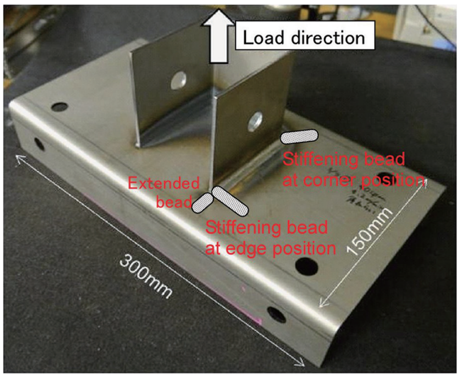

Fig. 8 Stiffening beads for welded bracket

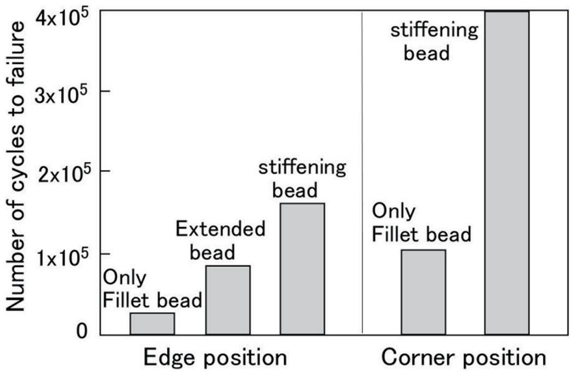

Fig. 9 Effects of stiffening beads on fatigue life

3. Corrosion Resistance of Weld Joints

In addition to extended fatigue life, higher corrosion resistance is required for the weld joints of chassis parts. The slag forming during welding causes defects of electrodeposition coating, which leads to poor corrosion resistance. The thickness of steel sheets used for a part is defined in the design stage in consideration of mechanical requirements such as fatigue life and rigidity and, in addition, thinning due to corrosion during use under widely varied conditions. For this reason, when thin sheets are used, the performance of the part decreases more prominently owing to material thinning due to corrosion, and for this reason, enhancement of corrosion resistance of weld joints becomes imperative.

Figure 10 shows the appearance change of a weld joint of 440 MPa class hot-rolled steel sheets, as welded (with a welding wire of mild steel), after chemical treatment and after electrodeposition coating. The photographs clearly show that the slag on the weld bead surface causes coating defects. This slag is formed when deoxidation elements such as Si and Mn in the molten weld pool combine with oxygen in the shield gas. For this reason, decreasing decarbonizing elements in weld metal and oxidizing gas in the shield gas are considered effective at decreasing slag formation.[15, 16]

On the other hand, through close examination of the slag and coating defects in Fig. 10, part of the slag that formed during welding falls off before the coating, and not all slag spots lead to coating defects but some of them are soundly coated.[17]

Therefore, to clarify the effects of slag properties on coating defects, we prepared weld joint test pieces using 440 MPa class steel sheets and three types of welding wires of different Si and Mn contents, and studied the relationship between the amount of slag formation and coating defects. **Figure 11** shows the ratio of the slag-covered area of weld beads, as-welded and after the chemical treatment, and the area ratio of coating defects after coating. The wire of high Si and Mn contents did not always lead to high coating defect ratios, but rather, the slag of that wire flaked off more easily than the slag of the other two did, and the coating performance tended to improve. With the wire of low Si and Mn contents, in contrast, little slag flaked off, and the area covered by the slag and coated by the electrodeposition in spite of the remaining slag tended to increase. The slag forming with the low-Si, low-Mn wire is composed mainly of Mn, which presumably improved the coating performance of the weld joints.[18]

Based on the finding that the slag composition change leads to a decrease in coating defects, we studied the possibility of improving coating properties by changing the chemical composition of the steel sheets. **Figure 12** shows the appearances of weld beads after coating; the specimens were prepared by welding 780 MPa class steel sheets of newly developed and conventional steels using a commercial welding wire of mild steel. As the photographs clearly show, coating performance is markedly better with the developed steel than with conventional steel. In addition, weld joints free from coating defects are obtainable by changing the shield gas from Ar+20%CO_2 to Ar+10%CO_2.

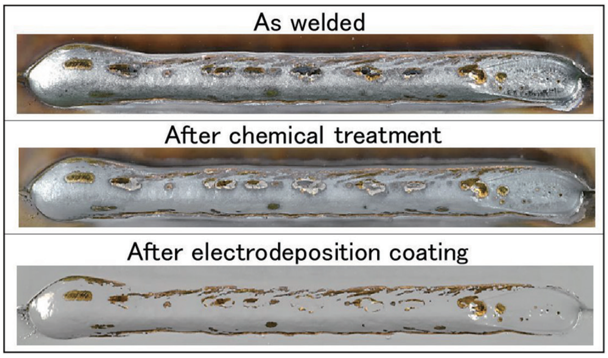

Fig. 10 Appearances of weld bead as welded, after chemical treatment and after coating

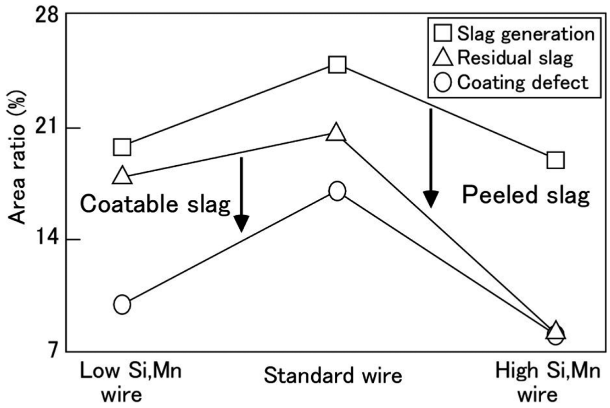

Fig. 11 Peeling and coating of slag with different welding wires

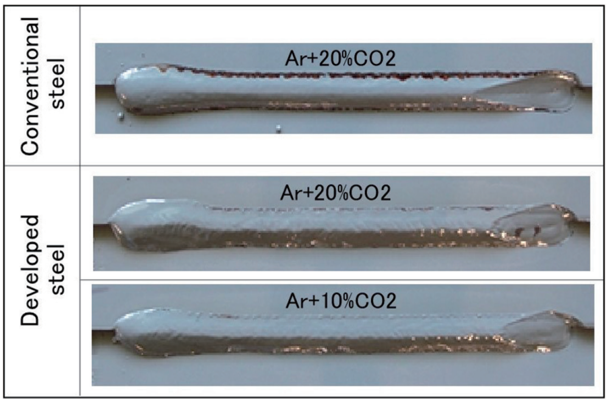

Fig. 12 Decrease in coating defects with developed steel

4. Improvement of Corrosion Resistance and Fatigue Strength by Shot Blasting

In the manufacture of press-formed automotive parts, shot blast is applied to non-coated parts of hot stamping sheets to remove the surface scale forming during hot stamping.[19] This seems to indicate the possibility of applying shot blasting to arc-welded auto parts of thin sheets without significantly affecting their dimensional accuracy. On the other hand, for bridges and other welded structures of heavy plates, shot blasting is used as a measure to improve the fatigue strength of weld joints,[19] but few studies have been conducted on its application to the weld joints of automotive parts of thin sheets. In consideration of the situation, we studied the possibility of improving the post-coating corrosion resistance and fatigue characteristics of arc weld joints of thin steel sheets for automotive use by shot blasting.[20] The results are explained below.

Weld joint test pieces were prepared using 2-mm thick steel sheets for hot stamping applications of 440 and 1 500 MPa classes, mild-steel welding wires for general use, and shield gas of Ar+20%CO_2.

Figure 13 shows appearances of the weld beads of the 440 MPa class sheets, as welded, after the coating and after the corrosion test. Here, the target thickness of the electrodeposition coating was 20 μm, and the specimens underwent 120 cycles of a 24-hour-cycle combined-cycle corrosion test. There were slag spots at the top and toes of the as-welded bead and fumes adhering to the HAZ surfaces. After shot blasting of the as-welded test piece, the slag spots on the bead and fumes on the HAZ surfaces were completely removed. Coating defects due to slag adherence and poor coating adhesion due to weld fume on HAZ surfaces are common problems of the coating performance of weld joints, but shot blasting seems promising for solving the problems in both these areas.

Through close examination of weld beads after the coating, while coating defects were found at slag spots in the weld beads that had been coated as welded, no coating defects were found in those that had been coated after shot blasting. In addition, after the corrosion test, there were coating blisters at the red-rusted portions of coating defects and areas around the beads of the as-welded and the coated specimens, and corrosion resistance was markedly poor, but little corrosion occurred in the area around the beads of the specimens that were coated after shot blasting.

Figure 14 shows the maximum corrosion depth of the weld joints of the 440 and the 1 500 MPa test pieces after the corrosion test. Whereas the maximum corrosion depth of the 440 MPa test pieces without shot blasting was roughly 1.1 mm, the same of the shot-blasted types was less than 0.2 mm. Shot blasting seems to have removed slag from the weld bead, and as a result, there were virtually no coating defects. In addition, coating adhesion was enhanced by removal of the fume, and all these seem to have significantly improved corrosion resistance.

Figure 15 shows the results of a repeated bending fatigue test of fillet arc weld lap joints. Note that the test pieces underwent pulsating flat bending, and fatigue strength is expressed in terms of stress range, and for this reason, these results cannot be directly compared with the fatigue test results described in Section 2.

With both 440 and 1 500 MPa steel sheets, the fatigue limit of as-welded test pieces was 360 MPa. The values of the two were substantially the same presumably because mild-steel welding wires were used for both of them. In contrast, the fatigue limit of the arc weld joints of the shot-blasted 440 MPa class test pieces was 450 MPa; it was increased by roughly 25% by shot blasting. The fatigue strength of the shot-blasted 1 500 MPa class test pieces was slightly higher than that of the 440 MPa class test pieces.

These higher fatigue limit values of shot-blasted specimens presumably resulted from compressive residual stress imposed on the surface portions of the weld joints by shot blasting. **Figure 16** shows the residual stress distribution near weld toes of the 440 MPa test pieces. While the compressive residual stress was substantially zero near weld toes of the as-welded test pieces without shot blasting, with shot-blasted test pieces, it was approximately 400 MPa in

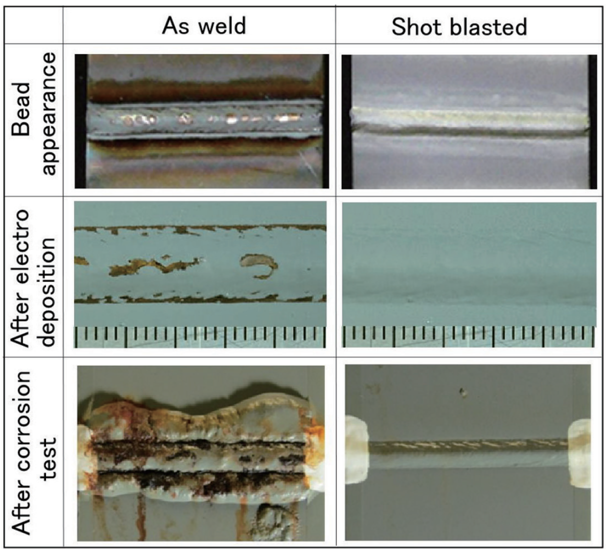

Fig. 13 Improvement of corrosion resistance of weld part by shot blast treatment

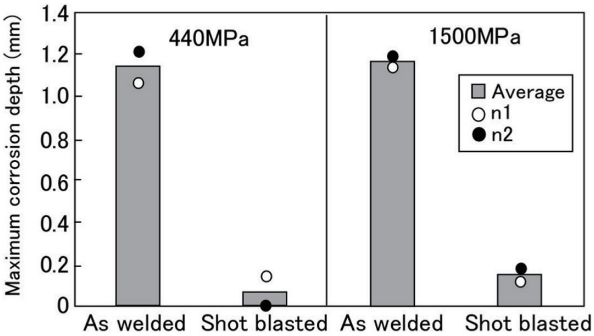

Fig. 14 Maximum corrosion depth after corrosion test

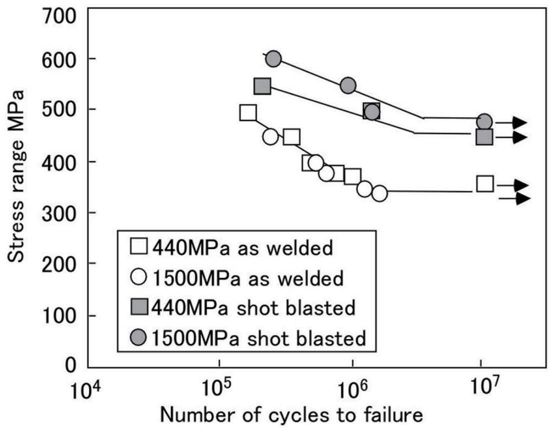

Fig. 15 Improvement of fatigue strength of weld part by shot blast treatment

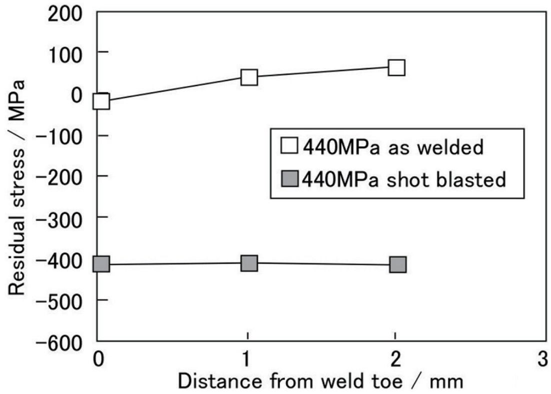

Fig. 16 Distribution of residual stress in weld joint

wide regions regardless of the distance from weld toes. When there is compressive residual stress, the tensile stress at the fatigue test is lowered and fatigue strength is increased. In consideration of this, the reason for the improvement of fatigue strength by shot blasting in the present test is, rather than the shape change of weld toes and material hardening, most likely the compressive residual stress created by shot blasting. The reason why the fatigue strength after shot blasting of the 1 500 MPa class sheets was greater than that of the 440 MPa class sheets is presumably that the hardness of the HAZ of the former near the position of crack development was high, and the compressive residual stress imposed by the blasting was not easily dissipated during the fatigue test.

It is clear from the above results that shot blasting is effective at markedly improving the corrosion resistance and fatigue strength of arc weld joints after coating. Although shot blasting is an additional step to conventional manufacturing processes, it is advantageous for enhancing the static strength of automotive chassis parts and the corrosion resistance and fatigue strength of weld joints of these parts after coating, especially for those made of high-strength steel sheets. While it is necessary for commercial application of shot blasting to study and select the most suitable shot material, blasting condition and shot material removal method in consideration of the shape and quality of the product, its application is expected to significantly contribute to the weight reduction and performance improvement of manufactured parts.

5. Conclusion

The present paper outlines the issues related to improvement of the fatigue strength and corrosion resistance of arc weld joints encountered in the efforts for weight reduction of automotive chassis parts, and the results of the latest studies related to them. The need for more use of thinner steel sheets of higher strength is increasing rapidly, and to do so, it is necessary to enhance the reliability of weld joints to an unprecedented level, and measures for the enhancement will be demanded in the fields not only of material engineering but also of manufacturing processes and product shape design. Arc welding is widely used for producing automotive chassis parts in appreciation of its high flexibility in joint shape and robustness with respect to positional errors in component assembly. While these advantages of arc welding will remain unchanged for some time to come, when advanced welding methods such as low-heat-input laser welding and laser-arc hybrid welding become commercially applicable, it will be possible to manufacture parts with higher fatigue strength and corrosion resistance. We intend to offer weld joints of high reliability making the most of the advantages of arc welding and contribute to the weight reduction of car bodies by developing and proposing new material joining methods.

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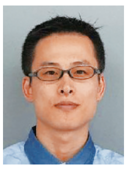

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