

Properties of Aluminum Coated Steels for Hot-Forming

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Abstract

Hot pressing, which involves heating steel plates to austenite temperature and then quenching them while pressing them into shape, has been attracting attention as a way of producing high-strength parts. Aluminized steel sheets are believed to be suitable for hot pressing because of surface oxidation during heating and subsequent corrosion resistance*. The material properties, surface properties, spot weldability, etc. of steel sheets with aluminum plating applied to a base material with excellent hardenability were investigated when using hot pressing. We found that strength of 1,500 MPa or more is obtained after quenching in a mold, the plating layer on the surface becomes an Fe-Al alloy phase when heated, the results of corrosion resistance testing using the JASO CCT method revealed the same corrosion resistance as hot-dip galvanized steel sheets with an alloyed coating, and spot weldability was excellent. (*A licensed product based on a global strategic partnership agreement with Arcelor (USIBOR1500))

Abstract

Production of parts with high strength by means of hot-forming process has been receiving considerable attention lately. Application of aluminized steel with good hardenability for this process has been investigated*. Tensile strength over than 1500MPa was obtained with steel containing around 0.2mass% C. Surface coated layer changed from Al-10% Si to Fe-Al(-Si) phases through the hot-forming process. The steel with Fe-Al(-Si) surface layer showed good paintability even without phosphatized treatment. After painting, they showed good corrosion resistance in JASO-CCT as galvanized steel did. The steel showed good spot weldability due to the stable surface layer at high temperature. (*license product within the frame of global strategic alliance with Arcelor (USIBOR1500))

1. Introduction

[01] In recent years, the use of high strength steel sheets has been actively pursued from the standpoint of reducing the weight of automobiles, which has been triggered by environmental issues, while also improving safety in the event of collisions. The use of high strength steel plates for some parts allows for greater weight reduction by narrowing the thickness of the steel plates. Therefore, the strength of steel plates used is not limited to 440 MPa or 590 MPa class, but has increased to 780 MPa class and higher. As steel sheet strength increases, formability generally deteriorates. To overcome this problem, high-strength steel sheets have been developed using various microstructural controls¹⁾. However, when the strength of a steel sheet is about 1500 MPa, press forming the sheet into complex shapes becomes difficult.

[02] In Europe, forming methods including mold quenching, hot forming, hot stamping, and hot pressing have been used to obtain parts with a strength of about 1500 MPa²⁾. In these forming methods, steel sheets are heated to a temperature in the austenite range of about 900°C and formed in a mold at room temperature to increase the strength of the hardened steel sheet. These methods have also been considered in Japan, and have been studied or implemented using unplated steel plates^{3, 4)}. In Europe, Arcelor has already developed and commercialized USIBOR1500, an aluminum-plated product with hot forming properties and excellent corrosion resistance^{2, 5, 6)}. Based on the global strategic alliance agreement with Arcelor, Nippon Steel has been studying manufacturing

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technologies and the product characteristics of the USIBOR1500 under a license agreement. This paper reports the results of our study on various properties of aluminum-plated steel sheets for hot forming applications.

2. Hot Forming Process

[03] The hot forming process is already in practical use. Figure 1 briefly illustrates the process. This process requires steel sheets to be heated to a temperature in the austenite range (A_{c3} or higher). For example, steel with a C content of about 0.2 mass% requires heating to a temperature of 850°C or higher. After heating, the steel sheet is taken out of the furnace and transported to a press machine, where it is pressed with a mold at room temperature and quenched at the same time. After forming, the entire steel sheet is held at bottom dead center until fully quenched.

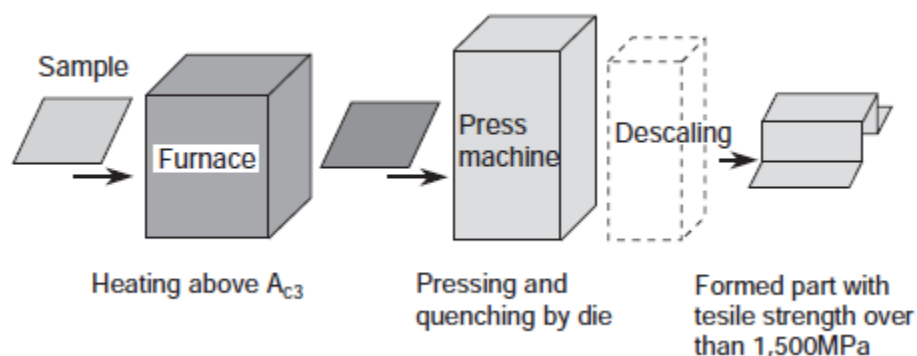


Figure 1: Schematic Diagram of the Hot Pressing Process

[04] In this forming process, when an unplated steel sheet is used, a non-oxidizing atmosphere is necessary to suppress scale formation and surface decarburization during heating. Even when heated in a non-oxidizing atmosphere, scaling occurs in the surface layer for a short time because of the atmospheric conditions between the furnace and the press. Press-formed products are given a coating during use, but the presence of scale on the surface layer can be problematic. Therefore, if unplated steel sheets are used, a process to remove the scale is required. The scale layer can be removed by shot blasting or pickling, but these methods increase costs. In addition, shot blasting may cause changes in shape. This process can be eliminated by using a plated steel sheet with excellent heat resistance.

3. Raw Materials

[05] As mentioned above, the hot press process requires excellent hardenability to increase strength by cooling the steel sheet rapidly. Plating with excellent heat resistance on the surface eliminates the need for controlling the atmosphere of the heating furnace and for descaling, thereby making the manufacturing process simpler. An aluminum-plated steel sheet with the composition shown in Table 1 can be used as a steel sheet that satisfies the above conditions. The amount of plating was 120 to 160 g/m². Various properties of the steel sheet are summarized below.

4. Base Material Properties

4.1 Tensile Properties Before and After Quenching

[06] Table 2 shows the properties of this steel sheet before and after quenching. Tensile testing was performed by preparing JIS No. 5 tensile test samples from 1.4 mm thick material. The strength at the time of shipment is in the 490 to 590 MPa range, and after quenching in the mold, the strength is over 1500 MPa. The strength can be adjusted based on the amount of C as shown in Figure 2. Figure 2 shows the results of a study of the mechanical properties of materials with varying C content after vacuum melting followed by quenching. As is well known, the mechanical properties after quenching increase with C content. The strength after quenching, that is, the strength of formed parts, can be

controlled by adjusting the amount of C. The effect of substitutional solid solution elements such as Mn and Cr on strength during quenching is known to be small. Since these substitutional solid solution elements affect hardenability, they are important to ensuring hardenability as discussed in the next section. However, it should be noted that the excessive addition of these elements will increase the strength of the product plate.

Table 1: Composition of Steel Sheets Used in the Study (mass%)

C	Mn	Cr	B
0.22	1.2	0.15	0.002

Table 2: Tensile Properties Before and After Quenching

	Yield strength (MPa)	Tensile strength (MPa)	Elongation (%)
As coated	394	615	26
As formed	1,280	1,530	8

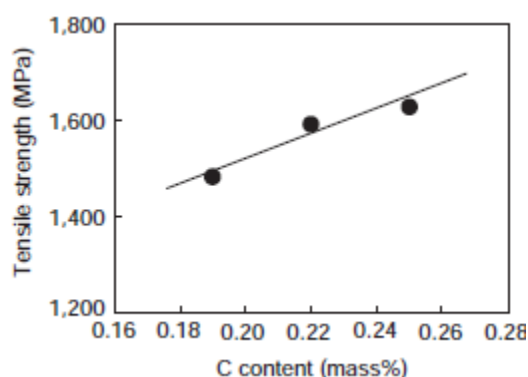


Figure 2: Relationship Between C Content and Tensile Properties

4.2 Quenching Properties

[07] Figure 3 shows the CCT curve (continuous cooling curve from 950°C) of this steel, and Figure 4 shows the relationship between cooling rate and hardness. Mn and B are added to this steel sheet to improve hardenability, and when the heating temperature is 950°C, the hardness can be in the range of HV 450 to 500 at a cooling rate of about 20°C/s or higher. This quenching rate is determined by conditions that avoid transformation to ferrite, pearlite, and bainite during cooling. Because these transformations occur more rapidly when the austenite grain size is smaller, that is, when the heating temperature is lower, the cooling rate required for quenching is faster. In this regard, heating temperatures between 900 to 1000°C was used in the study. However, in this range, the critical cooling rate was around 20 to 30°C/s at all heating temperatures without making much difference. Figure 3, Figure 4, and the experimental results at other heating temperatures mentioned above show that sufficient hardness can be obtained at any cooling rate as long as the cooling rate of the steel sheet during hot pressing is 30°C/s or higher. However, in the actual pressing process, the cooling rate is close to air cooling between the transfer from the heating furnace to the press machine and the start of pressing.

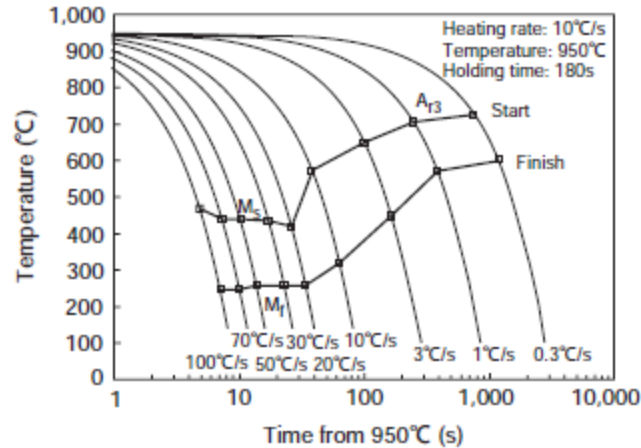


Figure 3: CCT Curve

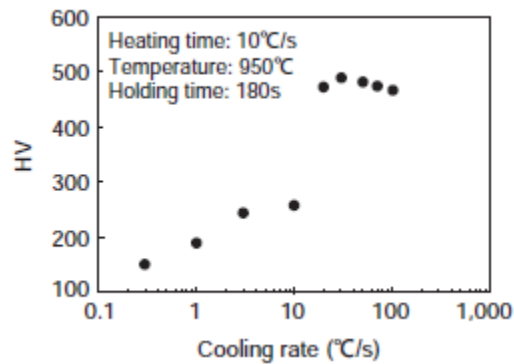


Figure 4: Effect of Cooling Rate on Hardness

[09] For a steel plate that is about 1.4 mm thick, cooling under atmospheric conditions results in a cooling rate of 10 to 15°C/s. Figure 3 and Figure 4 show that cooling below 600°C at this rate results in a decrease in the strength of the steel plate. The time from 950°C to 600°C is 23 to 35 seconds, which means that the material can be quenched if cooling in the mold starts within 23 seconds of removing the material from the furnace. Since this relationship depends on the heating conditions, the atmosphere during cooling, and the ambient environment, it must be determined based on the actual hot press working environment.

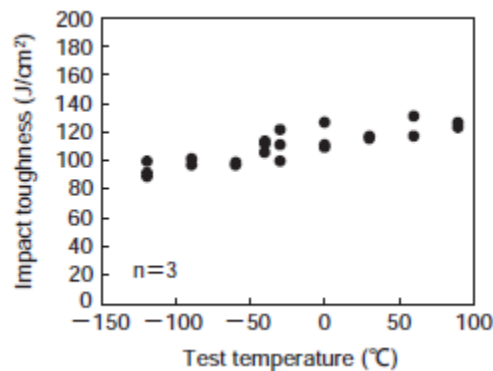


Figure 5: Relationship Between Impact Toughness and Temperature During Charpy Test

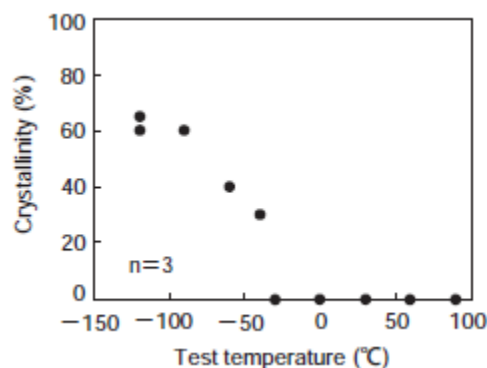


Figure 6: Relationship Between Brittle Fracture Surface Ratio and Temperature During Charpy Test

4.3 Toughness

[10] There is a concern that toughness, especially at low temperatures, may deteriorate when strength is secured in the martensitic phase by quenching. The results of Charpy impact testing are shown in Figure 5 and Figure 6. Figure 5 shows the relationship between impact roughness and temperature, and Figure 6 shows the brittle fracture surface ratio. This testing was performed on 4 mm hot-rolled plates, which was water quenched to produce a 2 mm U-notch 2.5 mm sub-size impact sample. The absorbed energy does not show much change from room temperature to -60°C . However, the brittle fracture rate increases below -40°C , reaching about 80% at -80°C , and the transition temperature (Tr_{550}) is about -60°C . The brittle fracture surface ratio tends to decline with decreasing plate thickness, and the transition temperature is believed to decrease more for plate thicknesses less than 2.5 mm. These results indicate that this steel sheet is used in a microstructure consisting mainly of the martensitic phase as quenched, but it is believed that there is no sudden change in absorbed energy or fracture morphology at low temperatures under normal environmental conditions.

5. Spot Weldability

[11] A 1.2 mm thick aluminum-plated steel sheet with 120 g/m^2 of plating was heated to 950°C for 5 minutes, and then quenched while clamped on both sides by a mold to make a sample for spot welding. The change in the surface plating layer is described in the next section, but it is Fe-Al alloy plating. A cold-rolled thin steel sheet of 440 MPa class with a thickness of 1.8 mm was used as the counterpart material. Spot welding was performed using DR6 ϕ type alumina-dispersed copper as the electrode, with 17 cycles (60 Hz) of current applied and 400 kgf of pressure applied. Figure 7 shows the relationship between nugget diameter and current density, and it can be seen that the range of current values where the nugget diameter is $4\sqrt{t}$, with t being the plate thickness, and dust is generated is about 3 kA. Figure 8 shows the relationship between shear tensile strength and current value, and Figure 9 shows the relationship between cross tensile strength and current value. Figure 10 shows the hardness distribution near the nugget. The hardness in the nugget and base metal has a Vickers hardness of about 480 and softens to about 300 in the heat-affected zone (HAZ) of the weld. Because of this hardness distribution, when the nugget diameter is large enough, the fracture zone is often this HAZ.

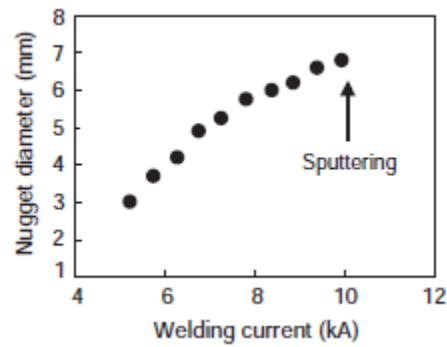


Figure 7: Relationship Between Nugget Diameter and Current Value for Spot Welds

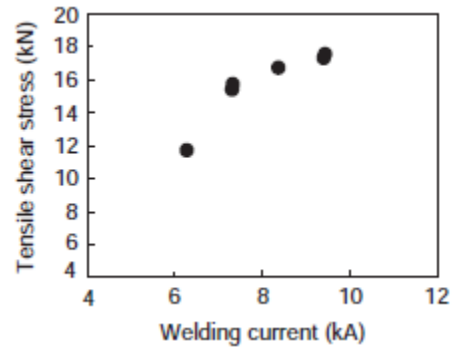


Figure 8: Relationship Between Shear Tensile Stress and Current Value for Spot Welds

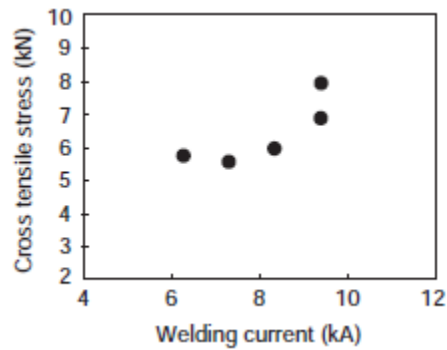


Figure 9: Relationship Between Cross Tensile Strength and Current Value for Spot Welds

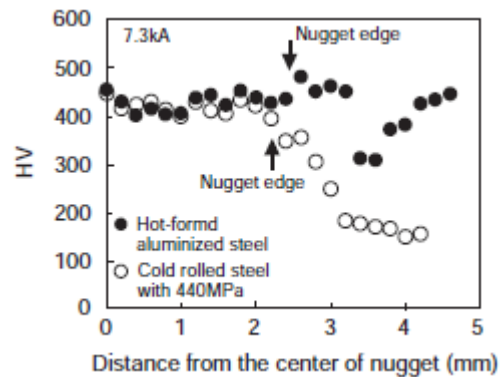


Figure 10: Hardness Distribution in Nugget

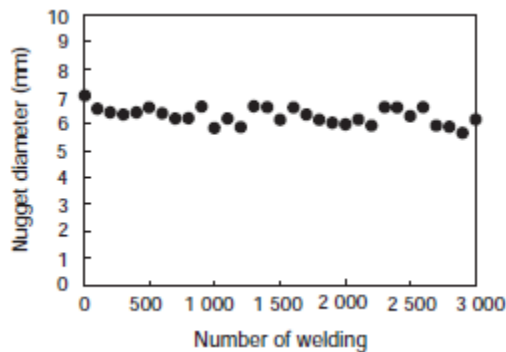


Figure 11: Change In Nugget Diameter With Continuous Spot Welding

[12] Figure 11 shows the results of the evaluation of continuous spot welding. The test was conducted at up to 3000 points, and it is estimated that continuous spot welding of more than 3000 points is possible because the nugget diameter does not change much in this range. The plating layer on the surface of this steel sheet is a Fe-Al alloy phase with a melting point of 1000°C or higher, which may be the reason for this continuous spot welding property.

[13] Although arc weldability is not shown here, the Fe-Al alloy phase has a boiling point of more than 2000°C and does not cause blow holes during arc welding, which is a problem with zinc-based coated steel sheets.

6. Plating Characteristics

6.1 Alloying of the Plating Layer During Heating

[14] The surface plating of this steel sheet is an aluminum plating containing 10% Si, which is known as Type 1. The melt temperature of this plating layer is about 600°C, so rapid heating will melt the plating layer. However, at a heating rate obtained in an electric furnace, a Fe-Al alloy layer with a high melting point is formed during heating and quickly reaches the surface layer, so the melt does not adhere to the furnace material, etc. When material with a thickness of 1.6 mm was heated in an electric furnace under atmospheric conditions, the time required to reach the holding temperature was approximately 2 minutes.

[15] Figure 12 shows the alloying state after holding at 950°C for 0.5 min, and Figure 13 shows the results of SEM-EDS measurements of Fe, Al, and Si concentrations in the surface plating layer in the direction of the plate thickness. As alloying progresses, a layered alloy phase with the Al and Fe concentrations shown in the figure is formed. Under these heating conditions, the alloy phase consists of five layers, and the Al concentration changes from the topmost layer to approximately 50%, 30%, 50%, 30%, and 10%. From the fourth layer to the base layer, the element concentrations change continuously.

[16] Figure 14 shows the state of the Fe-Al-Si system at 950°C, as calculated by Thermo-calc⁷⁾. The composition at each point in Figure 13 is superimposed on this figure. The Fe-Al-Si thermodynamic database for this calculation is from Z. Liu et al.⁸⁾. From Figure 14, the alloy layers from the surface layer are estimated to be Fe₂Al₅, BCC regular phase, FeAl₂, BCC regular phase, and BCC irregular phase. The alloy layers in the surface layer disappear from the topmost layer as Al diffuses into the base layer with increasing retention time. Figure 15 shows the plating layer when the holding time is set to 5 minutes. Although only one phase can be identified from the cross-sectional microstructure, SEM-EDS analysis reveals the presence of two phases. These phases are believed to be the BCC regular phase and the irregular phase.

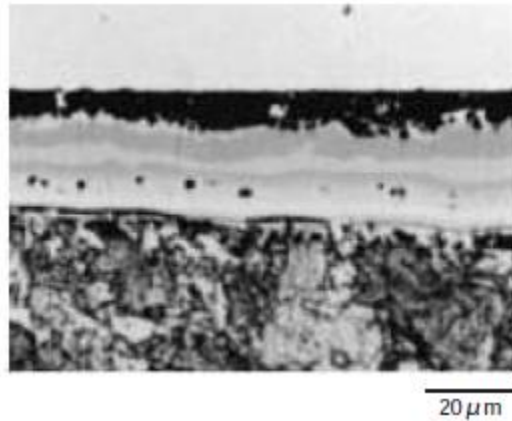


Figure 12: Cross-Sectional Optical Micrograph Showing the Structure of the Plating Layer in Sample Held at 950°C for 30 Seconds

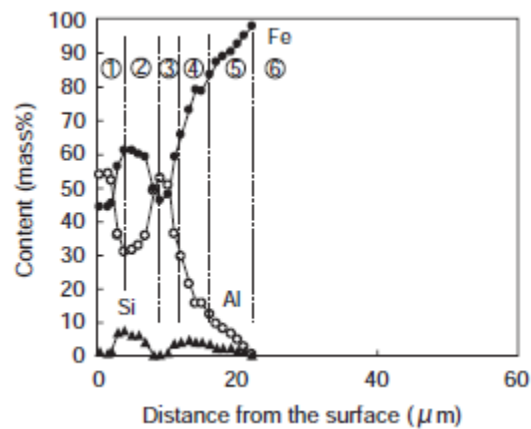


Figure 13: Change in Fe, Al and Si Element Concentration in the Thickness Direction of Sample in Figure 12

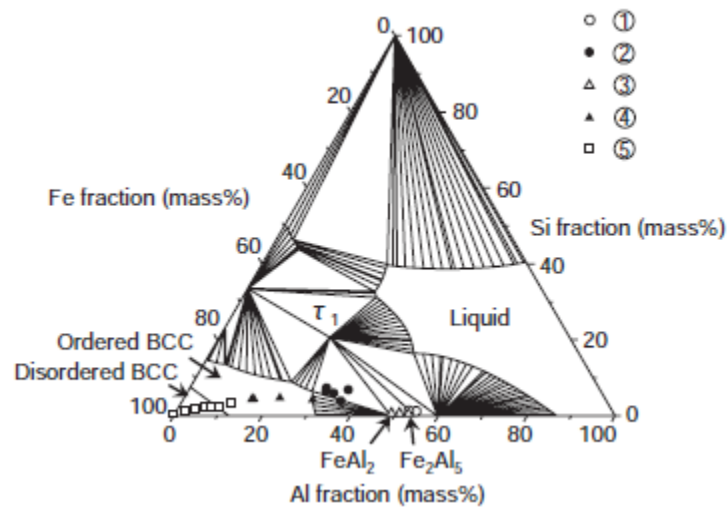


Figure 14: Isothermal Cross-Section of the Fe-Al-Si Equilibrium Diagram at 950°C

6.2 Paintability and Corrosion Resistance After Painting

[17] Steel sheets are electrodeposit-coated for automotive applications, and usually undergo passivation treatment before coating to ensure paintability. The passivation treatment is generally performed in a zinc phosphate solution to form a phosphate film on the surface. This film ensures paintability and paint adhesion, but the Fe-Al alloy phase does not form this passivation film when immersed in the passivation solution. This is because the Fe-Al alloy phase is very stable against acids. However, as Figure 16 shows, the surface after heat treatment is uneven, and the anchoring effect caused by this unevenness ensures paintability. The adhesion of an electrodeposition coating was examined by applying an electrodeposition coating with a thickness of approximately 20 μm to samples with and without passivation treatment. Table 3 shows the results, which indicate that sufficient characteristics are ensured. Thus, paint adhesion can be ensured with or without passivation treatment.

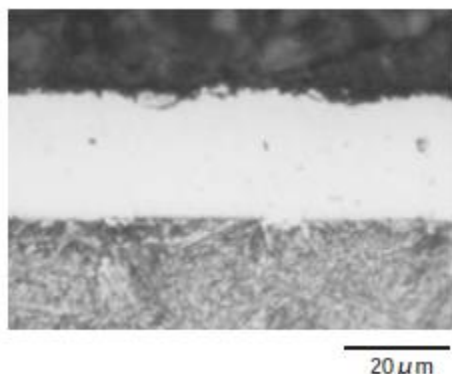


Figure 15: Cross-sectional Optical Micrograph Showing the Structure of the Plating Layer After Holding at 950°C for 5 Minutes

[18] An aluminum-plated steel sheet with 160 g/m² of plating was heated at 900°C for 2 minutes to produce Fe-Al alloy plating on the surface layer. This steel sheet was immersed in a passivation solution, and after electrodeposition coating of approximately 25 μm , the surface of the coating film was crosscut. The external appearance after 150 cycles (50 days) of combined corrosion testing (CCT) as specified in JASOM 610 is shown in Figure 17. The conditions for the JASO CCT test are as follows.

Salt spray (5% NaCl, 35°C, 2h) → Drying (60°C, 4h) → Humidification (50°C, 2h)

[19] Unplated cold-rolled steel sheets and alloyed hot-dip galvanized steel sheets (45 g/m² adhesion on one side) were used as comparison materials. These materials were subjected to passivation, and after confirming that a passivation film had been formed, they were tested. The coating blistering width from the crosscut area during the corrosion test was evaluated as the maximum blistering width on one side, and the results are shown in Figure 18. After 150 cycles, the depth of corrosion in the direction of the plate thickness was measured from the surface using a laser beam at five points per sample, the mean value and standard deviation were calculated, and the results are shown in Figure 19. These results show that the corrosion resistance of steel sheets with an Fe-Al alloy phase plating layer is superior to that of cold-rolled steel sheets in terms of both peeling width and corrosion depth, and is equivalent to that of alloyed hot-dip galvanized steel sheets. If post-coating corrosion resistance is important, the amount of plating should be about 150 g/m².

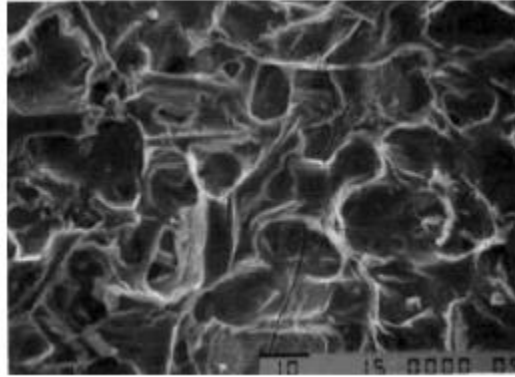


Figure 16: SEM Photograph Showing the Surface Morphology of the Plating Layer After Holding at 950°C for 5 Minutes

Table 3: Results of Paint Adhesion Evaluation

	Surface preparation	Primary adhesion*	Secondary adhesion**
Hot-formed aluminized steel	Phosphated	100/100	100/100
Hot-formed aluminized steel	Degreased	100/100	100/100
Galvannealed steel	Phosphated	100/100	100/100
Steel	Phosphated	100/100	100/100

*Primary adhesion test: 100 grid cross-cutting by 2mm and taping after painting

**Secondary test: dipping at 40°C water for 10 days and cross-cutting and taping

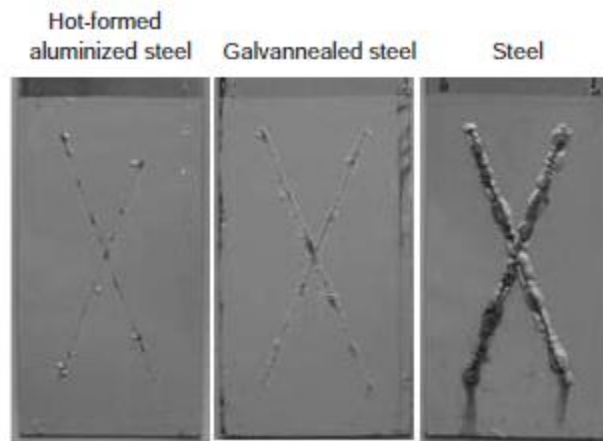


Figure 17: Appearance of Sample After 50 Days of JASO CCT Testing

6.3 Corrosion Resistance of Spot Welds

[20] Figure 20 shows the cross-sectional microstructure of the areas that were in contact with the electrode and the areas that were not in contact with the electrode during spot welding. This figure shows that the plating layer in the area in contact with the electrode hardly changes even though the temperature rises during spot welding and has the same thickness as before spot welding. Therefore, the corrosion resistance of this area after painting is not different from that of the flat plate area, and as shown in Figure 21, there is no corrosion at all even after 2000 hours of salt spray testing (SST). In the other plated steel sheets, when spot welding is performed, the plating in contact with the electrode melts and is drawn out between the electrode and base metal, causing the plated metal to rise and form protrusions. This area may not have sufficient coating thickness and may cause corrosion resistance problems.

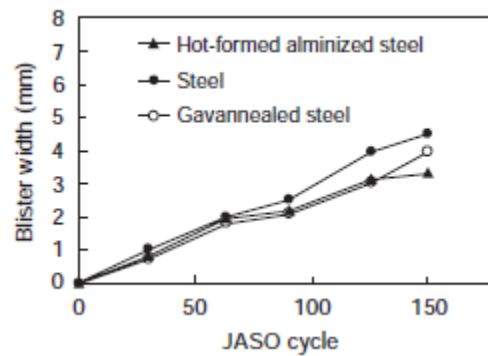


Figure 18: Change in Blister Width in JASO CCT Testing

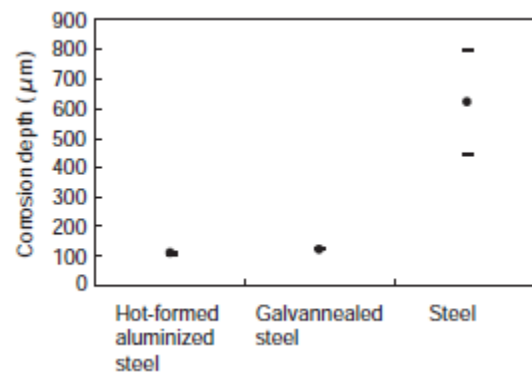


Figure 19: Change in Corrosion Depth in the Thickness Direction After 50 Days of JASO CCT Testing

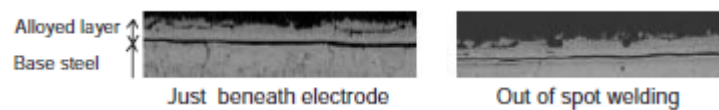


Figure 20: Plating Layer Under Electrode and Normal Area After Spot Welding (Corrosion solution: oxalic acid)

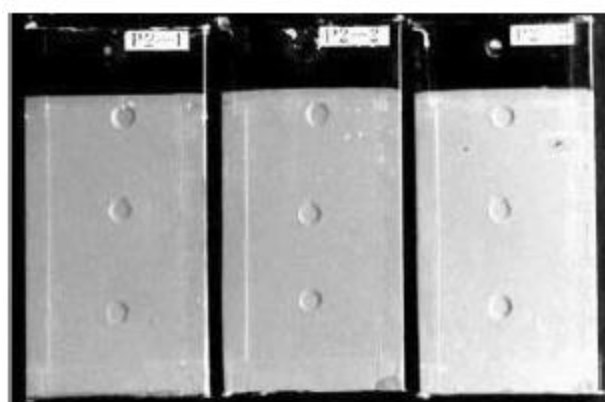


Figure 21: Appearance After 2000 hours of SST Evaluation of Corrosion Resistance After Coating of Spot Weld Area

7. Conclusion

[21] This paper describes the base metal and surface properties of aluminum-plated steel sheets for hot press applications. As for base metal properties, a part with uniform strength can be obtained if a cooling rate of 30°C/s or higher is ensured even if the cooling rate varies due to mold quenching during press forming. As for tensile properties, yield strength of 1280 MPa, tensile strength of 1530 MPa, elongation of 8%, and excellent resistance to hydrogen embrittlement are obtained. As for spot weldability, there is no deterioration due to the presence of the plating layer because the aluminum plating on the surface layer becomes an Fe-Al alloy phase with a high melting point when heated before pressing, and continuous spot weldability is excellent. As for corrosion resistance, the Fe-Al alloy phase is between that of an unplated steel sheet and that of an alloyed hot-dip galvanized steel sheet.

[22] By using steel sheets with the above characteristics in hot pressing, it becomes possible to produce high-strength, corrosion-resistant parts with relatively complex shapes.

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December 18, 2024