Effect of the strength of steel sheets and wires on residual stress of thin steel sheet lap-fillet GMA weld joint

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ABSTRACT
Weld residual stress of the lap filet GMA welding joints which was performed using two strength grades of steel sheets and two strength grades of welding wires were measured. In addition, to consider the effects of steel sheet strength and weld metal strength on welding residual stress, thermal elastoplastic analysis using FEM was carried out for the experiments. As a result of the analysis using the temperature history of the heat-affected zone as a fitting parameter, the residual stress distributions near the toe were in agreement with the measurement in the FE analysis. Comparing the residual stress distributions in the direction perpendicular to the weld line on the weld metal surface near the toe, which is the occurring point of fatigue cracks in the FE analysis results, with the same steel sheet, the higher the weld metal strength the smaller the tensile residual stress. And comparing with the same wire, the higher the steel sheet strength the higher the tensile residual stress. The reason for the former is that when using high-strength wire, cooling transformation occurs at a lower temperature than using low-strength wire. As a result, it is considered that the tensile residual stress was effectively reduced by causing transformation expansion while the surrounding strength was high. The reason for the latter is considered to be that each stress value changes based on the yield stress of the steel sheet and weld metal because the plastic strain continues to occur in each direction until transformation occurs after welding. It was considered that the larger the ratio of the hardness of the weld metal to the base metal, the smaller the ratio of the residual stress of the weld metal near the toe to the yield stress.

KEYWORDS
GMA welding; lap-fillet joint; residual stress; steel strength grade; wire strength grade

1. Introduction
Hot-rolled thin steel sheet for automobile undercarriage members is often welded by GMA welding [1]. The principal problems with GMA welds in undercarriage members involve fatigue strength and corrosion resistance. Countermeasures for corrosion resistance including maintaining the electric conductivity of welding slag [2–5] and improvement of coating properties by reducing slag [6,7] have been reported.

Known measures to maintain fatigue strength include increasing the strength of the weld metal [8] and reduction of the stress concentration factor at the weld toe [9]. Additional countermeasures for improving fatigue strength include additional processes after welding, such as blasting [10,11] and peening by UIT [12] and additional bead welding with the aim of stiffening [13] have been proposed. Since, however, additional processes after welding increase the number of processes and thus a decrease in construction efficiency, as-welded fatigue strength improvement measures are preferable. Fatigue strength improvement methods [14] by reduction of weld tensile residual stress using low transformation temperature (LTT) weld materials [15] have also been proposed, but concerns about increases in the cost of welding wire alloy elements and cracking due to a decrease in the toughness of the weld metal structure and problems associated with, for example, increases in tensile residual stress on the root side when these are applied to the fillet welds have been noted [16]. As the strength of the steel sheet is increased, to assure the static strength of the joints, even matched weld metal strength is necessary [17] and an increase in the strength of weld metal is a method that is effective for both static strength and fatigue strength.

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This is a translation from the original Work 薄鋼板重ね隅肉 GMA溶接部の残留応力に及ぼす鋼板、ワイヤ強度の影響 by 松田 和貴, 児玉 真二, published by permission of Japan Welding Society.

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It is known, on the other hand, that with welds of thick plates an increase in strength of the weld metal does not contribute to improving fatigue strength [18]. This is thought to be because the tensile residual stress of the weld increases along with the rise in yield stress and this offsets the effect of improving fatigue strength by an increase in strength. With a thin steel sheet, by contrast, the binding of the weld is small due to the thinness of the sheet and the fact that the tensile residual stress does not increase to approach the yield stress is the reason that here an increase in strength of the weld metal contributes to an improvement in the fatigue strength of the weld. Nagai et al. [19] prepared thin sheet lap fillet welds using 500 MPa steel and 780 MPa steel and subjected these welds to residual stress analysis. They reported that the results showed that compressive residual stress was generated in the base metal near the weld toe perpendicularly to the weld line and that the type of steel had almost no effect. However, in thin sheet GMA welds the origins of fatigue cracks are in the surface of the weld metal in the weld toe vicinity [20] and therefore the residual stress at this position is thought to affect weld fatigue strength. In the case of thin sheet GMA welding, the literature includes a few examples of detailed investigations of residual stress in the weld metal surface near the weld toe.

In the present study, lap fillet GMA welding was performed using two types of steel of different strengths and two types of welding wire, and the weld residual stress was measured. In these tests, thermo-elastic-plastic analysis was performed using FEM. The results are described with the effects of steel sheet strength and weld metal strength on weld residual stress taken into account.

2. Tests

2.1. Test materials

The test materials were SPFH590Y (JIS G 3134) and a specially produced hot-rolled thin steel sheet with a tensile strength of 980 MPa, and a thickness of 2.9 mm in all cases. The test welding wires were wire A (JIS Z 3312 YGW16) for mild steel and 490 MPa steel and wire B (corresponding to AWS A5. 28 ER110S-G) for 780 MPa steel and both were 1.2 mm diameter solid wire for use with Ar + CO₂ mixed gas. In this article, GMA weld specimens were prepared in four combinations using these two types of test steels and two welding wires.

2.2. GMA welding

Figure 1 is a schematic illustration of lap fillet GMA welding. The dimensions of both the upper and lower sheets of the specimen were 80 × 150 mm and the overlap was set at 10 mm. In GMA welding, a tack weld was first carried out at a position 10 mm from the edge of the sheet to the side of the weld end, then welding was performed over a welding length of 120 mm starting and ending 15 mm from each sheet edge. The GMA welding conditions are shown in Table 1. The restraint by the jig was released 180 s after welding, then the weldment was left on the jig and air-cooled. It was evident from Figure 14 below that the steel sheet temperature fell to ~100 °C by 100 s after welding and at 180 s the interior temperature of the

![Figure 1. Schematic illustration of lap fillet GMA welding.](image)

| Table 1. Welding conditions. |
|-----------------------------|
| **Current** | **A** | 235 |
| **Voltage** | **V** | 27.2 |
| **Speed** | m/min | 0.8 |
| **Torch angle** | deg. | 60 |
| **Shield gas** | Ar + 20%CO₂ |
| **Mode** | D. C. Pulse |
weld metal had fallen sufficiently for there to be no effect on welding residual stress.

The temperature history was measured during welding by thermocouples at a position on the front surface of the lower sheet 15 mm from the seam, shown as $\textcircled{1}$ in Figure 1, and a position at the back surface of the edge of the upper sheet, shown as $\textcircled{2}$ (10 mm from the edge). All of the specimens were welded at $n = 2$ and the temperature history was measured only when wire A was used.

The clamps were copper and the spacer beneath the upper sheet was steel. The restraints held the steel sheet uniformly in the direction of the welded line and the clamps that fixed the restraints were almost immediately above the welding start and end, as shown in the schematic illustration in Figure 1. Toggle clamps were used to fix the jigs and care was taken to fix the clamps with, as far as possible, the same load but, since some variation was unavoidable, the fixing load imposed by the clamps was measured. The fixing force was measured by measuring devices, adjusted to be the same thickness as the specimen, fixed by clamps. Measurement was performed 3 times.

### 2.3. Residual stress measurement

The residual stress of the specimen after welding was measured using an X-ray residual stress measuring device. The measuring positions for residual stress are shown in Figure 2. As shown in Figure 2, the X-direction residual stress in the base metal was measured at nine points at a 10 mm pitch and with a collimator diameter of 0.5 mm, at a position 10 mm from the weld line on the lower sheet (~5 mm from the weld toe on the lower sheet side).

### 2.4. Cross-sectional observations

Cross-sectional samples were taken from the centre of the weld bead after completion of the X-ray residual stress measurement of the specimens following GMA welding. The surfaces were etched with a picric acid aqueous solution and the weld cross-sections were inspected by optical microscopy. In addition, the Vickers hardness was measured linearly at a depth of 0.1 mm from the lower sheet surface of the same sample.

### 3. Test results

The measurement results for clamp loads are shown in Table 2. As is clear from Table 2, the binding force of the clamp load is somewhat higher on the S side and the total load applied to the fixing jig on the upper sheet side was 268 kgf.

Figure 3 shows the measurement results for X-ray residual stress. It is clear from Figure 3 that there is protrusive behaviour with a peak near the centre of all the sheets and the maximum value was $\approx 330$ MPa for samples other than 590-B, where it was $\approx 250$ MPa. Nagai et al. [19] also measured the base metal residual stress of thin sheet steel lap fillet welded GMA joints and found that the residual stress at this location (on the base metal surface 5 mm from the weld toe at the centre of the weld line) is tensile, a tendency that agreed with our findings.
Figure 4 shows photographs of the penetration shapes of the welds taken using an optical microscope. It is clear from these that the weld metal shapes obtained in all the specimens were broadly similar. Figure 5 shows the results for linear Vickers hardness measurements at a depth of 0.1 mm from the steel sheet surface. It is clear from Figure 5 that with 590-A the weld metal was slightly harder than the base metal while there was an overmatch with 590-B, an undermatch with 980-A, there was almost an even match with 980-B.

4. FEM analysis

Thermoelastic-plastic analysis by FEM was performed during GMA welding tests. MSC.Marc 2014 was used for the analysis code.

4.1. Analysis model

The analysis model was a three-dimensional 1/1 model and 8-node hexahedron solid elements were used as the elements. The outline of the model is shown in Figure 6 and the mesh division around the weld area in Figure 7. The weld area was divided into eight mesh divisions (2.9 mm/8 = 0.36 mm) in the sheet thickness direction. At the start of the analysis, the weld reinforcement was in a state where Young’s modulus was multiplied by 10^{-5}, and the build-up by welding was expressed by replacing the weld metal elements, including the penetration part, as the torch (the heat source) was moved.

4.2. Physical properties

Figure 8 shows the relationship between the various physical properties and temperatures used in the analysis. The coefficient $h$ of the heat transfer to the copper sheet was defined as in Equation (1) below using the thermal conductivities of steel and copper.
\[ h = C \frac{k_{Fe}k_{Cu}}{k_{Fe} + k_{Cu}} \]  

Here, \( k_{Fe} \): thermal conductivity of steel, \( k_{Cu} \): thermal conductivity of copper (\( = 402 \text{ [W/mK]} \)), \( C \): correction factor \([/m]\)

The copper plate was kept at constant room temperature. The thermal conductivity of the steel sheet has the temperature dependence as shown in Figure 9. A correction factor \( C \) of 0.1 (\( = 10\% \)) was used to fit these with the results for temperature measurement of the base metal described below. The same value for the temperature dependence of thermal conductivity was used for both the base metal and weld metal. In addition, a Formastor test was conducted on each of the steel sheets and the weld metal to measure the relationships between temperature and elongation. The Formastor test conditions were a temperature rise rate of 30°C/s, maximum temperature of 1200°C, and a cooling rate of 10°C/s. After the test, the weld metal microstructures were a mixed microstructure of ferrite and bainite in 590-A and 980-A, and a martensite microstructure in 590-B and 980-B, and these matched the microstructures of actual weld metals. The instantaneous coefficient of linear expansion was found by differentiating by temperature the relationships between temperature and elongation obtained by Formastor tests and these were further simplified for analysis. Since in the temperature range above 1200°C the microstructure was considered to be single-phase austenite, the instantaneous coefficient of linear expansion in the austenite region was used over this wider area. The temperature dependence of the coefficients of linear expansion thus obtained is shown in Figure 10. The coefficients of linear expansion for heating and cooling of the base metal (BM) were calculated. The coefficients of linear expansion for the weld metal were set solely for cooling since no weld metal existed during the temperature rise.

The temperature dependency of the stress-strain relationship was found by converting the data obtained in the high-temperature tensile tests into true stress. The temperatures were a constant room temperature (23°C), 200, 400, 600, and 800°C and in each case, heating to the required temperature was performed using an infrared furnace. The tensile rate was set to
2 mm/min. Since it could not be considered the thermal history of the welding and the differences in microstructures in the heat-affected zone, the stress-strain diagram may differ somewhat from the actual stress. But as it would be difficult to reproduce all of the thermal histories of the heat-affected zones, in this study the stress-strain diagram was treated as such in this study. The stress-strain relationship used in the analysis is shown in Figure 11. It is clear from Figure 11 that the decrease in strength of the two metals from room temperature to 400°C was gradual but the strength decreased rapidly at 600 and 800°C. Since the wire components were mixed with the weld metal, it was preferable to measure the stress-strain relationship of the base metal apart from the base metal. Since in this study, the tensile test specimens could not be taken from the weld metal, the hardness ratio of weld metal to base metal as shown in Table 3 was calculated and the stress-strain relationship of the weld metal as shown in Figure 11 was found by multiplying the stress-strain relationship of the base metal by this. The mean values for the hardness of the base metal and weld metal, as shown in Table 3, were found from the Vickers hardness distribution of the weldment shown in Figure 5. The relationships between the temperature and yield stress of each of the base metals and weld metals are shown in Figure 12. The yield stress and stress-strain diagram above 800°C were the same values as at 800°C. The yield stress and stress-strain diagram gave priority to the convenience of obtaining physical property values, there was no apparent distinction between heating and cooling. The effects of these on the analysis results can be assessed indirectly through a comparison between the test results and analysis results, as described below.

### 4.3 Boundary conditions and analysis conditions

The boundary conditions for the model set for FE analysis are shown in Figure 13. Atmospheric heat dissipation was the main condition at the periphery of the model and boundary conditions that take heat dissipation associated with the copper sheet into consideration were set for the immediate region restrained by the jig. Since the jig was copper, the back surface of the lower sheet for example was in contact with the copper sheet under the test conditions, but this contact with the copper sheet ended almost completely due to slight deformation of the sheet by welding and it was therefore decided only to consider atmospheric heat dissipation throughout the analysis. The jig was defined as a contact element for a rigid body. The jig of the bottom is regarded as being immovable and the test specimen model positioned on top of this, and a load of 268 kgf applied from above to the contact element to restrain the test specimen. The load was determined based on the measurement results for clamp loads shown in Table 2. The pressure applied by this jig was released in coordination with the test at 180 s from completion of welding. Since it was anticipated that there would be no contact with the copper sheet jig due to the resulting deformation of the specimen after releasing the jig, a change was made to

| Table 3. Vickers hardness and its ratio of weld metal to base metal. |
|------------------|------------------|
| HV 0.2 | /BM |
| 980BM | 314 | 1.00 |
| 980-A | 259 | 0.82 |
| 980-B | 321 | 1.02 |
| 590BM | 208 | 1.00 |
| 590-A | 224 | 1.08 |
| 590-B | 256 | 1.23 |
atmospheric heat dissipation from the entire test specimen periphery. After releasing the jig, the test specimen temperature was cooled to nearly room temperature (23°C) at which point analysis was ended.

Schematic diagrams of the bonding of the upper and lower sheets on the weld line are shown in Table 4. First, within the ranges $0 \leq y \leq 15$ and $145 \leq y \leq 150$, the upper and lower sheets were completely separated. Within
the range $135 \leq y \leq 145$, the upper and lower sheets were bonded only over a width of 0.9 mm throughout the analysis. This is the region where the tack welding is in the test. The temperature history of the tack welding was considered to be reset by the main welding. In the region of $15 \leq y \leq 135$, the upper and lower sheets were bonded over a width of 0.9 mm, the same as with the tack welding before the main welding and, after welding, these were sequentially replaced by weld metal elements and furthermore the physical property values were also changed to those of the weld metal. Although originally the upper and lower sheets were in a separated state before welding, since replacement by weld metal elements would be very troublesome if the upper and lower sheets were misaligned, slippage of the upper and lower sheets was minimized by tack welding, and it was assumed for the analysis that slippage between the upper and lower sheets was prevented before the torch passed.

The elements of the reinforcement part of the weld metal were found by multiplying Young’s modulus by $10^{-5}$ before welding and were in a state of no thermal conduction, and the temperature was set to $1500 \, ^\circ C$ at a welding speed of $0.8 \, m/min = 13.33 \, mm/s$ from the start of welding while returning the element Young’s modulus to single-fold. Due to this, the elements of the weld metal reinforcement are formed to match the shape of the base metal deformed during welding and the weld metal only undergoes shrinkage deformation due to cooling. Since the length of the weld metal elements in the weld line direction is 1 mm, advance through each element takes $1 \, mm \div 13.33 \, mm/s = 0.075 \, s$. The holding time at a temperature of $1500 \, ^\circ C$ was 0.6 s. This corresponds to the length of the molten pool $0.6 \, s \div 0.075 \, s = 8 \, mm$. No comparison was made with the measurement results for the length of the molten pool and the $1500 \, ^\circ C$ holding time was set by fitting this to the temperature measurement results for the base metal, as described below.

Thermal conduction analysis was performed under these heat input conditions and Figure 14 shows a comparison between the measurement results and the analysis results for the temperature history at measurement points 1 and 2 shown in Figure 1. The highest temperature attained at point 3, 15 mm on the front surface of the lower sheet 15 mm from the

| Range: years | Schematics of model | Remark |
|-------------|---------------------|--------|
| $0 - 15$, $145 - 150$ | | The upper and lower sheet are separated |
| $15 - 135$ | | The upper and lower sheet are continuous only in the range of 0.9 mm width |
| After welding | | Weld metal shape is adopted Material properties of weld metal is applied. |
| $135 - 145$ | | The upper and lower sheets are continuous only in the range of 0.9 mm width (Tack weld part) |
seam (the edge of the upper sheet), was 300–400 °C and the highest temperature attained at point 2, at the back surface of the edge of the upper sheet immediately below the welding position, was 1000–1100 °C. It can also be seen that the analysis results and measurement results broadly match. In the case of the highest temperature attained at the measurement point 1, the analysis result was higher than the measurement result and the change is more rapid, but this is thought to be due to a delay in tracking due to the thermal capacity of the thermocouple.

Since in the analysis, heat input was performed by applying a temperature of 1500 °C to the weld metal elements, the correspondence of this to the heat input calculated from the welding conditions shown in Table 1 is not clear. Accordingly, the welding heat input was estimated in a simplified form by finding the total of the amount of heat required to raise the temperature of the weld metal elements from 23 to 1500 °C and the amount of heat that flows to the base metal within 0.6 s after the torch has passed (calculated from the temperature rise of the base metal elements). Since radiation from the test specimen surface and the heat dissipation due to heat transfer are not included in this value, the evaluation is a slight underestimate. The proportion of this value to the quantity of heat calculated from the welding conditions (current × voltage/welding speed) is 61% and since the thermal efficiency of conventional MAG welding is said to be 60–90%, the heat input method in this analysis seems to be appropriate for the quantity of heat input.

4.4. Analysis results

A contour diagram of z-direction (sheet thickness) displacement in 590-A when the analysis is completed is shown in Figure 15. The lower sheet side base metal experiences vertical deformation with which the weld bead side becomes convex and also angular deformation with which the weld bead side becomes concave. In addition, the deformation of the upper sheet side base metal is small and this is thought to be due to jig restraint.

Figure 15 shows a comparison between the measurement results as given in Figure 2 and analysis results for (x-direction) residual stress of the base metal in the vicinity of the weld. It is clear from Figure 16 that convex tensile residual stress is created on the top of all of the test specimens and the analysis results are a good match with the test results. The analysis results are thus capable of reproducing the test results.

5. Discussion

Since, as described above, the measured values for the base metal residual stress in these tests matched the FE analysis results, the residual stress in the weld metal is discussed using the FE analysis results. There is a risk of fatigue cracking in lap fillet welded joints at the weld metal surface in the vicinity of the molten boundary at the weld toe on the lower sheet side [20]. Therefore the residual stress at this position has the greatest effect on the fatigue...
strength of the weld. Accordingly, Figure 18 shows residual stress in the x-direction, orthogonal to the weld line in the weld metal elements closest to the weld toe on the lower sheet side at the centre of the weld line, as shown in Figure 17. In Figure 18, the yield stress of each weld metal at room temperature was plotted along with the values obtained by dividing the residual stress by the yield stress. It is clear from Figure 18 that the x-direction residual stress in the weld metal near the weld toe is greater in 980 MPa steel than in 590 MPa steel, whatever the welding wire and that wire A showed greater residual stress than the high-strength wire B.

5.1. Stress and plastic strain

To discuss the behaviour of residual stress, it’s first necessary to consider each stress component and the plastic stress from the beginning of welding to after the end of welding. First, Figure 19 shows the temperature history at the weld metal surface near the toe at the bead centre (point M), shown in Figure 17. There is a plot of (1) the time when the welding torch passed, (2) the time when the welding of the test specimen was completed and the transformation start and finish temperature of each specimen during cooling were plotted together. As one example, these are plotted along with the
temperature history of the point on the reverse side immediately below point M in 590-A steel. It is clear from Figure 19 that there were almost no differences in the temperature histories under all of these conditions and that the temperature at the bead centre at the end of welding had fallen to \( \sim 800^\circ\text{C} \).

The time histories of the stress in the various directions at this position are shown in Figure 20. It is evident from direction x in Figure 20(A) that the stress decreased during transformation. It is clear that, with steels 590-A and 980-A, in which the start point of transformation is comparatively high, transformation occurs without the stress value varying significantly after completion of welding, and after the end of transformation (at the final stage of transformation in the case of 590-A) the stress value increased. With steels 590-B and 980-B in which the transformation temperature is low, it is clear that stress increased before transformation, then decreased during transformation. It is also clear that in all of these cases, both an increase of stress and a decrease due to transformation occur, with the result that 590-B has the smallest residual stress. The magnitude correlation of the x-direction stress at the 50 s point matches the magnitude correlation of the residual stresses at room temperature shown in Figure 18. It is thought that the transition of stress within 50 s corresponds to the residual stress behaviour at room temperature. It is clear from the y-direction in (b) that the stress in the weld line direction increases in each case after the completion of welding until transformation occurs, and then decreases during transformation to increase again after transformation ends. With the exception of 590-B, the stress behaviours after transformation are an approximate match and in the case of 590-B, the

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**Figure 19.** Temperature time histories.

**Figure 20.** Stress components time histories.
y-direction stress is lower than in other conditions. It is evident from (c) that, although stress in the sheet-thickness direction shows large differences under each of the conditions before and after transformation, the differences between the conditions after the end of transformation are small. Although the sequence in each of the directions differs according to the conditions, decreases in stress due to transformation expansion are preceded and succeeded by increases in stress. Since there are differences between the temperature histories in the weld line direction, these stress increases are thought to be due to transformation expansion at positions before and after point M.

The time histories of the plastic strain components at the same position are shown in Figure 21. Most of the plastic strain in each of these directional components occurs while the yield stress at high temperature is low. The plastic strains in the x and z directions are in the compressive direction and that in the y-direction is in the tensile direction. The plastic strain is greatest in the y-direction, smaller in the z-direction, and smallest in the x-direction.

5.2. Deformation in the weld line direction

The deformation in the weld line direction where the plastic strain was the greatest is described below. Deformation in the weld line direction included vertical deformation in which the weld line bends to form a peak and also contraction deformation of the whole bead. In order to assess these, the amount of vertical deformation $D_z$ and amount of longitudinal contraction $D_y$ were defined, as shown in Figure 22, using the bead start (point S), centre (point M), and end (point E) as coordinates. The time histories of the amount of vertical deformation and longitudinal contraction are shown in Figure 23. As is clear from Figure 23, the degree of deformation during welding is dependent on steel sheet strength; vertical deformation increases when the base metal is strong, and longitudinal contraction increases when the strength is low. For the purposes of this discussion, the period from the start of welding to the deformation of the weld metal during cooling is divided into 4 regions according to vertical deformation and contraction behaviours. A schematic diagram of the deformation in the weld metal and base metal in each of these regions is shown in Figure 24. In Figure 24, the deformation near the centre of the weld bead (point M) is assumed. At point M, although the time of the torch’s
passage is different by ±4.5 s between the start (point S) and the end (point E), the stationary region of the weld bead is considered to be the part that most affects weld deformation and deformation of the test specimen overall is therefore discussed in terms of the behaviour near the centre of the weld bead.

First, in region A, which is from the start of welding until welding has reached the bead central area, slight vertical deformation occurs and then decreases, and longitudinal contraction occurs immediately after the start of welding. It is evident that, in Figure 24(A), immediately after welding, the weld metal is at a high temperature near melting point, the yield stress is very small and there is almost no strength. Due to thermal conduction from the weld metal, there is a temperature gradient

Figure 23. Time histories of z deformation $D_z$ and y contraction $D_y$.  

Figure 24. Schematic illustration of deformation in base metal and weld metal during welding.
from the top to the bottom of the base metal and the upper part shows an upward convex vertical deformation due to thermal expansion. The weld is restrained by the jig but when the welding has progressed to some extent and the rigidity of the part which undergoes pressure from the jig decreases due to the temperature rise, the vertical deformation due to jig pressure decreases. Also, the temperature rise in the weld metal elements at the weld toe ends <1 s after the torch has passed and cooling then begins. Since contraction occurs consistently during the initial stage of cooling, longitudinal contraction occurs in all of the test specimens. Next, vertical deformation increases rapidly in region B where the welding torch has progressed from the bead centre to about 3/4 of the distance towards the end. The longitudinal contraction continues from region A. It is evident from Figure 24(B) that strength increases as cooling increases from the bottom of the base metal where the temperature is lowest, and upward convex vertical deformation increases due to the contraction of the bottom of the base metal. Cooling occurs overall and longitudinal contraction continues from region A. In Figure 24 the arrows in (A) indicate thermal strain immediately after the welding torch has passed, and the arrows in (B–D) indicate the thermal strain occurring at arbitrary points, although it should be noted that these do not always match the actual deformation direction. For example, as shown in Figure 21(B), y-direction tensile plastic strain occurs constantly in the weld metal from the start of welding to immediately after welding. This is because the contraction is restrained peripherally during the cooling process of the weld and the weld metal is located at the outside of the bend when convex bending deformation occurs at the top. In region C, which is the final stage of the welding, the degrees of vertical deformation and longitudinal contraction change according to the strength of the base metal. With 980 MPa steel, vertical deformation continues to increase in region B, but with 590 MPa steel, vertical deformation ceases to increase and longitudinal contraction is more marked than in 980 MPa steel. It is clear from Figure 24(C) that cooling progresses more in region C than in region B and the strength of the weld metal starts to improve. Since, however, in 980 MPa steel, the strength at low temperatures is higher than in 590 MPa steel, the difference in yield stress at the same temperature difference is greater than in 590 MPa steel. Due to this, deformation is dependent on the contraction of the base metal at lower temperatures and, as in the case of region B, upward convex vertical deformation is large. With 590 MPa steel, on the other hand, the difference in strength between the low-temperature base metal and high-temperature weld metal is small and the uniform contraction correspondingly great. Finally, in region D, the stage at which welding is completed and the entire test specimen begins to cool, with 980 MPa steel the increase in upward convex vertical deformation changes to a decrease, and the direction changes to downward convexity. With 590 MPa steel, on the other hand, increases and decreases in vertical deformation are small. It is clear from Figure 24(D) that with 980 MPa steel, the difference in strength between the weld metal and base metal reduces when the cooling of the weld progresses further. Further, since the weld metal is at a higher temperature than the base metal and the cooling rate is faster, it is thought that the magnitude correlation between the thermal stresses produced by the weld metal and base metal reverse, and vertical deformation tends to change to a convex downward direction. On the other hand, although a similar phenomenon occurs with 590 MPa steel since the strength of the base metal is small, it is thought that uniform contraction continues from region C. In the case of 590-B in particular, it is clear from Figure 23(A) that the amount of vertical deformation changes very little in region D, and the behaviour is the closest of the four conditions to uniform contraction. As shown in Figure 21(C), the z-direction compressive plastic strain is greater in 590 MPa steel than in 980 MPa steel. It is also thought that this is supporting evidence for the supposition that, in y-direction deformation, the proportion of uniform contraction to bending deformation is greater in the 590 MPa steel than in 980 MPa steel. The comparison of the front and back temperature histories in Figure 19 shows that the front/back temperature difference at the 15 s point is <10 °C, which means the temperature distribution in the sheet thickness direction decreases until about 15 s, and deformation behaviour then gradually changes to a uniform contraction. Figure 24
schematically illustrates deformation behaviour in terms of temperature differences and strength differences between the weld metal and base metal and, although the discussion above has been based on deformation and stress in the weld line direction, it is thought probable that similar deformation behaviour also occurs in the direction orthogonal to the weld line.

**5.3. Influence of base metal and wire strength**

First, the reason that the tensile residual stress increases when a high-strength wire is used, is discussed. It is clear from Figure 21(B) that y-direction tensile plastic stress after welding continues to increase until the stress relaxes due to transformation expansion. In particular, in 590-B and 980-B in which the transformation point is low, the increase in the tensile plastic strain in region D is large, and the deformation is shown in Figure 24(D) continues for longer than in 590-A and 980-A. In the deformation in region D, tensile plastic deformation occurs but since there is relatively little contraction due to thermal strain, the weld metal dimensions are reduced and strain in the weld metal is relaxed. Accordingly, it is thought that the longer the deformation period in region D, the lower will be the residual stress of the final weld metal. Since the strength of the entire test specimen increases as cooling progresses further and since expansion due to transformation in 590-B and 980-B occurs in a state in which plastic deformation does not readily occur, expansion strain generated in the weld metal effectively reduces the tensile stress and, as shown in Figure 18, reduces the final residual stress. This behaviour is evident in 590-A and 980-A, where the stress decreased by transformation increases with the subsequent cooling due to the x-direction stress shown in Figure 20(A), but this increase is less in 590-B and 980-B due to the start of transformation being later. The phenomenon in which residual stress is reduced in the low transformation-temperature weld metal is widely known and it is used in LTT weld materials [14]. It is also clear that tensile residual stress is relaxed by a reduction in the transformation temperature of the weld metal even with the solid welding wire for 780 MPa steel used in this test.

The effects of the strength of the base metal are discussed next. It is evident from Figure 21 that until transformation occurs after completion of welding, plastic strain continues to occur in each direction and it is considered that each stress value changes based on the yield stress of the metal sheet and the weld metal and this is a causal factor for the tensile residual stress being finally greater in 980 MPa steel than in 590 MPa steel. It is also clear from Table 3 that when the strength of the weld metal is greater than that of the base metal, the thermal contraction stress produced in the weld metal, as shown in Figure 24, becomes greater than that in the base metal and is capable of relaxing the residual stress in the final weld metal. The greater the weld metal hardness/base metal hardness (β/σ), as shown in Figure 18, generally becomes smaller. Since, however, when the high-strength wire is used, the welding residual stress decreases due to the effects of transformation at low temperature, as described above, when 980-B and 590-A with similar weld metal hardness/base metal hardness are compared, the σR/σY value is clearly lower in 980-B. Accordingly, the fact that 590-B, the combination of low-strength 590 MPa steel base metal and high-strength wire with which the residual stress is smallest under the conditions used in this study and the x and y direction stresses in 590-B are the smallest, as shown in Figures 20(A,B), is for the above reasons.

**6. Conclusion**

In this study, lap fillet GMA welding was carried out using two types of steel sheets with different strengths and two types of welding wire, and the weld residual stress was measured. In these tests, thermal elastic-plastic analysis was performed using FEM for the examination of the effects of steel sheet strength and weld metal strength on weld residual stress. The results obtained were as follows.

1. As a result of conducting thermal-elastic-plastic analysis using the temperature history of the base metal in the weld vicinity as the fitting parameter, a good match between measurement and FE analysis was obtained for the residual stress distribution in the weld start vicinity.
According to the FE analysis results, comparisons of the residual stress distribution in a direction orthogonal to the weld line on the weld metal surface near the weld toe, the fatigue crack initiation point, in the same type of steel showed that tensile residual stress was smaller at greater weld metal strengths and the comparisons when the same wire was used showed that tensile residual stress was greater at greater steel sheet strengths.

3. The reason for the former of these is that tensile residual stress is reduced more effectively when the high-strength wire is used than when wire for mild steel is used due to transformation occurring at low temperatures during cooling and strain occurring due to transformation expansion when peripheral strength is high.

4. The reason for the latter is considered to be that plastic strain continues to occur in every direction until transformation occurs after completion of welding and stress values change according to the yield stress of the steel sheet and the weld metal.

5. When the strength of the weld metal is greater than that of the base metal, thermal contraction stress generated in the weld metal becomes greater than that in the base metal, allowing relaxation of residual stress in the final weld metal. The greater the ratio of weld metal hardness to that of the base metal, the smaller is the ratio of residual stress to the yield stress in the weld toe vicinity.

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