Flux Cored Wire for Steel Sheet with Fatigue Strength Improvement*

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A flux cored wire for steel sheet welding in automobile industries has been developed. The present wire is designed to reduce the slag formation to the level of conventional solid wire by controlling oxides in the flux. The present wire also contains comparatively high C, Ni and Cr so as to improve fatigue strength of a lap joint. The experimental results of plane bending fatigue tests reveal that the fatigue strength at 2 million cyclic loading is about 50% higher than that of ordinary solid wire. The charpy tests using the 1/4-size V notch specimens show that the absorbed energy of the present wire’s weld metal at –40°C is almost equivalent to that of the conventional solid wire. Hence, it is concluded that the flux cored wire developed in the present work can be applied to steel sheet welding in automobile industries with high fatigue strength and high charpy impact properties.

Key Words: steel sheet welding, flux cored wire, slag, fatigue, charpy property

1. Introduction

In the automobile industries, solid wires are mostly used. One of the merits of solid wires is small amount of slag formed on the weld metal. However, the flexibility of the solid wires about change in chemical compositions is not so good as that of flux cored wires. The flux cored wire, since it is easy to control the chemical contents of the flux inside the wire, has high flexibility about the modification of chemical compositions. The recent trends show that higher tensile strength steels are likely to be used in automobile industries, and consequently the welding consumables may be requested to meet the same mechanical requirement of the base material such as fatigue strength. To meet the requested mechanical properties, the chemical compositions of the wire should be flexibly controlled.

In the case of high tensile strength steels, fatigue properties of welded joints tend to become crucial. As is well known, the fatigue strength of a welded joint does not increase although the strength of steel becomes higher1). One of the reasons for this phenomenon is said to be the residual stress and the stress concentration. Recently, Ohta et al.2) utilized the residual stress to improve fatigue strength of a welded joint. They used the 10%Ni and 10%Cr type solid wire to reduce the transformation temperature of the weld metal, and the volumetric expansion accompanying with the phase transformation is used to make the residual stress at the weld toe compressive, which improves the fatigue strength. This kind of wire is so called LTT wire (Low Transformation Temperature). The transformation temperature of 10%Ni-10%Cr wire is about 250°C. On the other hand, Tominaga et. al.3) reported that 350°C transformation temperature is sufficient to improve the fatigue strength.

In the present work, we develop a flux cored wire applicable to steel sheet welding with the reduction of slag formation. In order to improve fatigue strength of a lap joint, we add C, Ni and Cr to the wire to reduce the transformation temperature to about 350°C. Since the restraint of sheet welding is very low, we consciously use C to avoid high Ni and Cr contents. We also examine the charpy impact properties of butt welds, which will be shown later.

2. Experimental procedure

In the present work, we conduct three types of experiments, i.e., the weight measurements and the chemical analysis of slag, the fatigue tests to examine the effects of chemical compositions of the weld metals, and the charpy impact tests of butt joints. Their purposes are to reduce the slag formation to the extent of solid wires, to improve fatigue strength of a lap joint (a typical joint of steel sheet welding), and to confirm the toughness of a welded joint. All experiments are for developing a flux cored wire applicable to sheet welding.

2.1 Weight measurements and chemical analysis of slag on the weld metal

Table 1 shows the chemical compositions of flux cored wires made on an experimental basis. The wires A1 to A5 are for the chemical analysis of the slag and the wires B1 to B3 are to examine the effect of oxides in the flux on the slag formation. We firstly conducted the bead on plate welding whose welding condition is shown in Table 2. The weld bead was just 250mm, and the base metal is conventional 780MPa grade steel with the thickness of 3.2mm. After completing the welding, we measured
the weights of the welded steel sheets, and then removed all of the slag formed on the weld metal. The slag removed from the sheets was used for the chemical analysis. After the slag removal, we again measured the weights of the sheets. The difference between the weights before and after the slag removal is defined as the weight of the slag.

### 2.2 Fatigue tests and the residual stress measurement

Since a typical joint of sheet welding is a lap joint, we conducted lap joint welding whose welding condition is shown in Table 2. The flux cored wires used for fatigue tests are C1, C2, C3 and D1 wires shown in Table 1. The fatigue test specimens whose dimension is illustrated in Fig. 1 were machined from the lap joints. The plane bending fatigue tests were conducted under the condition that the stress ratio, R, is 0.1. The strain gauge was attached to the specimen in order to confirm the stress level in the vicinity of the weld toe. In the present study, we define the fatigue strength as the maximum stress range of 2 million cyclic loading at which no fatigue crack was observed. For example, the fatigue strength 300MPa means that the fatigue stress that ranges from 33MPa to 333MPa was 2 million times applied to the specimen and that no fatigue crack was observed. We also conducted the deposited metal experiments to examine the relation between the chemical compositions of the wire itself and the all weld metal. The welding condition of the deposited metal experiments is the same of the bead on plate welding, and the welding procedure with the V groove is described in JIS Z 31111). At the same time, we measured the residual stress of the specimen by the X-ray method to discuss the mechanism of the fatigue strength improvement.

In addition, the formaster specimen of 3mm diameter and 10mm length was machined from the deposited metal of D1 wire to measure the transformation temperature. Furthermore, we conducted the butt joint welding to examine the charpy properties of the weld metals.

### 3. Result and discussion

#### 3.1 Reduction of slag formation

Table 3 shows the chemical compositions of the slag of A1 to A5 wires. From Table 3, we can see that the slag mostly consists of oxides such as SiO₂. In addition, these five types of slag hardly contain Ni, Cr and Mo. This means that Ni, Cr and Mo do not contribute to the formation of slag. We also found that this tendency is not influenced by carbon. These results are considered very favorable because we can use such elements to reduce the transformation temperature of the weld metal without worrying about the slag formation.

The fact that the slag mostly consists of oxides means that the
reduction of oxides in the flux may be effective to reduce the slag formation. In fact, the flux inside the wire contains some amount of oxides for several purposes. Hence, we reduce the oxides in the flux without any difficulty in welding and examine the effect on the slag formation. B1, B2 and B3 wires were prototyped to measure the weight of the slag. B2 and B3 wires are designed to reduce the slag formation. Fig. 2 shows the results of the weight measurements. To compare the case of an ordinary solid wire (YGW110, symbol is SW), we also measured the weight of the slag using the solid wire and the results are also included in Fig. 2. Fig. 2 shows that the formations of the slag of B2 and B3 wires are almost as low as that of the solid wire with 100% CO₂ shielding gas. Fig. 3 shows the bead appearances of B1, B2 and the solid (SW) wires. It can be seen that the amount of slag of B1 wire is larger than those of the others. The minimum slag formation is of the solid wire (SW) with Ar + 20%CO₂ shielding gas. However, since 100% CO₂ welding with solid wires is acceptable for today’s automobile industries, we concluded that the reduction of oxides in the flux cored wire to 0.25% is sufficient for sheet welding use.

3.2 Fatigue strength improvement

C1, C2 and C3 wires were used to examine the fatigue strengths of lap joints. As shown in Table 1, C3 wire itself contains 0.6% carbon. In general, such a high carbon wire is likely to occur solidification cracking in the weld metal. However, we found no cracking. The reason is probably that the restraint of the lap joints, thanks to thin sheets of 3.2 mm thickness, is very low and that the carbon content of the weld metal is expected not to be as high as 0.6%. Table 1 also shows the chemical compositions of the deposited metals of C1, C2 and C3 wires. Fig. 4 shows the relationship between the carbon contents of the wire and the deposited metal. From Fig. 4, we see that the carbon content of the deposited metal of C3 wire is 0.35%, which is about 60% of that of C3 wire itself. The same tendency that the carbon of the deposited metal is about 60% of that of the wire can be recognized in both cases of C1 and C2 wires. This is probably because the carbon inside the wire partly reacts with oxygen to form CO and/or CO₂ and escapes from the weld. On the other hand, in the case of Mn, Ni, Cr and Mo, the chemical compositions of the wire and the deposited metal are almost the same. Hence, to keep some amount of carbon in the weld metal, which is necessary to reduce the transformation temperature, we need to add considerably high carbon to the wire. The carbon contents of C1, C2 and C3 wires were determined considering this phenomenon.

Fig. 5 shows the S-N curves of C1, C2, and C3 wires. We can see that the fatigue strength increases as the carbon content increases from C1 to C3 wires. Fig. 5 also includes the experimental results of the solid wire (SW). We understand that the fatigue strength of C1 wire under the condition of 2 million cyclic loading is almost the same of the solid wire (SW) (more precisely, the fatigue strength of C1 wire is slightly higher than that of SW wire, but the difference is less than 10%), while that of C3 wire is about 50% higher. The reason of the fatigue strength improvement is considered due to the reduction of the phase transformation temperature. But, 0.35% carbon in the weld metal may be detrimental to the weld metal toughness, as will be described later. Hence, we made D1 wire whose chemical compositions are shown in Table 1. The carbon level of D1 wire is similar to that of C1 wire. However, to reduce the transformation temperature, we increased Ni in D1 wire up to

<table>
<thead>
<tr>
<th>Wire</th>
<th>SiO₂</th>
<th>MnO</th>
<th>Fe₂O₃</th>
<th>Al₂O₃</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>25</td>
<td>31</td>
<td>15</td>
<td>12</td>
</tr>
<tr>
<td>A2</td>
<td>30</td>
<td>27</td>
<td>14</td>
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<tr>
<td>A3</td>
<td>19</td>
<td>15</td>
<td>31</td>
<td>13</td>
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<tr>
<td>A4</td>
<td>27</td>
<td>21</td>
<td>27</td>
<td>10</td>
</tr>
<tr>
<td>A5</td>
<td>27</td>
<td>23</td>
<td>24</td>
<td>11</td>
</tr>
</tbody>
</table>
2.5%. In addition, we added no Mo to D1 wire considering the charpy impact property. Fig. 5 also shows the S-N curve of D1 wire. The fatigue strength of D1 wire is the same of C3 and about 50% higher than that of the solid wire (SW). As shown later, the charpy property of D1 wire is better than that of C3 wire, so we here examined D1 wire furthermore.

The mechanism of the fatigue strength improvement is considered the reduction of residual stress at the weld toe. To confirm this, we measured the transformation temperature of the deposited metal of D1 wire. The result is shown in Table 4, and the transformation temperature is 340°C. We also measured the residual stresses at the weld toe of the lap joints made with D1 wire and the solid wire (SW). The measurement method is the X-ray method. The residual stress measurement was conducted at the two points for each specimen, i.e., at the mid-width of the specimen and 5mm away from the mid-width of the specimen, as illustrated in Fig. 1. The results are also shown in Table 4.

The transformation temperature 340°C is not as low as that of 10%Ni-10%Cr wire that Ohta et. al. used. The transformation temperature of their wire is about 250°C. However, the residual stress of D1 wire is considerably lower than that of the solid wire (SW). Tominaga et. al. reported that 350°C transformation temperature is sufficient to improve the fatigue strength, which meets the present result. Hence, we next conducted the FEM analysis of the lap joint to check the effect of the transformation temperature on the residual stress in the weld. The FEM code is Quick Welder by Research Center of Computer Mechanics INC.

The Young modulus at 0°C, 600°C, 1000°C and 1500°C was assumed to be 206000MPa, 167000MPa, 147000MPa and 98000MPa, respectively. The yield stress of the base metal at 0°C, 300°C, 600°C, 800°C and 1500°C was assumed to be 690MPa, 440MPa, 200MPa, 20MPa and 10MPa, respectively. The yield stress of the weld metal at 0°C, 200°C, 300°C, 600°C, 800°C and 1500°C was assumed to be 880MPa, 690MPa, 290MPa, 150MPa, 10MPa and 10MPa, respectively. All the above physical properties at the other temperatures were calculated by the linear interpolation. The Poisson ratio, the density, the specific heat and the thermal conductance were assumed to be 0.3, 0.78×10⁻⁵ [kg/mm³], 0.63×10³ [J/kg°C], 0.035 [J/mm°C], respectively. These properties were assumed to be constant. We conducted the 3 dimensional FEM analysis for the cases that the transformation start temperatures were 300°C, 400°C and 500°C. We assumed that the transformation finish temperature was 100°C lower than transformation start temperature, and that the total linear expansion accompanying with the phase transformation was 1%. This assumption may not be correct. However, we think the general aspect can be described.

Fig. 6 shows the residual stress distribution, σx (x is the direction perpendicular to the weld bead). The results of 300°C and 400°C transformation start temperatures show that the residual stress at the weld toe is compressive, while the transformation start temperature of 500°C does not produce the compressive residual stress. This result can explain the present fatigue test results. But the transformation start temperature that can produce the compressive residual stress, 340°C, seems to be relatively higher than expected from Ohta’s results. The purpose of the present study is to develop a flux cored wire applicable to sheet welding, and not to clear the mechanism of residual stress reduction.
However, we would like to consider the reason a little more.

Fig. 7 shows the temperature distribution when the temperature of the weld bead is less than 450°C. From Fig. 7, we can see that the temperature at the bottom is over 350°C. This means that the welding heat easily reaches the bottom surface because of the thickness of 3.2mm. The volumetric expansion of the weld metal starts at this temperature range. Hence, in the case of thin sheet welding, the thermal shrink of the weld metal after the completion of the phase transformation is not so restricted by the bottom part of the sheet, because the bottom part concurrently shrinks. On the other hand, in the case of thick plate, since the bottom part of the plate stays at lower temperature (at room temperature in some cases), the thermal shrink of the weld metal is strongly restricted by the bottom part. This tends to turn the compressive stress at the weld toe to the tensile. We, hence, think that the reason why 340°C is enough in the case of sheet welding may be due to the temperature distribution during sheet welding.

As mentioned already, the high carbon content of the weld metal may be detrimental to the toughness properties. So we conducted the butt welding to machine the 1/4 size charpy specimens using C1, C2 C3 and D1 wires. 2mm depth V notch was made at the center of the weld metal. For the comparisons, we also measured the impact energies of the solid wire (SW). Table 5 summaries the charpy absorbed energies of each wire at -40°C. The absorbed energy of C1 wire is comparable to that of the solid wire (SW), while the absorbed energy of C3 wire is obviously lower. The absorbed energy of D1 wire is the best of the prototyped wires. Hence, we conclude that D1 wire is the best candidate for steel sheet welding in the automobile industries.

4. Conclusions

In the present work, we have developed the flux cored wire, D1 wire, for steel sheet welding whose amount of slag can be reduced to the level of 100% CO_2 solid wire, and its fatigue strength of the lap joint at 2 million cyclic loading is about 50% higher than that of the conventional solid wire. The X ray residual stress measurement shows that the mechanism of fatigue strength improvement is considered due to the compressive residual stress at the weld toe. We also showed the good charpy properties of D1 wire.

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Reference