Low Heat Input Welding to Improve Impact Toughness of Multipass FCAW-S Weld Metal

Kook-soo Bang*, Chan Park** and Ho-shin Jeong**

*Department of Materials System Engineering, Pukyong National University, Busan, Korea
**Department of Materials Science and Engineering, Pukyong National University, Busan, Korea

KEY WORDS: FCAW-S, Reheating, Heat input, Impact toughness, Hydrogen content

ABSTRACT: Multipass self-shielded flux cored arc welding with different heat inputs (1.3-2.0 kJ/mm) was conducted to determine the effects of the heat input on the proportion of the reheated region, impact toughness, and diffusible hydrogen content in the weld metal. The reheated region showed twice the impact toughness of the as-deposited region because of its fine grained ferritic-pearlitic microstructure. With decreasing heat input, the proportion of the reheated region in the weld metal became higher, even if the depth of the region became shallower. Accordingly, the greatest impact toughness, 69 J at -40°C, was obtained for the lowest heat input welding, 1.3 kJ/mm. Irrespective of the heat input, little difference was observed in the hardness and diffusible hydrogen content in the weld metal. This result implies that low heat input welding with 1.3 kJ/mm can be performed to obtain a higher proportion of reheated region and thus greater impact toughness for the weld metal without the concern of hydrogen cracking.

1. Introduction

Self-shielded flux cored arc welding (FCAW-S) has advantages over semi-automatic welding processes by virtue of its self-shielding capability, which makes it especially suitable for site erection welding of structural steel, shipbuilding, and in constructing offshore oil production platforms(Keeler, 1981; Rodgers and Lochhead, 1987; Hesbrok, 1993). Because no external shielding gas is used, strong nitride formers such as Al must be added in the weld metal(Killing, 1980; Kotecki and Narayanan, 2005). This induces a bainitic microstructure in the as-deposited weld metal and results in low impact toughness. As it is known that the reheating of the as-deposited weld metal by successive passes in multipass welding retransforms the brittle bainitic microstructure to the tough fine polygonal ferrite, research works(Dorling et al., 1978; Pisarski et al., 1987; Boniszewski, 1992) have been conducted to find out a suitable welding procedure to get a higher proportion of reheated region in the weld metal. Boniszewski(Boniszewski, 1992) reported that, when welded with a stringer bead technique, the proportion of reheated region becomes higher as travel speed becomes faster, i.e., heat input becomes lower. In contrast, Dorling and Rogerson(Dorling and Rogerson, 1982) reported that, when welded with a weaving technique, the proportion of reheated region becomes higher in higher heat input welding. This suggests that the effect of welding procedure, especially welding technique and heat input, on the proportion of the reheated region and thus the impact toughness of multipass FCAW-S weld metal is complicated.

If low heat input welding is performed to get a higher proportion of reheated region, the possibility of hydrogen cracking in the weld metal should be concerned. Hydrogen cracking is one of the most serious welding problems and may result in expensive time consuming repair operations. Hydrogen cracking basically depends upon the following three factors: hydrogen content, residual stress, and hardness of the weld metal(Easterling, 1992). Among these three factors, low heat input welding especially influences following two factors: hydrogen content and hardness. Low heat input welding facilitates fast cooling of the weld metal, giving less time for the hydrogen to diffuse away from the weld metal, and easily hardening the weld metal. This implies that attention should be paid when low heat input welding is utilized to get a higher proportion of reheated region in the weld metal. However, studies on the effect of heat input on
the hydrogen content are rarely found. In this work, multipass FCAW-S weld metals were fabricated with different heat inputs. The improvement of impact toughness in the reheated region was ascertained first, and then the effects of heat input on the proportion of the reheated region, impact toughness, and hydrogen content of weld metal were investigated.

2. Experimental Procedures

Three FCAW-S multipass welds with different heat inputs, 1.3, 1.6, and 2.0 kJ/mm, were fabricated in a 29 mm thick plate using 2.0 mm diameter AWS E81T8-Ni1 wire. The weld beads were laid using the stringer bead technique in a Vee butt joint. The welding parameters and joint configuration used are shown in Table 1.

| Current [A] | Voltage [V] | Speed [mm/min] | Heat input [kJ/mm] | Joint configuration |
|-------------|-------------|----------------|---------------------|---------------------|
| 200         | 20          | 120            | 2.0                 |                     |
|             |             | 150            | 1.6                 |                     |
|             |             | 180            | 1.3                 |                     |

Constant values of welding current, 200 A, and voltage, 20 V, were used for all welds, and a range of travel speeds from 120 to 180 mm/min was used to obtain three different heat inputs. Macrosections of three welds are shown in Fig. 1. Standard optical microstructural observations in the weld metals were conducted. Vickers hardness of the weld metals was also measured.

The diffusible hydrogen content in weld metals was determined according to AWS A4.3-86. The test specimens, which were composed of a center test piece and the starting and run-off tabs, were made from 600 MPa grade high tensile strength steel (JIS G 3103 SM570). For the removal of residual hydrogen before welding, the specimens were degassed at 400°C for two hours in air. After degassing, the specimens were ground to remove the oxide layer and degreased in acetone. The specimens were assembled in a copper welding fixture and welded with three different heat inputs. The weld was quenched rapidly after welding and stored at -70°C or a lower temperature. The mercury displacement procedure using eudiometer tubes was used to measure diffusible hydrogen contents according to the recommendations of the AWS specification. After measuring the amount of weld metal hydrogen, the values were corrected for the standard temperature, atmospheric pressure, and humidity conditions. The values were reported in terms of 100 g deposited metal.

3. Results And Discussion

In multipass welding, except for the final layer, all layers are reheated by successive passes and thus the weld metal consists of two regions: as-deposited and reheated regions. As the microstructures differ considerably between the two regions, it is possible to distinguish the two by optical microscopic observations. Figure 2 shows a typical microstructure of a weld metal containing two regions. Region (a) is an as-deposited region. Region (b) is a reheated region that is affected by the successive pass. Magnified microstructures of each region are shown in Fig. 3. The as-deposited region (a)
Fig. 2 Typical microstructure of multipass weld metal reveals a bainitic microstructure with grain boundary ferrite. In contrast, the reheated region (b) shows a fine grained ferritic-pearlitic microstructure. Microhardness measurement (load 500 g) showed that the as-deposited and reheated region has 224 Hv and 196 Hv, respectively. From the microstructural observation and microhardness measurement, it is expected that the reheated region could have higher impact toughness than the as-deposited region. However, impact toughness of two regions have not been measured and compared yet because each region is too small in size to extract impact toughness specimens. In this study, thermally simulated specimens that have a duplicated microstructure for each region by thermal simulation were used to measure impact toughness of the two regions. Theoretically, a reheated microstructure should be obtained by reheating an as-deposited microstructure. However, according to Evans (Evans, 1985), when the weld metal is reheated above A3 temperature by thermal simulation, the microstructure of the simulated weld metal does not depend on whether the simulated specimen is as-deposited or reheated and is only determined by the composition of the weld metal and simulating schemes. Therefore, the specimens for the thermal simulation in the size of 11×11×55 mm were extracted from the mid-thickness of the weld metal and then thermally simulated. Based on the A3 temperature of the weld metal which was calculated using the equation developed by Brandis (Eisenhuttenleute, 1992), three different peak temperatures, 1300°C, 1100°C, and 950°C were selected to simulate the reheating. Specimens were heated to each peak temperature within 10s and maintained for 5s. The specimens were then cooled at a cooling rate of 20°C/s in the temperature range from 800 to 500°C. After thermal simulation, the standard 2mm V-notch Charpy impact test specimens were machined and tested at −20°C. The results of the impact tests are compared in Fig. 4. The impact absorbed energy of the specimen heated to 1300°C was about 50 J. However, this doubled to about 100 J in the
specimens heated to 950°C and 1100°C. Figure 5 shows the microstructures of the simulated specimens heated to 1300°C and 950°C. It shows that the specimen heated to 1300°C (a) has a similar microstructure to the as-deposited microstructure shown in Fig. 3 (a). In contrast, the specimen heated to 950°C (b) has a similar microstructure to the reheated microstructure shown in Fig. 3 (b). This indicates that reheating to 1300°C could duplicate the as-deposited microstructure, while reheating to 950°C could duplicate the reheated microstructure even if the simulation samples are extracted from the multipass weld metal. Above results suggest that the higher the proportion of the reheated region in the multipass FCAW-S weld metal, the greater the impact toughness of weld metal.

The proportion of the reheated regions is expected to increase with increasing the number of the regions. In this regard, low heat input welding is more desirable because it gives more successive passes as shown in Fig. 1. However, in addition to the number of the region, the depth of the region itself should also be taken into account because the depth would become shallower in lower heat input welding because of the smaller heat of the subsequent pass. As the microstructure of reheated region is quite different from the as-deposited region, the depth of the reheated region can be measured easily using optical micrographs. The average depth of the regions was 1.64, 1.20, and 0.97 mm, respectively, in 2.0, 1.6, and 1.3 kJ/mm heat input, confirming shallower depth in lower heat input welding. Therefore, the effect of heat input on the proportion of the reheated regions reflects the two contradictory factors: number and depth. Standard 2mm V-notch Charpy impact test specimens were extracted from the weld metals. Figure 6 shows the location of the specimens. Reheated regions are indicated as dotted line in the figure. The notch was positioned 4mm away from the center of the weld metal. The proportion of the reheated regions at the notch location was 37, 40, and 48 %, respectively, in 2.0, 1.6, and 1.3 kJ/mm heat input. This result indicates that, when low heat input welding is performed, even if the depth of the reheated region becomes shallower, the overall proportion of the region becomes higher because of the larger number of the regions. The results of impact tests at -40°C are shown in Fig. 7. While about 50 J of impact absorbed energy is obtained in 1.6 and 2.0 kJ/mm heat input, 69 J is obtained in 1.3 kJ/mm heat input, indicating a beneficial effect of lower heat input welding on the impact toughness of multipass FCAW-S weld metal because of higher proportion of the reheated regions. In addition to the microstructural modification effect discussed above, stress relief effect, if any, is also expected by the successive pass. However, no attempt was made to investigate the stress relief effect in this experiment. The effect of stress relief on the weld metal toughness requires further investigations.
If lower heat input welding is conducted to utilize the beneficial effect on the impact toughness, weld metal hydrogen cracking can be a problem. After welding, weld metal inevitably contains some diffusible hydrogen; in combination with the hardened microstructure, this can lead to hydrogen average in parentheses cracking in weld metal. Welding with lower heat input facilitates faster cooling of the weld metal, giving less time for hydrogen to diffuse away from the weld metal. Moreover, hardened microstructures are easily formed during fast cooling. Cooling rate was determined to estimate the effect of heat input on the cooling time in this experiment. Cooling curve was obtained by plunging a W-5%Re/W-26%Re thermocouple of 0.3 mm diameter into a weld pool. Figure 8 shows a typical cooling curve obtained in 1.3kJ/mm welding for an example. It shows that the time for the weld metal to cool down to 300°C is about 14s. Meanwhile, the time was 17 s in 1.6 kJ/mm, and 19 s in 2.0 kJ/mm. Even if faster cooling rate is observed with lowering heat input, its difference is minimal. Vickers hardness measurement (load 10 kg) in the weld metal was made at the root region where hydrogen cracking starts in general. Irrespective of the heat input, three weld metals showed almost same hardness, 222 Hv - 225 Hv. The results of diffusible hydrogen content measurements are summarized in Table 2. The contents were 11.4, 11.4, and 11.2 mL/100g, respectively, when heat input is 1.3, 1.6, and 2.0 kJ/mm. Above results indicates that the difference of cooling rate or heat input in this experimental range gives little effect on the hardness and diffusible hydrogen content in the weld metal. This shows that low heat input welding with 1.3 kJ/mm can be performed to get a high proportion of the reheated regions and thus high impact toughness without the risk of hydrogen cracking in the weld metal.

### 4. Conclusions

Multipass self-shielded flux cored arc welding with different heat inputs, 1.3-2.0 kJ/mm, were conducted to determine the effects of heat input on the proportion of the reheated region, impact toughness, and diffusible hydrogen content of weld metal. Important findings are as follows.

1. Due to the fine grained ferritic-pearlitic microstructure, the reheated region in the weld metal had much higher impact toughness than the as-deposited region. The thermal simulation test showed that the reheated region has two times greater impact toughness than the as-deposited region.

2. Even if shallower reheated regions are formed, a higher proportion of reheated region was obtained in lower heat input welding because of the larger number of reheated regions. Accordingly, the largest impact toughness, 69 J at -40°C, was obtained in the lowest heat input welding of 1.3 kJ/mm.

3. Because of little difference of cooling rate between the heat inputs, almost same hardness and diffusible hydrogen content are obtained in the weld metals. This suggests that low heat input welding with 1.3 kJ/mm can be performed to get a high proportion of reheated regions and thus high impact toughness without the risk of hydrogen cracking in the weld metal.
impact toughness without the risk of hydrogen cracking in
the weld metal.

Acknowledgement

This work was supported by a Research Grant of Pukyong
National University(2014)

References

Boniszewski, T., 1992. Self-shielded Arc Welding. Abington
Publishing, Cambridge, UK.

Dorling, D.V., Rodrigues, P.E.L.B., Rogerson, J.H., 1978. A
Comparative Study of the Effect of Welding Conditions
on the Microstructure and Toughness of Self-shielded
Arc and Manual Metal Arc Weld Metals. Proceedings on
Trends in Steels and Consumables for Welding. London,
UK, 351-359.

Dorling, D.V., Rogerson, J.H., 1982. The Factors Which Control
the Toughness of Self-shielded Flux Cored Arc Weld Deposits
in Carbon-manganese Structural Steels. Proceedings on
Fracture Toughness Testing. Cambridge, UK, 239-249

Easterling, K., 1992. Introduction to the Physical Metallurgy
of Welding. 2nd Edition, Butterworth-Heinemann Ltd,
Oxford, UK.

Eisenbutterleute, V.D., 1992. Steel. Handbook for Materials
Research and Engineering. Springer-Verlag, Berlin.

Evans, G.M., 1985. The Effects of Heat Treatment on the
Microstructure and Properties of C-Mn All Weld Metal
Deposits. Metal Construction, 17(10), 676-682.

Hesbrook, W.G., 1993. Adopting Self-shielded Wire Welding for
Shipbuilding. Welding & Metal Fabrication, 6, 223-224.

Keeler T., 1981. Innershield Welding. Part 1: Development
and Application. Metal Construction, 13(11), 667-673.

Killing, R., 1980. Welding with Self-shielded Wires-The Mechanism
of Shielding and Droplet Transfer. Metal Construction,
12(9), 433-436.

Kotecki, D.J., Narayanan, B., 2005. Welding Consumable
Developments in the Aftermath of the Northridge Earthquake.
Welding in the World, 49(1/2), 42-46.

Pisarski, H.G., Jones, R.L., Harrison, P.L., 1987. Influence of
Welding Procedure Variables on the Fracture Toughness
of Welds made with Self-shielded Flux Cored Wire.
Proceedings of 6th Intl Symposium on Offshore Mechanics
& Arctic Eng. Houston, USA, 111-119.

Rodgers, K.J., Lochhead, J.C., 1987. Self-shielded Flux Cored
Arc Welding-The Route to Good Fracture Toughness.
Welding Journal, 66(7), 49-59.