

Metallurgical Controlling Factors for Toughness of Multi-layered Weld Metal in Beam-to-column Connections —Application of Fraction of Columnar Structure in Assessing Toughness of Weld Metal Derived from YGW18 Solid Wire—

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Abstract

Metallurgical controlling factors for toughness of multi-layered weld metal in beam-to-column connections were investigated by considering the heterogeneity of microstructure as a dominant factor of scatter of Charpy absorbed energy. The fraction of as-welded zone of weld metal included in notch part of the test piece for Charpy impact test was defined as fraction of columnar structure (f_c). Charpy impact test for the weld metal was examined with constant f_c (f_c : 0% and 80%) to reduce the heterogeneity of microstructure as much as possible. The validity of f_c as an index of heterogeneity of microstructure was verified, and the clarification of the influence of heat input and interpass temperature on the toughness of weld metal was tried.

1. Introduction

Beam-to-column connections are essential structural components for the seismic resistance of a building steel frame. Against the background of increased interest in the seismic performance of buildings especially after the Hanshin-Awaji Earthquake in 1995, many studies have been conducted regarding the performance of weld joints¹⁻¹¹⁾ and increasingly stringent measures for improving the performance have been proposed and practically applied. Lately, to prevent brittle fracture of weld joints, there have been various proposals to specify quality requirements for many types of weld joints of a steel column in more detail in consideration of required performance of a building and stress imposed on structural members. In the meantime, current design standards require higher toughness for a beam-to-column connection than earlier standards did; the toughness presently required

for this type of connection is generally 70 J or more in terms of the Charpy absorbed energy at 0°C (vE₀)¹⁾.

Multi-pass CO₂ arc welding is commonly employed for beam-to-column connections, and solid wires such as YGW11 and YGW18 under JIS Z 3312 are widely used as the welding consumables for the application.

To prevent poor performance of weld joints due to excessive heat input or interpass temperature, steel frame fabricators specify upper limits of these parameters for field practice. Since the principal factors that determine the mechanical properties of a weld metal are its chemical composition and thermal history (cooling rate), it is currently a usual control practice for field welding work to specify upper limits of heat input and interpass temperature for various types of welding consumables.

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From the viewpoint of operating efficiency, however, setting upper limits for these parameters lowers deposition rate of weld metal and increases cooling time after each pass, which significantly deteriorate work efficiency. For rational welding work, therefore, it is desirable to have a means for predicting an optimum welding condition to realize required performance of a weld metal.

From the viewpoint of development of welding consumables, on the other hand, it is important to clarify the relationship between the performance of a weld metal and cooling rate. However, many past studies showed that the Charpy absorbed energy of a weld metal at 0°C often fluctuated remarkably depending on the combination of welding consumables and work conditions (heat input and interpass temperature)²⁾. A factor causing the fluctuation of the absorbed energy is the possibility that the ductile-brittle transition temperature of the weld metal in question is near 0°C, and another is the fact that the weld metal at the notched position of a Charpy test piece has different metallurgical structures from one to another because of complex thermal history and varied shapes of weld-metal layers, which are inevitable with multi-pass welding.

In consideration of the above, an investigation was conducted on the relationship between Charpy absorbed energy and cooling rate through a series of test using YGW18 weld metal, which was widely used for beam-to-column joints. Then, understanding that the structural unevenness of weld metal due to the changing thermal history peculiar to multi-pass welding was a main governing factor of its toughness, an attempt was made to clarify the relationship between the toughness and cooling rate of weld metal taking the macroscopic structural heterogeneity of weld metal into consideration by making a correlation between Charpy absorbed energy and macroscopic structural fractions of weld metal at the notched position of a test piece.

2. Introduction of Fraction of Columnar Structure

The mechanical properties of weld metal depend on the structure that is determined by its chemical composition and cooling rate, which is dependent on thermal conditions such as heat input and interpass temperature. In the present test, it was assumed that the metallographic structure of the notched position of a test piece was different from one to another, and this caused the test results of Charpy absorbed energy of multi-layered weld metal to fluctuate. That is, by multi-pass welding, the structure of an as-welded zone of the weld metal of a previous pass undergoes reheating during a succeeding pass, and a reheated structure having mechanical properties different from those of the as-welded zone forms as a result. For this reason, even if test pieces are cut out from the same position in the

thickness direction of specimen joints, the ratio between the as-welded and reheated zones of weld metal at the notched position is likely to be different with different Charpy test pieces, or different weld joints to evaluate, because of the difference in weld-metal layers and disturbances in work conditions.

In view of the above, the fraction of columnar structure (α_c) was defined as an index to express the heterogeneity of weld metal structure, which it was assumed to be different from test piece to test piece. Fig. 1 schematically shows weld-metal layers of a weld joint; the structures of subject weld metal at the notched position of a Charpy test piece are classified into an as-welded zone in columnar structure and a reheated zone mainly in granular structure. A more precise way of classification would be necessary metallographically, but to use as simple an index as possible, it was considered that this classification into two would be adequate, and the ratio of the as-welded zone to the whole structure ($\alpha_c = \text{as-welded zone} / (\text{as-welded zone} + \text{reheated zone})$) at the notched position of a Charpy test piece was defined as its fraction of columnar structure.

3. Test Method

3.1 Investigation of toughness fluctuation of YGW11 and YGW18 multi-layered weld metals

Before calculating the relationship between cooling time and Charpy absorbed energy of YGW18 weld metal, a series of tests were conducted to investigate the actual fluctuation of Charpy absorbed energy of YGW11 and YGW18 weld metals and that of α_c of different test pieces.

Fig. 2 (a) shows the shape and dimensions of the T-joint specimens (weld length of 300 mm) prepared for the test. The thickness of the plate corresponding to a skin plate of a square-section column was 36 mm for all the specimens, and the thickness (t) of the plate corresponding to a flange of a beam was changed to 19, 25, 32 and 40 mm, and its bevel angle to 20, 30 and 35°. Plates of JIS SN490 steel and solid wires 1.4 mm in diameter of YM-26 and YM-55C (products of Nippon Steel & Sumikin Welding Co., Ltd. corresponding to YGW11 and YGW18 under JIS Z 3312, respectively) were used for the specimen joints.

The welding method was underhand, semi-automatic, multi-pass, CO₂-gas-shielded arc welding by continuous, reversing build-up sequence. In the field welding practice of beam-to-column joints, heat input is not always the same in all the passes: the heat input of the root pass is often lower than that of passes for upper layers. For this reason, heat input of different passes was not controlled to a constant value in the present test. Furthermore, the final layer was formed in two-passes for all the specimen joints, but each of the other layers

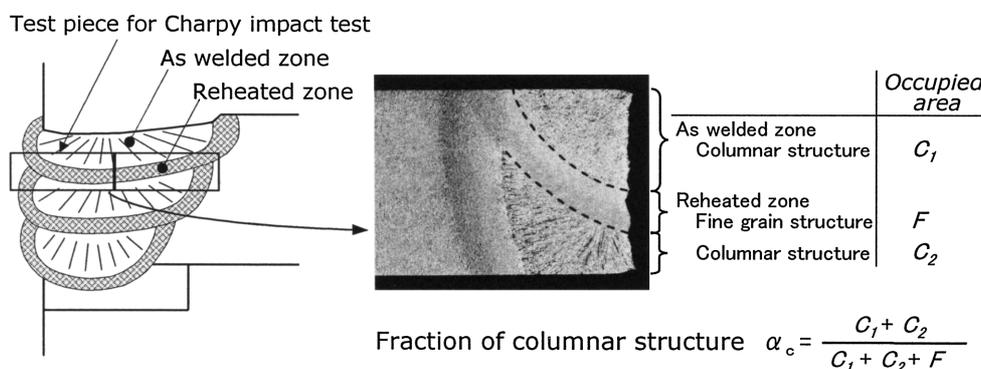


Fig. 1 Definition of fraction of columnar structure

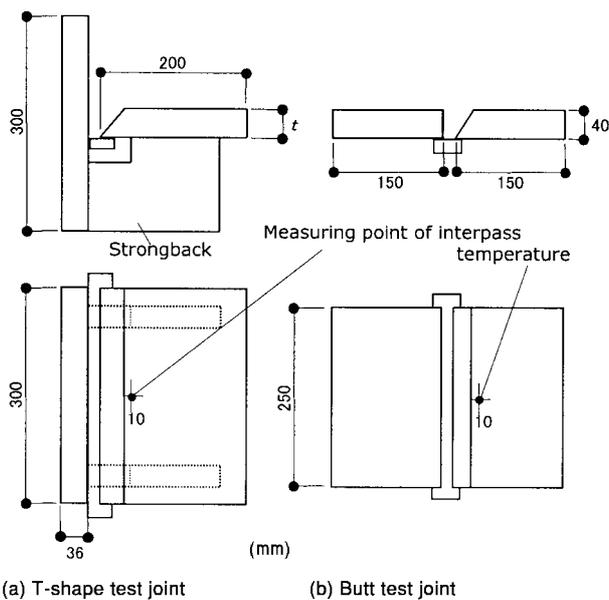


Fig. 2 Schematic illustrations of test joint geometry

below it were either formed in a single pass (build-up condition D1 in Table 1) or in two passes per layer after the interpass temperature reached 350°C (build-up condition D2 in Table 1).

Table 1 shows the combinations of plate thicknesses, welding consumables and bevel angle, and the welding conditions (heat input, maximum interpass temperature, etc) for the test. The heat input of the pass at the position corresponding to 1/4 t was as follows: 3.0 to 3.3 kJ/mm for YGW11 and plates 19 and 25 mm in thickness; 2.0

to 4.2 and 4.9 to 5.1 kJ/mm for YGW11 and plates 32 and 40 mm in thickness, respectively; and 2.8 to 3.5 kJ/mm for YGW18 and plates 32 mm in thickness.

Charpy test pieces were cut out from the 1/4-t position of the beam flange plates nearer to the upper side, additional test pieces were taken from the specimens using plates 32 and 40 mm in thickness at the 3/4-t position nearer the root. The notch was cut at the center of the weld metal of each test piece.

3.2 Investigation of toughness of YGW18 multi-layered weld metal with constant columnar structure fraction

After the above, specimen joints were prepared using YGW18 weld metal and minimizing disturbance in welding conditions, cut out test pieces having the same columnar structure fraction c_c from specimen joints welded under the same conditions, and subjected to a Charpy impact test. The objects of this test were to verify the adequacy of the columnar structure fraction as an indicator of structural heterogeneity, to calculate the cooling time from 800 to 500°C as a function of heat input and interpass temperature, and to clarify the effects of heat input and interpass temperature over the toughness of weld metal.

The specimen joints were butt joints (weld length of 250 mm) simulating a beam-to-column connection; Fig. 2 (b) shows their shape and dimensions. Plates of JIS SN490 steel 40 mm in thickness and solid wires 1.4 mm in diameter of YM-55C (a product of Nippon Steel & Sumikin Welding Co., Ltd. corresponding to YGW18 under JIS Z 3312) were used. A total of 11 welding conditions combining the following were tested: heat input of 3.0, 4.0 and 5.0 kJ/mm and interpass temperatures of 350, 400, 450 and 500°C. To minimize disturbance in welding work, all the passes were welded under the same heat input. Because interpass temperature was set higher than in normal field practice, and to stably realize the intended interpass tem-

Table 1 Welding conditions of test joints

No.	Welding Wire	Plate thickness (mm)	Groove angle (°)	Welding conditions					Build-up condition*	
				Total pass	Current (A)	Voltage (V)	Heat input (kJ/mm)	Maximum interpass temperature (°C)		
1901	YGW11	19	25	4	380	40	2.3-3.1	470	D1	
1902			30	4	400	40	2.3-3.3	491		
1903			35	5	400-410	42	2.7-3.7	516		
2502		25	30	6	420	44	3.2-4.0	513		D2
2503			35	7	400-420	44	2.4-3.6	553		
3202		32	30	8	380	42	2.7-4.6	502		D1
3203			35	8	360-400	42	2.2-4.8	520		
3204			25	11	300-420	32-46	1.2-3.2	≥ 350		
3210			30	11	340-390	40	2.6-4.1	550		
3211			25	8	390-420	42	2.7-3.6	440		
3213		40	30	8	380-440	42	2.5-3.8	485	D1	
4002			30	9	400	42	2.7-5.9	596		
4003			35	10	380-420	42	2.7-5.3	599		
3206		YGW18	32	25	8	300-400	32-44	1.7-3.8	-	D1
3207	25			8	300-400	33-44	1.8-4.1	-		
3208	30			8	380-400	44	1.9-3.9	-		
3209	30			8	380-400	44	2.1-3.4	-		
3215	25			9	360-410	42-40	2.2-3.6	-		
3216	30			9	360-420	40-42	2.5-4.2	530		

* Build-up conditions

D1 Dual-pass per layer only in final layer

D2 Dual-pass per layer after reaching an interpass temperature of 350°C

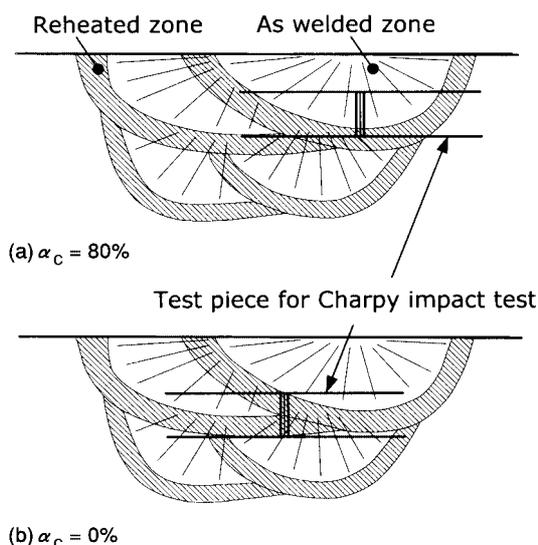


Fig. 3 Position of test pieces for Charpy impact test

perature near the final layer, from which each test piece would be cut out, the specimen joints were soaked in a furnace of 350°C and then subjected to fully automatic welding by a welding robot under conditions controlled to the respectively specified heat input and interpass temperatures.

For the control of interpass temperature, the temperature was measured at a plate surface position at the center of the weld length and 10 mm away from the upper end of the bevel. The thermal history of weld metal was measured with a thermocouple submerged in the molten pool; as a result, it was possible to accurately measure the cooling time from 800 to 500°C.

The Charpy test pieces were cut out under microstructural observation so that α_c at the notch position was 0% (100% reheated zone) or 80% (mostly as-welded zone) as schematically shown in Fig. 3.

4. Test Results and Discussion

4.1 Fluctuation of Charpy absorbed energy of YGW11 and YGW18 multi-layered weld metals

First, the results of the test of 3.1 above are described. The carbon equivalents of the welding consumables YGW11 and YGW18 used for the test were as follows: 0.271 to 0.296 mass % with YGW11 and 0.328 to 0.365 mass % with YGW18. Here, the carbon equivalent (Ceq) was calculated according to the equation $Ceq = C + Mn/6 + Si/24 + Ni/40 + Cr/5 + Mo/4 + V/14$ (in mass %).

The value of α_c of each test piece was determined through structural observation of the fracture surface at the notch position after the Charpy impact test. Fig. 4 shows the relationship between the Charpy absorbed energy at 0°C (vE_0) and α_c .

The Charpy absorbed energy at 0°C of YGW18 weld metal was 70 J or more in a wide range of α_c , and its fluctuation was small. The value of vE_0 tended to decrease as α_c increased.

On the other hand, while the absorbed energy of YGW11 weld metal fluctuated more than that of YGW18 did, the tendency of vE_0 to decrease with larger values of α_c was substantially the same as that of YGW18. This is presumably due to the difference in toughness between the as-welded and reheated zones; it suggests the possibility that the reheated zone, the structure of which is finer than that of the as-welded zone, has a higher toughness.

In this test, vE_0 and α_c were correlated as shown in Fig. 4 be-

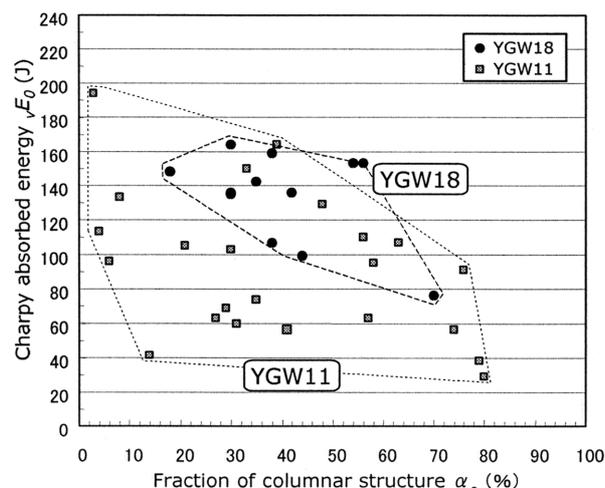


Fig. 4 Relationship between Charpy absorbed energy and fraction of columnar structure

cause it was assumed that the fluctuation of α_c was mainly responsible for that of vE_0 . However, the correlation between the two was not very clear especially with YGW11 weld metal, and the possibility of there being other influencing factors could not be ignored. One of the reasons why the fluctuation of vE_0 could not be explained using only α_c was presumably that, in the present test, the welding work conditions (heat input, interpass temperature, shapes of weld-metal layers, etc.) at the test piece position changed from specimen to specimen.

4.2 Charpy absorbed energy of multi-layered YGW18 weld metal with constant columnar structure fraction

In the preceding sub-section 4.1, it was pointed out that the fluctuation of welding conditions was a suspected factor of the fluctuation of vE_0 . This sub-section describes the results of the test of 3.2 above, where the fluctuation of welding conditions (heat input and interpass temperature) was minimized.

Fig. 5 shows the relationship of vE_0 with heat input and interpass temperature. Although vE_0 showed no clear tendencies with respect to changes in heat input or interpass temperature in the test results of 4.1, vE_0 of test pieces having the same value of α_c tended to decrease as heat input and interpass temperature increased, as the graph clearly shows. With multi-layered YGW18 weld metal, vE_0 decreased under most of the welding conditions as α_c decreased, or as the ratio of the reheated zone increased: the difference between vE_0 when α_c was 80% (hereinafter written as $vE_0(\alpha_c=80\%)$) and that when α_c was 0% (hereinafter written as $vE_0(\alpha_c=0\%)$) was approximately 40 J at the largest.

This points to a conclusion that the toughness of weld metal fluctuates significantly owing to the facts that heat input and interpass temperature are different from joint to joint in the field practice of multi-pass welding, and that the ratios of the as-welded and reheated zones at the notch position are different from test piece to test piece. Accordingly, one can understand that the fact described in 4.1 that the toughness of YGW18 weld metal tended to decrease as α_c increased is due to the differences in the heat input and interpass temperature at the test piece position between different specimen joints.

Fig. 6 shows the relationship between the cooling time from 800 to 500°C ($t_{8/5}$) and vE_0 . Both $vE_0(\alpha_c=80\%)$ and $vE_0(\alpha_c=0\%)$ tended to decrease as $t_{8/5}$ increased. As far as the conditions of the present test are concerned, there is a correlation between the cooling

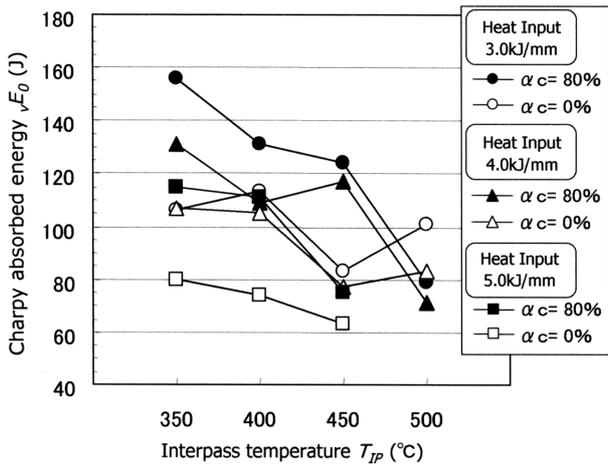


Fig. 5 Relationship between Charpy absorbed energy and welding condition

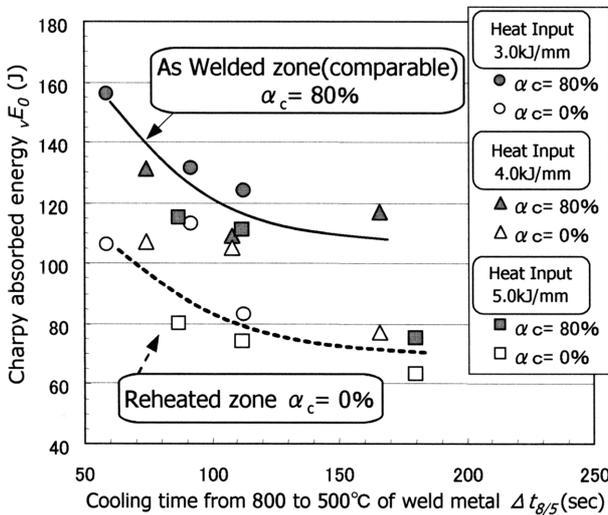


Fig. 6 Relationship between Charpy absorbed energy and cooling time from 800 to 500°C

time from 800 to 500°C and vE_0 of test pieces having the same value of α_c , and thus it is possible to conclude that the change in the toughness of weld metal due to changes in both heat input and interpass temperature is attributable to the change in cooling time.

5. Summary

In consideration of the heterogeneity of the metallographic structure of multi-layered weld joints, a study was conducted on the effects of heat input and interpass temperature at multi-pass welding on the Charpy absorbed energy of test pieces of multi-layered YGW18 weld metal having the fraction of columnar structure (α_c) controlled to 0 and 80%, and obtained the following results:

- Even under the same heat input and interpass temperature, there are cases where the Charpy absorbed energy (vE_0) of multi-layered weld metal fluctuates, but when α_c is constant, vE_0 shows a clear tendency to decrease as heat input or interpass temperature increases. This indicates that α_c is effective as an indicator of structural heterogeneity and that one of the main reasons why vE_0 shows significant fluctuation is presumably that the ratios of the as-welded and reheated zones at the notch position are different from test piece to test piece.
- Since there is a close correlation between vE_0 and the cooling time from 800 to 500°C ($t_{8/5}$), it is reasonable to consider $t_{8/5}$ to be a unified index of thermal conditions that influence the toughness of weld metal, covering heat input and interpass temperature.

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