FRACTURE TOUGHNESS CHARACTERISTICS IN HIGH ENERGY DENSITY BEAM WELDED JOINT OF HIGH TENSILE STEELS

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Abstract

The purpose of the study is to evaluate fracture toughness on the Laser and the electron beam welded joints of high tensile steels (HT500, HT550, HT650) by using 3-point bend CTOD and Charpy impact test.

WM (weld metal) CTOD tests have been carried out using two kinds of CTOD specimen, the Laser beam welding (108mm length, and 24mm width, and 12mm thickness) and the electron beam welding (171mm length, and 38mm width, and 19mm thickness). WM Charpy impact specimen is a standard V-notch type, and the temperature of the experiment is changed from –45 to 20 degree of centigrade. FE-analysis is also performed in order to investigate the effect of stress-strain fields on fracture characteristics.

Results of the standard V-notch Charpy test are influenced by strength mis-match effect and the absorbed energy vE depends on crack path, and The transition temperature of Laser beam welded joints is more higher than that of electron beam welded joints. Results of the 3-point bend test give low critical CTOD and the crack path is in the weld metal of all specimens.

These results indicate fracture toughness characteristics of the welded joints and transition temperature of HT500 are similar both a Laser beam welded joint and an electron beam welded joint. But the fracture toughness and the transition temperature of the electron beam welded joints of HT550 and HT650 are higher than those of the Laser beam welded joints.

Key-Words: Laser beam welding, electron beam welding, CTOD, Charpy absorbed energy, fracture toughness, fracture pass deviation

1. Introduction

The research and development about an electron beam and a Laser beam welding are performed actively. It is expected to apply electron beam and Laser beam welding to the thin plate for the large structures and the pipelines.

In order for utilizing high energy density beam welding effectively, the fracture stability in the welded joints must be secured but in case of the welded joints by high energy density Beam that has a narrow weld metal and lager strength ratio against base metal, if the existing fracture toughness evaluation method is applied, some problems are often indicated. Namely, FPD (Fracture Path Deviation) comes out in the range of temperature above the transition temperature in the Charpy impact test and fracture toughness of the weld metal may not be appropriately evaluated. Moreover, if a weld metal narrow and a strength ratio of weld metal is larger than that of base metal in three points bending CTOD test, the variation of Fracture Path or the obtained Fracture toughness must be investigated.

Therefore, in this study, the three kinds of the generalized structural steel or the steel for pipeline are selected for the test and an electron beam welding and a Laser beam welding are carried out. Charpy impact test and 3-point bend CTOD are performed against the welded joint in the specimen and Fracture toughness characteristics in the weld metal are investigated.

As a result, in case of the welded joints by electron beam welding, the fracture toughness is estimated at the weld metal since the fracture occurs at welded metal in both Charpy impact test and 3-point bend CTOD test. At the other hand, in case of the welded joint by Laser beam welding, it is difficult to evaluating the Fracture toughness at weld metal since FPD takes form in the specimen having the high absorbed energy in Charpy impact test. Also, Fracture path having problem appears such as FPD and cracking along the dendrite structure in the 3-point bending CTOD test.

2. Welding condition

In this experiment, with using the 490MPa-class high tensile steel (HT500) of the generalized structural steel, the low carbon contented steel of 550 and 650 MPa-class steels (HT550 and HT650) as a test specimen. The tests are performed on the 6 joints of the specimen that are welded by the electron welding and Laser welding. The plate thickness is changed into 19mm for the electron beam welding and 12mm for the Laser beam welding to make a difference on the width of the weld metal. The chemical composition and mechanical properties of the base metal are shown on Tables 1, 2. Tables 3 and 4 illustrate the welding conditions for the electron welding and the Laser welding, respectively

Table 1 Chemical composition of steels used

Steel	C	Si	Mn	P	S
HT500	0.15	0.26	1.14	0.011	0.002
HT550	0.041	0.29	1.30	0.009	0.0006
HT650	0.048	0.28	1.83	0.009	0.0017

Table 2 Mechanical properties of steels used

Steel	Tensile test				CVN	
	σ_T (MPa)	σ_T (MPa)	El. (%)	Y.R. (%)	Temp. (°)	Ave. (J)
HT500	390	530	22.8	73.6	0	340

HT550	391	573	34.4	68.2	-10	362
HT650	566	671	27.6	84.4	-40	234

Table 3 Welding condition of 42KW EBW

Steel	Acceleration Voltage	Beam current	Welding speed	Beam operation
HT500	50kV	350mA	0.5m/min	OFF
HT550	50kV	350mA	0.5m/min	OFF
HT650	50kV	350mA	0.5m/min	OFF

Table 4 Welding condition of 12kw CO2 LBW

Average output	Working gas	Gas capacity	Welding speed	Focus
10kW	He	40L/min	1.2m/min	189mm

3. The distribution of Hardness in the welded joint by High Energy Beam

In the High Energy Beam welding, the hardening of weld metal by rapid heating and cooling is known to have an effect on the Fracture Path in the fracture toughness and fracture toughness test and Vickers hardness is measured on the points (1/4t, 1/2t, 3/4t) from the surface to the center of weld metal. The measurement results are shown in Table 5, Table 6. The weld metal of HT500 is hardened remarkably and has the large strength ratio against a base metal and the weld metal by Laser beam welding is hardened more than that by electron beam welding.

Table 5 Average of Vickers Hardness of base metal and weld metal for EBW

	BM			WM			Sr		
Steel	HT500E	HT550E	HT650E	HT500E	HT550E	HT650E	HT500E	HT550E	HT650E
1/4t	154	171	200	210	205	215	1.36	1.2	1.08
2/4t	158	183	205	215	211	224	1.36	1.15	1.09
3/4t	154	172	203	219	199	219	1.42	1.16	1.08
Average	155	175	203	230	221	224	1.38	1.17	1.08

Table 6 Average of Vickers Hardness of base metal and weld metal for LBW

	BM			WM			Sr		
Steel	HT500L	HT550L	HT650L	HT500L	HT550L	HT650L	HT500L	HT550L	HT650L
1/4t	258	187	218	350	254	247	2.22	1.36	1.13
2/4t	160	204	228	324	224	267	2.03	1.20	1.17
3/4t	161	196	227	255	255	276	1.98	1.30	1.22
Aver.	155	190	233	251	251	269	2.08	1.29	1.17

4. Charpy impact test

4.1 Ductile-to-brittle transition behavior by the electron beam charpy impact test

The test is carried out in the range of temperature (–45℃~ 20℃) and the results are shown on Fig. 1. According to the increase of temperature, the results show that the absorbed energy is in proportional but all material has a different transition behavior.

HT500E draws a gentle transition curve to the test temperature but HT550E shows the lower absorbed energy at 20℃and the small change of absorbed energy in the range of the test temperature. HT650 shows that the low absorbed energy in the range of temperature(-20℃~0℃) but the transition curve ascend rapidly at 20℃. The absorption energy value distributes widely in HT500E and HT650E. As a result, if comparing the transition temperature, the high toughness is in order HT500E>HT650E>HT550E.

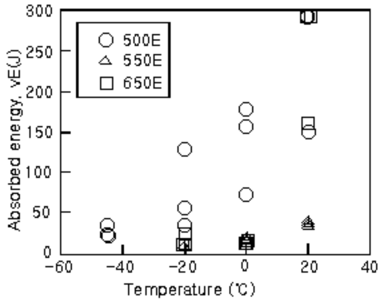

Fig .1 Charpy transition curve of weld metal for Electron beam welded joints

4.2 Ductile-to-brittle transition behavior by Laser Charpy impact test.

To examine Ductility-brittleness transition behavior of Laser beam weld metal,Charpy impact test is implemented within the range of temperature (-80℃ ~ 0℃) with using specimen designed to have a notch in the middle of weld metal. The test results are shown on Fig.2. the absorption energy in HT500L is divided into two parts at 45℃ and it is divided into two parts at not only -45℃ but also 0℃ in HT550L and appears clearer than in HT500L.

It is considered that transition area in HT650L exist in the range of temperature (-20℃ ~ 0℃), but some specimen show the high absorbed energy 60℃.

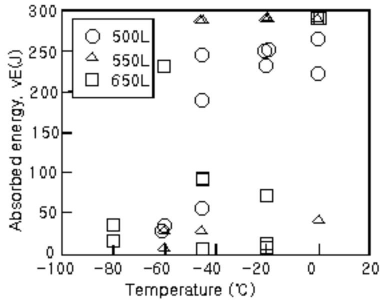

Fig. 2 Charpy transition curve of weld metal for Laser beam welded joints.

5. 3-point bend test

5.1 Ductile-to-brittle transition behavior by the electron beam 3-points CTOP test

As the preceding section, the test carried out within the range of temperature (-20℃ ~ 20℃), with using the 3-point bending CTOD specimen designed to have the notch that is plate thickness and penetration type at the center of weld metal.

The relations between the critical CTOD value and the test temperature obtained from Load-creep gauge opening displacement curve are illustrated in Fig 3. HT500E shows the higher critical CTOD value but HT550E and HT650E show the lower critical CTOD value in the range of test temperature abnormally. As a result, the high toughness shows in order of HT500E>HT650E>HT550E.

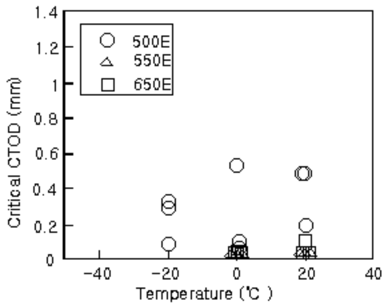

Fig. 3. Temperature dependency of critical CTOD values for Electron beam welded joints

5.2. Ductile-to-brittle transition behaviors by the Laser 3-points CTOD test

With using the 3-point bending CTOD test specimen designed to have plate thickness and a penetration type notch at the center of weld metal, the tests are carried out within the range of temperature (-45℃ ~ 20℃) Fig.4 shows the relation between the critical CTOD value and specimen temperature. HT550L shows the high toughness but the fracture path is to be investigated to find out if it is an accurate fracture toughness evaluation.

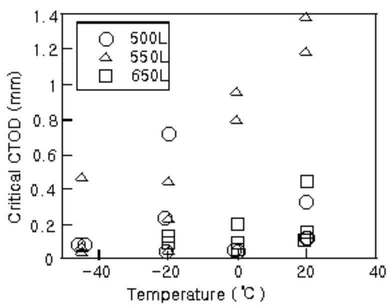

Fig. 4. Temperature dependency of critical CTOD values for Laser beam welded joints.

6. The thermal elastic-plastic analysis

The thermal elastic-plastic simulation is performed to estimate the welding residual stresses caused by High-energy beam welding.

With considering the mechanical symmetry, the two dimensional analysis is carried out to the 1/2 model. Fig. 5 shows the restriction conditions applied for analysis and Fig. 6 shows the stress components that distribute at Z=0.15mm along the Y-axis as the analysis result of HT500 to the Laser beam welding. σx (in direction of the welding line) causes a tensile component between weld metal and HAZ, σy (in the perpendicular direction of welding line) causes a compression stress at the weld metal and changes into a tensile stress gradually and σz is a tensile stress.

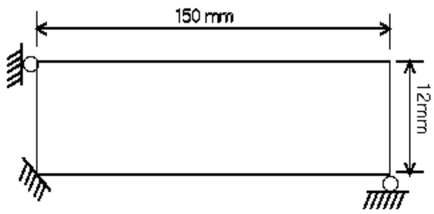

Fig. 5 Boundary condition for simulation

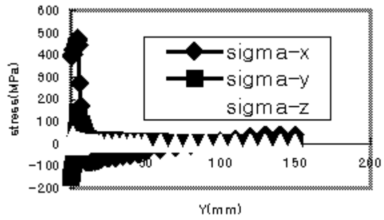

Fig. 6 Distribution of welding residual stress along the Y-axis

7. Conclusion

Electron beam welding

(1) If comparing the temperature of ductile-to-brittle transition of each materials, the high toughness is HT500E>HT650E>HT550E in order in Charpy impact test.

In the 3-point bend CTOD test, the high toughness is the same order with that in Charpy impact test, and moreover, the structure of weld metal is microscopic in order of HT500E>HT650E>HT550E.

Laser beam welding

(2) In the charpy impact test, the absorbed energy is divided into two parts in all material, the fracture path deviates to the base metal in the specimen having the lower absorbed energy. As a result, it is not appropriate to be evaluated the fracture toughness by Charpy impact test in the Laser beam weld metal.

(3) In the 3-point bend CTOD test, 4 paths of fracture that are the fracture in weld metal, FPD, the fracture along the dendrite structure and the welding defects are observed. It is considered that the welding defects are investigated in detail, but when it comes to the rest of them, it is considered that the fracture toughness of the weld metal is the same with the critical CTOD values obtained from the test or the above.

(4) In the Laser beam welding on HT500, the welding residual stresses occur between the weld metal and HAZ as the high stress, and it is estimated that σ_x is the tensile stress and σ_y tend to change the compression stress into the tensile stress

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