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METALLURGICAL AND MECHANICAL FEATURES OF API 5L X65 PIPELINE STEEL WELDMENT

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ABSTRACT

Substantial differences amongst metallurgical and mechanical properties of base metal (BM), weld metal (WM) and heat-affected zone (HAZ) occur in general in welded steel structures It is common practice in various engineering structures to evaluate the fracture performance of welded structures by mechanical testing. Especially, the HAZ of steel welded joints shows a gradient of microstructure and mechanical properties from the fusion line to the unaffected base metal. This study is concerned with the effects of metallurgical and mechanical factors on the fracture performance of API 5L X65 pipeline steel weldments, as they are generally used for main natural gas transmission pipelines in Korea. First of all, we investigated the microscopic and macroscopic fracture behavior of the various micro-zones within the HAZ from the viewpoint of metallurgical factors. The effects of mechanical factors such as welding residual stress in steel weldment and strength mismatch between BM and WM, particularly in high strength steel weldments, are also analyzed Therefore, the fracture performance of API 5L X65 pipeline steel weldment was mainly dependent on the change of microstructure and its distribution in the welded joints.

INTRODUCTION

Natural gas, with abundant reserves being confirmed and distributed the world over, has a great advantage with regards to stable supply. It is also a relatively clean and safe energy source, in that the combustion of natural gas causes less emission of greenhouse gas, CO_2, one half that of coal and two thirds that of petroleum. With these advantages, demand for natural gas as a primary energy source is predicted to increase further in Korea for distributed power generation and other industrial applications. LNG (liquefied natural gas), that is natural gas produced in oversea fields and liquefied, is shipped to Korea and stored in LNG storage tanks at a receiving terminal Then according to the demand, the LNG is turned to gas in a vaporizer and transported in a high-pressure pipeline, which is embedded into the ground along the national road, to city gas companies and power generators. The main natural gas pipelines operated in Korea have diameters from 500 mm to 760 mm and wall thickness from 10 3 mm to 17.5 mm with design pressures ranging from 70 to 80 kg/cm^2, and amount to 2,150 km in total length as of the year 2000.

In Korea, API 5L X65 pipeline steels are used for gas transmission pipelines, they are manufactured by Thermo-Mechanical Control Processing (TMCP) and have lower carbon equivalent for good HAZ toughness and weldability [1-4]

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These advantages offered by TMCP steels, however, must be considered carefully when using multipass welding processes because of the possibility of very low toughness in the HAZ of the welded joints [4] In other words, under welding conditions, mechanical properties of the TMCP steels can be altered significantly by more complex HAZ microstructures. Generally, the HAZ of welded structures shows a gradient of microstructure and mechanical properties from the fusion line to the unaffected base metal. Significant research regarding the microstructural change and the mechanical properties in the HAZ has been performed. HAZ toughness, however, is one of the most difficult properties to achieve specified requirements.

This study is mainly concerned with the correlations between the microstructural change and the fracture characteristics of API 5L X65 pipeline steel weldments. Mechanical factors such as the strength mismatch between weld metal and base metal and welding residual stresses in weldment are also examined to interpret the fracture toughness data.

EXPERIMENTAL PROCEDURES

The material used in the investigation was API 5L X65 pipeline steel generally used for the natural gas transmission pipeline in Korea Its chemical composition is summarized in Table 1. Pipe produced by the SAW (Submerged Arc Welding) process in the seam weldment was used and its diameter and thickness were 760 mm and 17.5 mm, respectively. For the welded specimen preparation, GTAW (Gas Tungsten Arc Welding) and SMAW (Shielded Metal Arc Welding) were used for girth weldment with V groove configuration. Welding was carried out under the same conditions as those used during the installation of the pipelines in Korea. The welding materials and welding conditions are listed in Table 2. No significant defects were found in the completed weldments by non-destructive X-ray examination. As shown in Fig. 1, the base metal microstructure corresponds to a typical ferrite-pearlite structure with an average grain size of 10 μ m whereas that of weld metal displays a typical ferrite structure with carbides on grain boundaries The microstructure of the reheated areas of the girth weld has a fine ferrite-pearlite structure.

Charpy V-notch impact tests and CTOD tests were made in order to identify the potential regions of low fracture toughness Charpy impact tests were carried out with specimens of both seam and girth weldment having different notch positions varying from the fusion line through to base metal. The design temperature range of the main gas transmission pipeline in Korea is 243 K – 313 K. We selected the testing temperatures as 233 K, 273 K, and 298 K for the severe case Also, in order to assess the change of impact toughness according to the test temperature, temperatures were varied from 77 K to 298 K with 20 K intervals. Impact tests were conducted using a Tinius Olsen impact tester with a capacity of 409 J according to ASTM E23. CTOD was determined using SENB (Single edge notched bending) specimens according to ASTM E 399 for the more detailed investigation of the fracture behavior in the HAZ region. The machined notch locations of CTOD tests were the same as those of impact tests, and the tests were done at 233 K and 298 K Microstructure and fractured surfaces were examined by optical and scanning electron microscopy Samples for metallographic examination were prepared using conventional metallographic techniques.

To determine the representative tensile properties of each region of the pipeline weldment, specimens were extracted from the base metal, weld metal and HAZ. First, in the base metal, the specimens were picked at the upper, middle and lower region of thickness direction to consider the variation of properties when rolling a plate used to make a pipeline The shape of the specimen is the subsize rectangular type of 25mm gauge length and 4mm thickness by ASTM E8. Next, in the weld metal, the specimens were extracted from only the weld metal and their dimensions were the same as that of the base metal. The tensile tests were performed at a strain rate of 0 5 mm/min and at room temperature using Instron 5582. Thirdly, the HAZ was so narrow that the subsize specimen could not be extracted. So, micro-tensile specimens (12.5 mm gauge length and 0.5 mm thickness) were extracted from the centerline of the weldment through the HAZ to the base metal. These specimens were tested at room temperature and a strain rate 0.005 mm/min because of the specimen size.

RESULTS AND DISCUSSION

Experimental Results

The results of Charpy V-notch impact tests with respect to the testing temperatures are shown in Fig. 2. Impact energy had the lowest value in the specimens from the fusion line and increased as the notch position moved away from the fusion line for all the temperature ranges The Charpy impact energy for the fusion line had the lowest value at 233K According to the

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specification of API 5L for the 16-20 mm-thickness pipelines, however, Charpy impact energy is required to be an average of 68 J, with an minimum of 27 J at 273 K for each of the specimens. So impact characteristics of API 5L X65 steel HAZ used in this work met the API 5L specification [5]. Figure 3 shows the DBTT (ductile-to-brittle transition temperature) calculated from the transition temperature curves and is defined as the temperature corresponding to the average value of the upper shelf energy and the lower shelf energy. DBTT decreased as the tested position moved away from fusion line as expected in Fig. 2. The DBTT of the fusion line and weld metal were within the design temperature ranges. So, if a defect was found in these regions, careful attention should be paid to the assessment of the existing defect and/or the continuous operation of the pipelines in spite of the favorable toughness over the specification.

In order to obtain the fracture mechanical toughness data to ensure fracture mechanical integrity, CTOD tests were performed on specimens at several positions within HAZ regions at 233 K and 298 K. Figure 4 shows the CTOD test results with respect to the notch positions, which were the same as those of the Charpy impact tests. Fracture toughness of girth weldment for this natural gas pipeline, i.e. the CTOD value, decreased as the tested position approached fusion line, and toughness degradation was observed in some specimens as expected These results were similar to Charpy impact test results. More detailed investigations of the CTOD test results were performed and they are discussed in the following sections

Figure 5(a) shows the true strain – true stress curves of the base metal and weld metal A difference in tensile properties at the upper, middle and lower parts along the through-thickness direction of the base metal was observed. Yield strength and tensile strength of the middle part are lower than those of the upper and lower region, and the tensile curves of the upper and lower parts overlapped each other in an error range lower than 5% These were caused by strain hardening effects originated during the rolling procedures in TMCP. The surface of the pipeline during rolling was generally more hardened than middle regions by a strain hardening mechanism. In the HAZ specimen, micro-tensile test specimens were used to evaluate the local variation of tensile properties because of a gradient in the microstructure in the HAZ Figure 5(b) shows the variation of ultimate tensile strength in the upper region of the HAZ together with the variation of hardness Similar tendencies between the results of ultimate tensile strength and hardness were obtained, which verified the validity of the micro-tensile test used in this study. Additionally a HAZ softening effect, which was generally occurred in TMCP steel weldment due to the relaxation of the strain hardening effects during welding thermal cycles, could be observed in the region near the base metal.

Metallurgical Factors

First of all, the variation in fracture characteristics can be explained by the metallurgical effects. As mentioned above, the actual HAZ has such a gradient of microstructures that the strengthening effects of TMCP have been lost due to the welding cycle in this steel. HAZ toughness depends on its microstructure, which varies continuously from the fusion line to the unaffected base metal Microstructures of API 5L X65 pipeline steel weldment in this work are shown in Fig 6. The widths of the HAZ were 7 mm from the fusion line. As shown in Fig. 6(a), HAZ microstructures at the region near fusion line were coarsened by the welding thermal cycle and mainly consisted of M-A constituent, upper bainite, and coarse ferrite. It is indeed well known that upper bainite and M-A constituent have a low toughness. In the case of TMCP steel, the lower bainite with only a small amount of martensite formed by TMCP always has the best toughness, but the toughness deteriorates due to weld thermal cycle according to the change in the microstructure that tends to promote coarse upper bainite The coarse upper bainite and coarse ferrite formed by welding thermal cycles were mainly responsible for the toughness decrease [6]. On the other hand, as shown in Fig 6(b), the microstructure of the region near base metal was very fine-grained as expected and mainly consisted of equiaxed ferrite and pearlite which resulted in high toughness. Its grain size was about 3-4 μm. Thus, the toughness variation was mainly dependent on the grain size and the distribution and constituent of the microstructure in HAZ.

To verify the controlling microstructure of the HAZ regions, more detailed constituents of the microstructures were examined using the simulated HAZ specimens. The low toughness is generally caused by certain microstructural features, one being identified as islands of high-carbon, martensite-austenite (M-A) constituent in which the martensite has a twinned substructure The M-A is located in a relatively continuous path along prior austenite grain boundaries. The M-

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A is primarily the result of intercritical reheating, which is produced by the subsequent weld pass. The drastic decrease in the impact energy at the CGHAZ (coarse grained HAZ) was attributed mainly to the significant increase in the amount of M-A constituent [6-9]. In HAZ regions in this work, M-A constituents could be observed using a two-stage electrolyte etching method. The volume fraction of M-A constituent was varied with respect to the simulated specimen. Elongated type M-A constituents were observed in all the simulated specimens Of the CGHAZ regions, IC CGHAZ (inter-critically reheated CGHAZ) has the highest fraction of M-A constituent and FGHAZ (fine grained HAZ) has a very low fraction. So, the main factor controlling the toughness of the pipeline steel weldment was the volume fraction of M-A constituents.

Mechanical factors

Besides the metallurgical effects, mechanical factors such as strength mismatch and welding residual stress also affect the fracture performance of the welded joints.

Strength mismatch is generally defined as the ratio of the yield strength of weld metal and base metal, i.e. $\sigma_{y,WM}/\sigma_{y,BM}$. From the results of the tensile tests, the strength mismatch of the pipeline steel weldment used in this work was 1.17 In order to assess the effects of the strength mismatch on fracture characteristics, crack propagation was examined by after-test-examination method as shown in Fig. 7 (CTOD test) [10]. In the case of a near fusion line specimen, the crack propagated through linearly. But, in the case of the specimens located at FL+3 mm, crack propagation deviated from linearity to the ductile base metal at both 263 K and 298 K. Therefore, the results for FL+3 mm were overestimated due to the deviation of crack propagation. The specimen near the fusion line, which neighbored the regions having low toughness such as the IC CGHAZ, represented the low toughness due to the constraint effects of the neighboring brittle zones. On the other hand, the specimen near the base metal, whose toughness was relatively higher than other zones, showed the deviation of the crack path due to the adjacent soft zones, and thus its toughness could be overestimated

Welding residual stress affects the validity of fracture toughness data. To verify the validity of fracture mechanical toughness test such as CTOD, K_{IC} or J_{IC} tests, pre-cracks should be introduced in front of the mechanical notch tip and the linearity of the fatigue pre-crack secured according to the limitation of the test standard such as ASTM or BS specifications Figure 8 represents the results showing the observation of fatigue pre-crack shape after the CTOD test In case of Korean gas transmission pipeline, the pipe wall thickness was not so thick (only 17.5 mm), and deviation from linearity due to the welding residual stress could not be observed. These results were verified by the BS 5762 specification, which define the validity of fatigue pre-crack. From the above results, we can verify the validity of the CTOD tests.

To ascertain the distribution of the welding residual stresses, cutting methods were used. After attaching the arrays of strain gauges on the as-welded specimens from weld metal to base metal, the specimens were mechanically sawed along the transverse direction to the weld metal. After cutting, the contractions or expansions of specimens were detected by the arrays of strain gauges and converted into the welding residual stresses using the general Hooke's law. This method is similar to the hole drilling method except that a wide range of cutting was performed instead of drilling of holes. The resultant welding residual stress distribution is shown in Fig 9 Slight tensile residual stress existed in the HAZ region near weld metal and HAZ regions near base metal showed compressive residual stress. The magnitude of the existing welding residual stress is approximately one-third of the yield strength of this steel weldment.

CTOD tests using the heat-treated specimens were made to assess the welding residual stress effects. Figure 10 shows the comparison of CTOD values between as-welded specimens and heat-treated specimens There was little difference between them in spite of the existence of the welding residual stress. But, such effects are still under discussion and will be presented elsewhere.

CONCLUSIONS

Correlation of the metallurgical and mechanical factors with the fracture behaviors was investigated on the API 5L X65 pipeline steel weldment. The test results can be summarized as follows.

1 HAZ microstructures near the fusion line mainly consist of coarse ferrites, M-A constituents and upper bainite, while fine-grained ferrite could be observed near the base metal.
2. Charpy impact energy and CTOD had the lowest values in the specimens from the fusion line and increased as the

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notch position was moved away from the fusion line. The metallurgical factors are the dominant factors for the toughness variations in this steel weldment.

3 Strength mismatch between weld metal and base metal was 1 17. Strength levels of the neighboring zones act as plastic constraints or the crack path deviations could affect the toughness data

4 Welding residual stress along the transverse direction to the weld metal existed in the steel weldment and the magnitude of the residual stress was approximately one-third of the yield strength of base metal.

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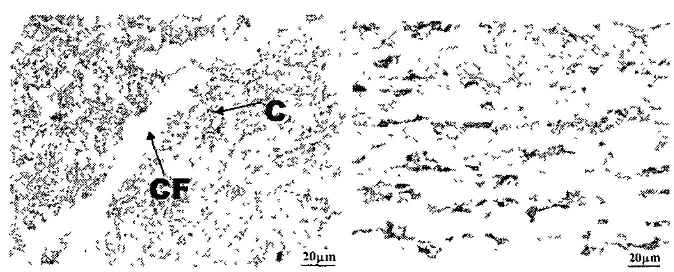
Table 1. Chemical composition of API 5L X65 pipeline steel used in this work.

Element	C	Mn	P	S	Si	Fe
Weight Percentage	0.08	1 45	0 019	0 003	0.31	Bal.

Table 2. Welding Materials and conditions used in this work.

	Welding method	AWS	Groove shape	Heat input (kJ/cm)
Girth Weldment	GTAW+ SMAW	ER70S-G E9016-G	V	3.0~30.0



(a) (b)

Fig. 1. Microstructure of (a) weld metal and (b) base metal (C: carbide, CF: coarse ferrite).

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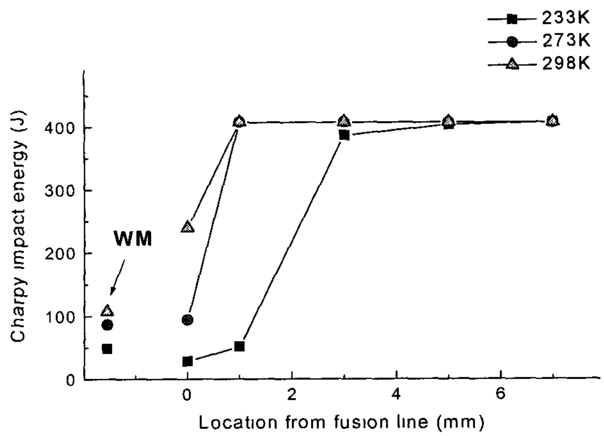


Fig. 2. Variation of Charpy V-notch impact energies with respect to the notch location.

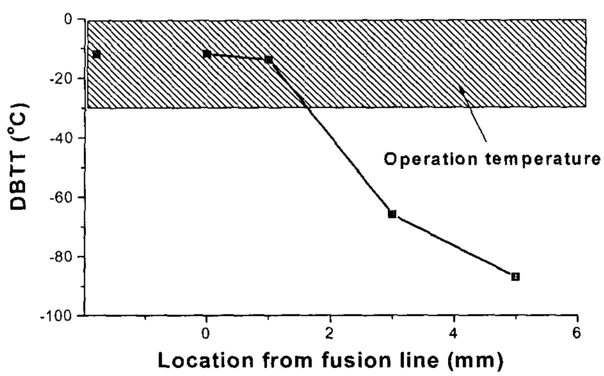


Fig. 3. DBTT variation with respect to the notch location.

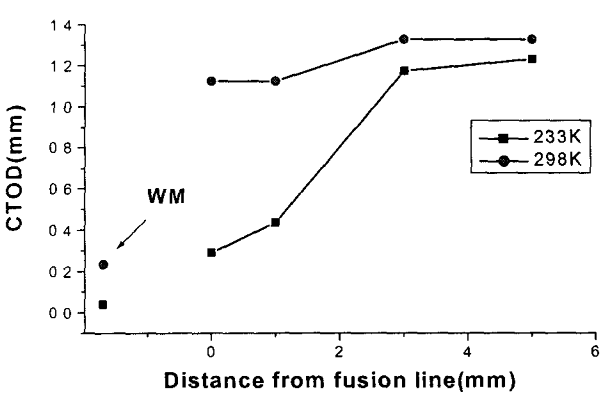
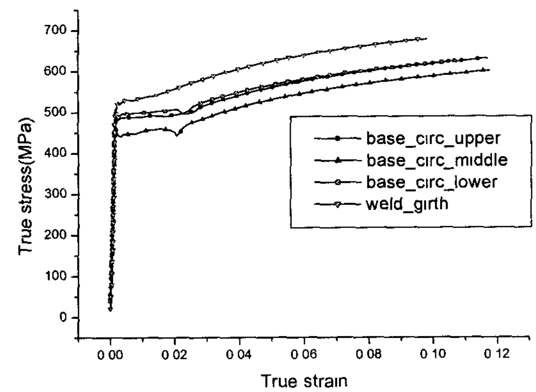
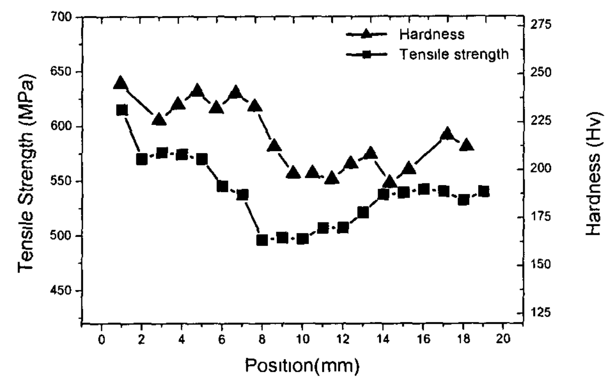


Fig. 4. Variation of CTOD with respect to the notch location.



(a)



(b)

Fig. 5. (a) True strain – true stress curves of weld metal and base metal and (b) tensile strength and hardness of HAZ.

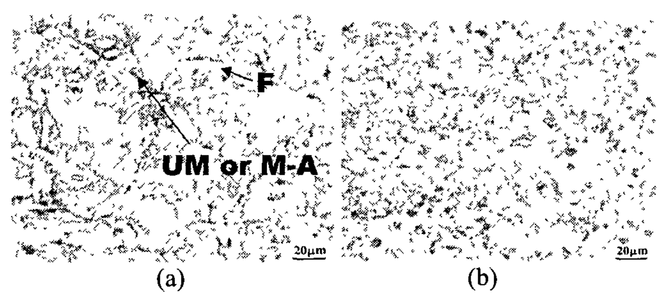


Fig. 6. Optical micrographs at the HAZ region (a) near the fusion line and (b) near the base metal (F: ferrite, UB: upper bainite, and M-A: martensite island).

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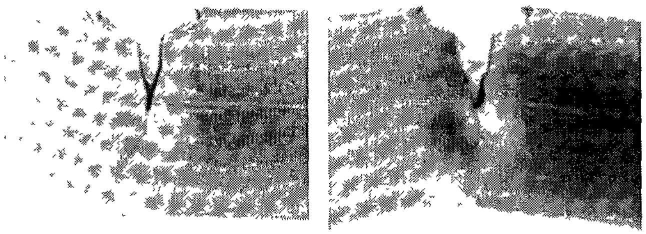

(a) (b)

Fig. 7. Crack path of the CTOD specimen (a) near fusion line and (b) near base metal.

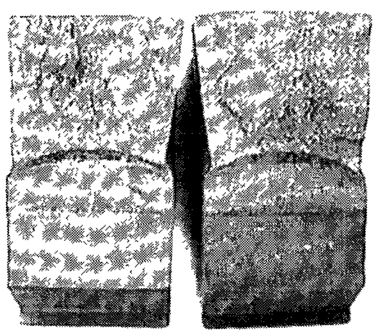

Fig. 8. Fractographs of CTOD specimen showing linear fatigue pre-crack.

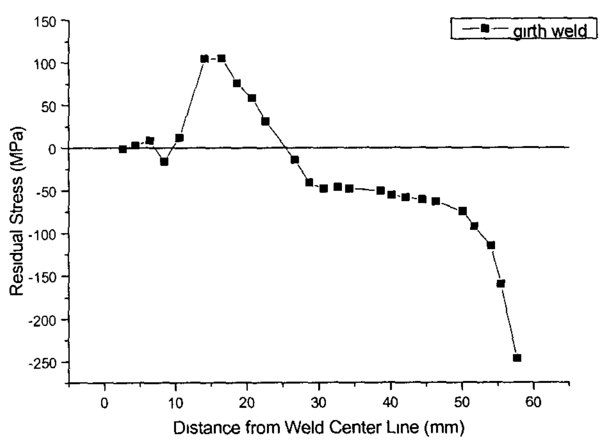

Fig. 9. Distribution of welding residual stress.

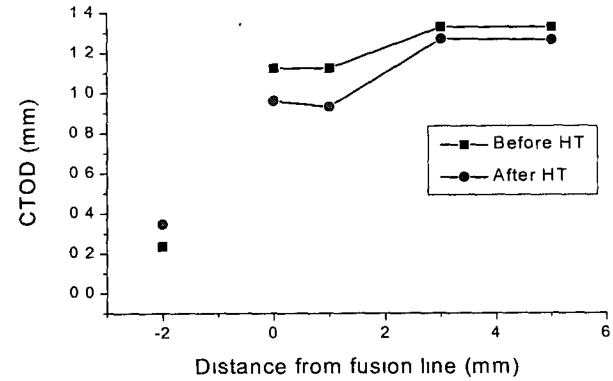

Fig. 10. CTOD results to assess the effects of welding residual stress at 298 K.

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