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Article

An Investigation of the Mechanical Properties of a Weldment of 7% Nickel Alloy Steels

Jeong Yeol Park, Jae Myung Lee and Myung Hyun Kim *

Department of Naval Architecture and Ocean Engineering, Pusan National University, Busan 46241, Korea; cpu2565@pusan.ac.kr (J.Y.P.); jaemlee@pusan.ac.kr (J.M.L.)
* Correspondence: kimm@pusan.ac.kr; Tel.: +82-51-510-2486

Academic Editor: Giuseppe Casalino
Received: 31 August 2016; Accepted: 14 November 2016; Published: 19 November 2016

Abstract: During the last decade, the demand for natural gas has steadily increased for the prevention of environmental pollution. For this reason, many liquefied natural gas (LNG) carriers have been manufactured. Since one of the most important issues in the design of LNG carriers is to guarantee structural safety, the use of low-temperature materials is increasing. Among commonly employed low-temperature materials, nickel steel has many benefits such as good strength and outstanding corrosion resistance. Accordingly, nickel steels are one of the most commonly used low-temperature steels for LNG storage tanks. However, the study of fracture toughness with various welding consumables of 7% nickel alloy steel is insufficient for ensuring the structural safety of LNG storage tanks. Therefore, the aim of this study was to evaluate fracture toughness of several different weldments for 7% nickel alloy steels. The weldment of 7% nickel alloy steel was fabricated by tungsten inert gas (TIG), flux cored arc welding (FCAW), and gas metal arc welding (GMAW). In order to assess the material performance of the weldments at low temperature, fracture toughness such as crack tip opening displacement (CTOD) and the absorbed impact energy of weldments were compared with those of 9% nickel steel weldments.

Keywords: liquefied natural gas; nickel steel; weldments; crack tip opening displacement

1. Introduction

Recently, the demand for liquefied natural gas (LNG) is constantly increasing for the prevention of environmental pollution. In this trend, various types of LNG carriers have been developed and are operating worldwide. As shown in Figure 1, LNG carriers are divided into two categories—membrane and independent types, according to the classification of International Maritime Organization (IMO). The membrane-type tanks have a very thin primary barrier of Invar alloy or SUS 304L inside the cargo tank. The most common types of membrane-type tank are GTT Mark III and No. 96 types. Mark III consists of two layers of R-PUF (reinforced polyurethane foam) separated by triplex in order to configure an insulation system [1]. On the other hand, the No. 96 type composes a grillage structure made of plywood and filled with perlite in order to maintain tightness and insulation [2]. Independent-type tanks are perfectly self-supporting and do not come under a vessel's hull structure. The most common types of independent-type tank are Moss and SPB types. The Moss-type tank system is formed in such a way that a self-supporting spherical tank of an aluminum alloy is fixed to the hull by a cylindrical support structure (skirt) [3]. The SPB type, which is an IMO independent Type B tank, is designed using an aluminum alloy or 9% nickel steel [4]. One of the most important issues in the design of various types of vessel is the structural integrity of storage tanks under cryogenic temperature. Therefore, LNG storage tanks are typically manufactured using low-temperature materials considering the operation temperature of LNG.

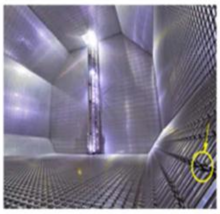
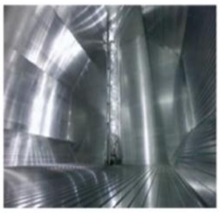
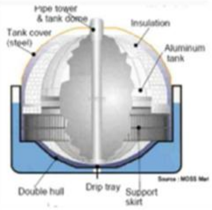
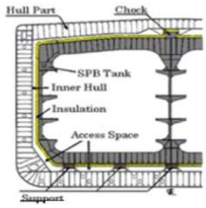
Type	Membrane		Independent	
	GTT MARK III	GTT NO96-2	MOSS	IHI-SPB
Figure				
Material	SUS 304L	Invar alloy	Al alloy (Al 5083)	Al alloy or 9% Ni
Thickness	1.2 mm	0.7 ~ 1.5 mm	50 mm	30 mm

Figure 1. Detailed information of liquefied natural gas (LNG) storage tanks [4].

In particular, 9% nickel steel has been the most common material for LNG storage tanks over the last 50 years. Fatigue and fracture characteristic studies of 9% nickel steel have been consistently conducted by many researchers. Saitho et al. studied the mechanical properties of 9% nickel steel considering various welding consumables and processes [5]. Yoon et al. estimated fatigue crack growth characteristics of a 9% nickel steel welded joint [6]. Khourshid et al. investigated the influence of welding parameters on the brittle fracture of 9% nickel steel [7]. Despite the advantages at low temperature, the price of 9% nickel steel fluctuates substantially according to the price of nickel. In particular, the price of welding consumables is also greatly influenced by the price of nickel. Therefore, shipyards have a considerable interest in employing 7% nickel alloy steel instead of 9% nickel steel in order to reduce the cost of the material. However, research on the weldment of 7% nickel alloy steel is not sufficient compared with the weldment of 9% nickel steel.

In this regard, the major objective of this study was to evaluate the mechanical properties of 7% nickel alloy steel weldments considering several different welding consumables. Based on the results of tensile, Charpy-V impact, and crack tip opening displacement (CTOD) tests performed in this study, the most suitable weldment for 7% nickel alloy steel was determined. In addition, fracture performances of a weldment for 7% nickel alloy steel were compared with those of 9% nickel steel for applications at cryogenic temperature, e.g., −163 °C.

2. Materials and Methods

Nickel steel has many benefits, such as good strength, outstanding corrosion resistance, and applicability in a wide range of temperatures. As shown in Table 1, the International Gas Code (IGC) provides the proper amount of nickel according to low-temperature applications [8].

Table 1. Various temperature application of nickel steels [8].

Minimum Design Temperature (°C)	Chemical Composition and Heat Treatment	Application
−60 −65	1.5% nickel steel—normalizded 2.25% nickel steel—normalized or normalized and tempered	Liquefied Propane Gas
−90 −105	3.5% nickel steel—normalized or normalized and tempered 5% nickel steel—normalized or normalized and tempered	Liquefied Ethane Gas
−165	9% nickel steel—double nomalized and tempered or quenched and temperd	Liquefied Natural Gas

In this study, 7% nickel alloy steel was considered for replacing the conventional 9% nickel steel for LNG storage tanks. The chemical composition of 7% nickel alloy steel, considered in this study, is summarized in Table 2. The 7% nickel alloy steel in this study was treated with a thermo-mechanical control process (TMCP), as shown in Figure 2. The TMCP applied to direct quenching, lamerallizing, and tempering (DQ-L-T), in which lamerallizing was inserted between direct quenching and tempering, was utilized to form a more stable retained austenite, making it finely dispersed and increasing the content [9].

Table 2. The chemical composition of 7% nickel alloy steel.

Material	C	Si	Mn	P	S	Cr	Ni	Mo
7% nickel alloy steel	0.04	0.06	0.78	0.002	0.004	0.46	7.13	0.09

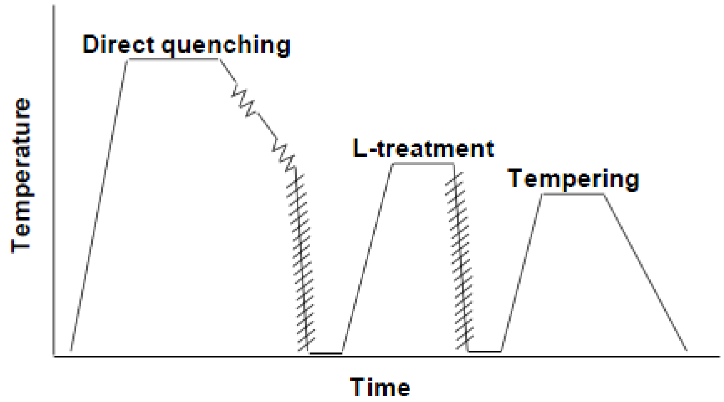


Figure 2. Schematic illustration of the manufacturing processes [9].

In Figure 3, the mixture of tempered-martensite, bainite, and retained austenite was observed in the microstructure of 7% nickel alloy steel. The weldments of 7% nickel alloy steel were produced by using three different welding procedures—flux cored arc welding (FCAW), gas metal arc welding (GMAW), and tungsten inert gas (TIG). The welding consumable employed for FCAW and GMAW was ERNiCrMo-3 in the AWS 5.14 code. On the other hand, a high manganese welding consumable was used for the TIG welding. The chemical compositions of the welding consumables are summarized in Table 3.

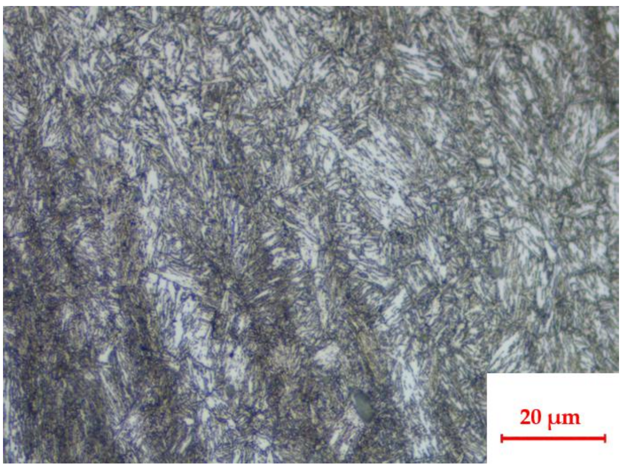


Figure 3. Microstructure of 7% nickel alloy steel.

Table 3. The chemical composition of welding consumables [13].

Welding Consumable	C	Si	S	Mn	Ni	Cr	Mo	Co	Nb	N
High manganese	0.01	-	0.41	7.25	15.77	20.59	2.9	0.13	0.06	0.16
ERNiCrMo-3	0.018	0.47	0.001	0.36	62.91	22.51	9.01	-	3.65	-

The tensile test was conducted in accordance with ASTM E8 [10]. In addition, the fracture toughness tests, i.e., the CTOD and Charpy-V impact tests, were carried out according to BS 7448 Part 2 and ASTM E23, respectively [11,12]. As shown in Figure 4, compact tension specimens 12 mm in thickness, 48 mm in width, and 57.6 mm in height were used for fracture toughness tests. CTOD test specimens for the heat affected zone (HAZ) were fabricated 1 mm from the weld fusion line (F.L.).

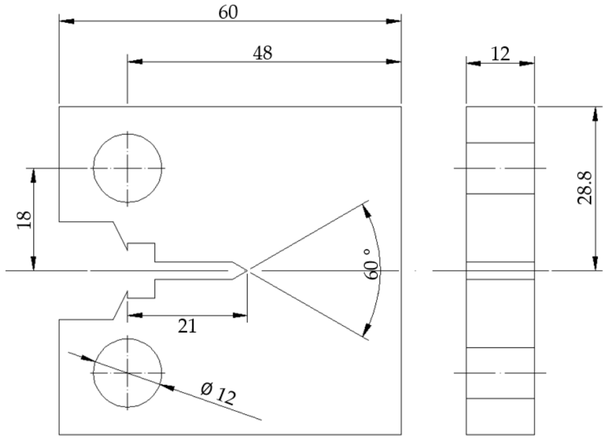


Figure 4. Compact tension specimen of crack tip opening displacement (CTOD) test.

Before the CTOD test, a fatigue pre-crack of 3 mm was inserted into the notch tip of each specimen. The fatigue pre-crack can simulate a natural crack well enough to provide a satisfactory CTOD test result [11]. The conditions of the fatigue pre-crack were a sinusoidal wave, a stress ratio of 0.1, and a frequency at 10 Hz. The CTOD test was conducted at room (25 °C), low (−100 °C), and cryogenic (−163 °C) temperatures to assess the applicability of each material for LNG storage tanks.

The test equipment used for the CTOD test was a servo hydraulic testing machine (Instron 8800, INSTRON, High Wycombe, UK) with a maximum load capacity of ±500 kN. In addition, low and cryogenic temperatures were controlled by the cryogenic chamber (ILWON FREEZER, Namyangju-si, Korea). Test temperatures were maintained by a liquid nitrogen gas inlet-outlet control system. The total equipment for the CTOD test are shown in Figure 5.

(**a**) (**b**)

Figure 5. Test equipment: (**a**) servo hydraulic testing machine; (**b**) temperature control system.

3. Test Results

3.1. Mechanical Properties

Table 4 summarizes the tensile test results of the three weldments. The weldments of ERNiCrMo-3 with FCAW and GMAW exhibit a similar tendency in yield and tensile strengths as expected.

Table 4. The mechanical properties of the weldments [13–15].

Classification	YS (Mpa)	TS (Mpa)	E.L. (%)
High manganese & TIG	473	614	36
ERNiCrMo-3 & FCAW	509	781	68.7
ERNiCrMo-3 & GMAW	506	753	75.0
BV requirement [14]	480	670	22
DNV requirement [15]	490	640	25

On the other hand, the weldment of high manganese with TIG has the lowest mechanical properties. In addition, it does not satisfy the requirements of mechanical properties from Bureau Veritas (BV) and Det Norske Veritas (DNV) [14,15]. It has been well known since the 1980s that high manganese welding consumables have several problems, such as weldability and strength [16]. Therefore, the weldment of high manganese with TIG was determined to be unsuitable for 7% nickel alloy steel. Accordingly, ERNiCrMo-3 with FCAW and GMAW are considered in the latter part of this study.

3.2. Charpy-V Impact Test

Table 5 shows the Charpy-V impact test results of the three weldments. The Charpy-V impact tests were carried out at −196 °C. As a result, all weldments satisfied the requirements of BV and DNV [14,15]. However, the weldments of ERNiCrMo-3 and FCAW were about 55% and 58% lower than that of the high manganese with TIG and ERNiCrMo-3 with GMAW, respectively. Therefore, ERNiCrMo-3 and GMAW were more applicable to the 7% nickel alloy steel weldment than were ERNiCrMo-3 and FCAW.

Table 5. Charpy-V impact test results of the weldments [13–15].

Classification	Test Temp. (°C)	Charpy-V Impact Test (J)			
		1	2	3	Average
High manganese & TIG	−196	91	105	89	95
ERNiCrMo-3 & FCAW		47	39	41	42
ERNiCrMo-3 & GMAW		104	100	96	100
BV requirement [14]		-	-	-	34
DNV requirement [15]		-	-	-	

Figure 6 presents the Charpy-V impact test results for various locations of the HAZ. In the case of FCAW, F.L. exhibited the lowest impact absorbed energy, while GMAW had the lowest value at F.L. + 1 mm. This result is attributed to the difference in heat input from each welding process. For all locations, absorbed energies of GMAW were about 12% (the maximum) higher than those of FCAW except F.L. + 1 mm. Therefore, it appears that GMAW is slightly better than FCAW in terms of impact absorbed energy.

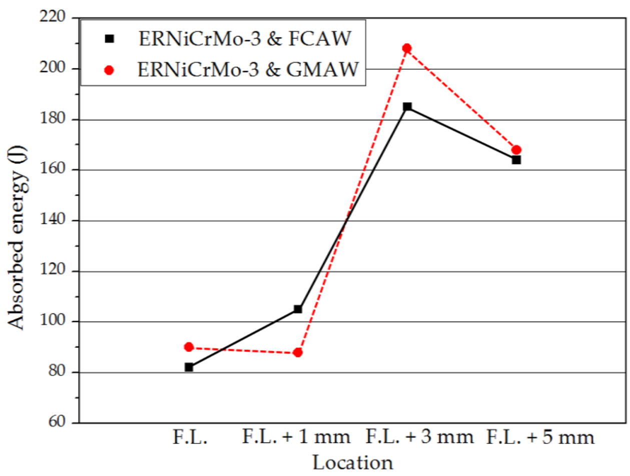


Figure 6. Charpy-V impact test results for various locations of the HAZ [13].

3.3. The CTOD Test

Based on the above results, the CTOD tests were performed on the weldment of ERNiCrMo-3 and GMAW as an optimal candidate for 7% nickel alloy steel. Figure 6 shows the CTOD values of weld metal. As shown in Figure 7, the CTOD values at cryogenic temperature satisfies the DNV requirement. It is estimated that the fracture resistance of the weldments of 7% nickel alloy steel decrease with decreasing temperature from room to cryogenic temperatures. Figure 8 shows the CTOD values of GMAW being compared with other welding processes such as shielded metal arc welding (SMAW) and gas tungsten arc welding (GTAW) [17]. In addition, chemical compositions of other welding consumables are summarized in Table 6. As the nickel content of the welding consumable increases, CTOD values also tend to increase. In addition, welding consumables of the 70% Ni type with GTAW has the highest CTOD value at cryogenic temperatures. As is well known, higher heat input results in a greater possibility of brittle fracture [18]. Therefore, it appears that SMAW has higher heat input than GTAW.

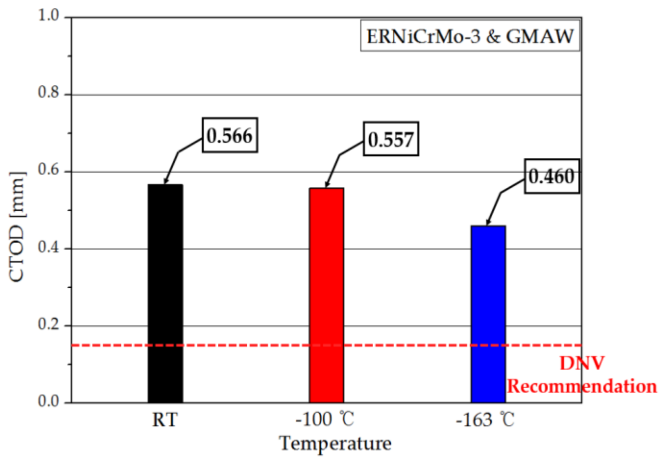


Figure 7. CTOD values of the weldment at various temperatures.

Table 6. The chemical composition of other welding consumables [13,17].

Welding Consumable	C	Si	S	Mn	Ni	Cr	Mo
ERNiCrMo-3	0.018	0.47	0.001	0.36	62.91	22.51	9.01
70% Ni type	-	-	-	-	70	-	-

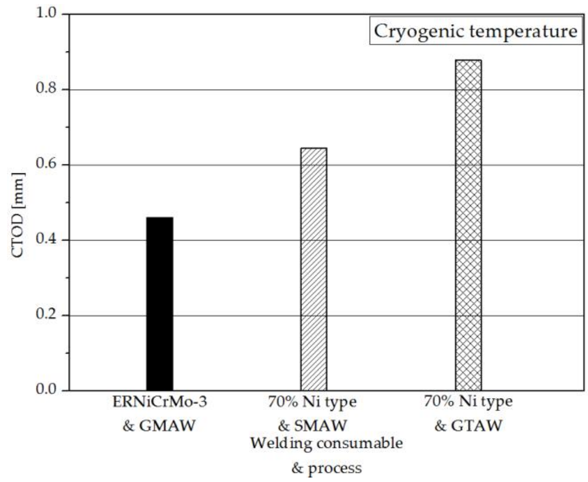


Figure 8. Comparison of the CTOD values of the weldments for other welding processes [17].

Figure 9 shows CTOD values at the HAZ. The CTOD values at the HAZ are more sensitive to the temperature decrease than those of the weldment. At a cryogenic temperature, the CTOD value at the HAZ satisfies the requirement of DNV. As shown in Figure 10, the CTOD values at the HAZ by SMAW and GTAW has a similar tendency. On the other hand, the CTOD value at the HAZ by GMAW is about 50% lower than those by GTAW [17].

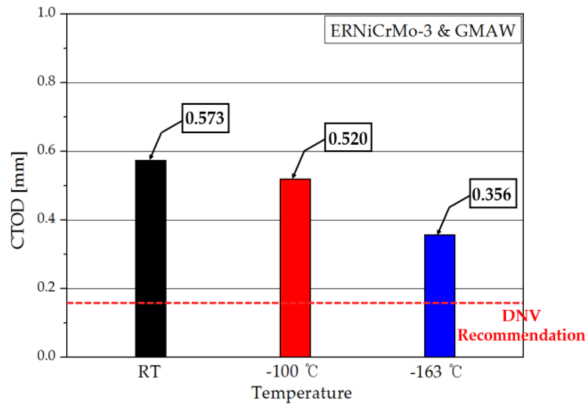


Figure 9. The CTOD values of the HAZ from room to cryogenic temperatures.

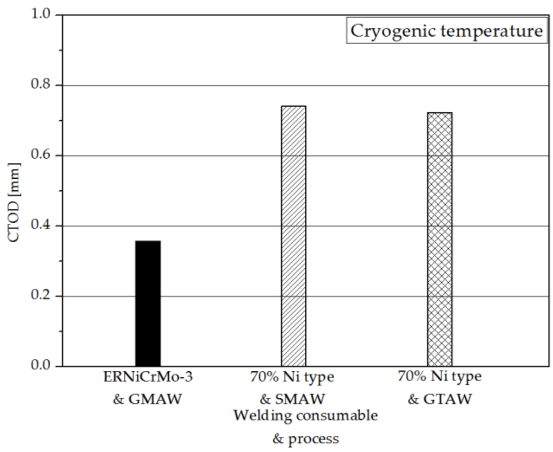


Figure 10. Comparison of the CTOD values of the HAZ for other welding process [17].

4. Discussion

The CTOD values of the weldment of 7% nickel alloy steel were compared with those for 9% nickel steel considering welding processes, as indicated in Figure 11 [5].

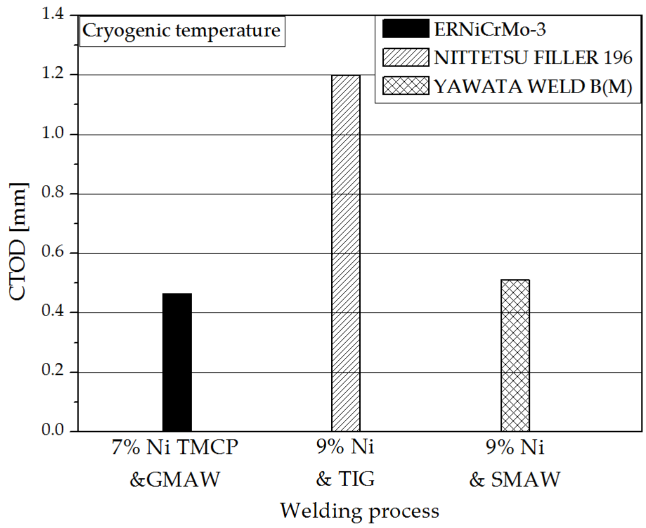


Figure 11. CTOD values of the weldment for 9% nickel steel and 7% TMCP nickel steel [5].

The chemical compositions of welding consumables for 9% nickel and 7% nickel alloy steel are summarized in Table 7 [5]. The welding consumable with TIG welding has the highest nickel content among welding consumables. It is known that a high nickel content has been used extensively to improve fracture toughness [19]. Therefore, the weldment of TIG has the highest CTOD value at cryogenic temperature. In addition, the weldment of 7% nickel alloy steel exhibits similar CTOD values compared to that of 9% nickel steel with SMAW. In this regard, the welding consumable affects the fracture toughness more than the welding process. Therefore, the weld metal of 7% nickel alloy steel is considered to replace 9% nickel steel in terms of fracture toughness.

Table 7. Chemical composition of welding consumables for 9% and 7% TMCP nickel steels [5].

Welding Consumable	C	Si	Mn	Ni	Cr	Mo	W	Nb	Fe
NITTETSU FILLER 196 (9% Ni & TIG)	0.04	0.40	0.45	72.5	-	19.0	2.91	-	3.5
YAWATA WELD B(M) (9% Ni & SMAW)	0.09	0.20	3.22	65.1	15.8	3.35	-	1.60	10.2
ERNiCrMo-3 (7% TMCP Ni & GMAW)	0.018	0.47	0.36	62.91	22.51	9.01	-	3.65	-

5. Conclusions

In this study, the mechanical characteristics of 7% nickel alloy steel weldments were evaluated based on tensile, Charpy-V impact, and CTOD test results. In addition, the fracture performances of 7% nickel alloy steel weldments were compared with those of 9% nickel steel for LNG storage tank applications. The conclusions from this study are summarized as follows:

- In the 7% nickel alloy steel, the weldment of ERNiCrMo-3 with FCAW had the highest yield and tensile strengths among other weldments. The mechanical properties of high manganese weldment with TIG did not satisfy the minimum requirements of BV and DNV. Therefore, the weldment of high manganese with TIG was determined to be unsuitable for 7% nickel alloy steel in terms of mechanical properties.

- The weldment of ERNiCrMo-3 with GMAW is about 2.3 and 1.05 times higher than that of ERNiCrMo-3 with FCAW and high manganese with TIG in terms of the absorbed energy at −196 °C, respectively. Based on the tensile and Charpy-V impact test results, the weldment of ERNiCrMo-3 with GMAW is the most appropriate for 7% nickel alloy steel.
- The weldment of ERNiCrMo-3 with GMAW exhibited the lowest CTOD values compared with other conventional weldments of 7% nickel alloy steel. It is estimated that the CTOD value of the weldment was affected by the nickel content of the welding consumables.
- Compared with the CTOD value of 9% nickel steel weldment, 7% nickel alloy steel weldment exhibits comparable CTOD values except the TIG welding process. Therefore, the weld metal of 7% nickel alloy steel is considered to be a viable alternative to 9% nickel steel from a cost-effective perspective.

Acknowledgments: This work was supported by the National Research Foundation (NRF) of Korea, grant funded by the Ministry of Education, Science, and Technology (MEST) of the Korean Government through GCRC-SOP (No. 2011-0030013). This work was also supported by Human Resource Training Program for Regional Innovation and Creativity through the Ministry of Education and NRF of Korea (NRF-2014H1C1A1073088).

Author Contributions: Myung Hyun Kim formulated this research with cooperation from Jae Myung Lee. Jeong Yeol Park performed the experimental work and, with the help of Myung Hyun Kim, interpreted the results and prepared the manuscript. All co-authors contributed to the manuscript proof and submissions.

Conflicts of Interest: The authors declare no conflict of interest.

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