Effect of Laser-Beam And Hybrid-Laser-Arc Welding Parameters and Filler Metal on Microstructure and Mechanical Properties of Thick Heat-Treated Steel X8ni9+Qt640 for Cryogenic Service

A. EL-BATAHGY[1], S. GOOK[2*], A. GUMENYUK[3], M. RETHMEIER[2,3,4]

1: Manufacturing Technology Department, Central Metallurgical R & D Institute (CMRDI), Egypt
2: Fraunhofer Institute for Production Systems and Design Technology, Germany
3: Federal Institute for Materials Research and Testing BAM, Germany
4: Technical University of Berlin, Germany
* Correspondent author: sergej.gook@ipk.fraunhofer.de

Abstract

The present research work encloses results of experimental investigations of the interaction between welding process parameters for laser-beam and hybrid-laser-arc as well as type of the filler metal and the achievable mechanical properties of the weld joints on steel grade X8Ni9+QT640 for cryogenic service containing 9% nickel. The results obtained contribute to the development and conversion in the industrial practice a new laser beam-based welding technology for the automated manufacturing of facilities for the liquefaction, storage and the transport of natural gases (LNG facilities). The results show, that the martensitic microstructure of the laser weld metal including low amount of retained austenite not exceeding 3.5% leads to the relatively low V-notch impact energy. The remarkable heterogeneity in the chemical composition of the weld metal through the weld thickness could be recognized in the case of hybrid-laser-arc welding with ERNiCrMo-3 austenitic filler metal, what also led to insufficient impact toughness of the weld metall. The most promising results could be achieved by using 11%Ni filler wire, which is similar to the base metal and provides a homogeneous microstructure with uniform distribution of Ni through the weld seam. It is remarkable, that a correlation between Charpy impact toughness and wire feeding speed and respectively process heat input exists. The highest toughness values were 134±58 J at -196°C. The both laser as well as laser-hybrid welds passed the tensile test. The failure stress of 720±3 MPa with a fracture location in the base material was achieved for all samples tested.
Keywords: Cryogenic steel, Laser-beam welding, Hybrid-laser-arc welding, Microstructure, Toughness, Hardness, Tensile strength

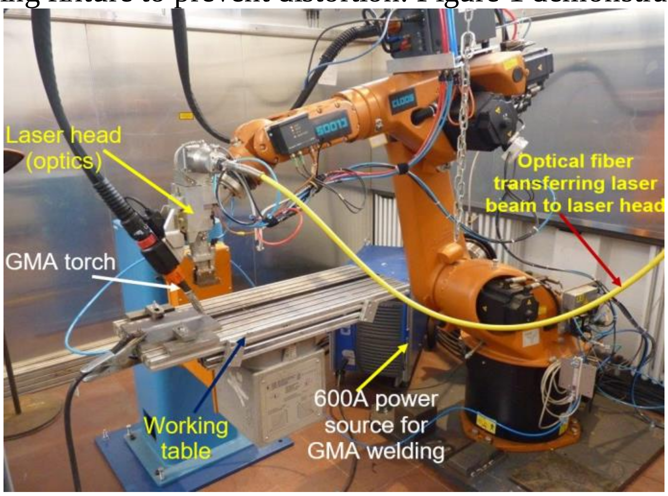
1. Introduction

The global demand for natural gas as a cleaner source of energy with lower CO_2 emissions than coal and oil is steadily increasing in terms of reducing environmental impact [1]. The transport and storage of natural gas is becoming an increasingly important role. The liquefaction of the gas is of considerable interest in order to reduce its volume, which certainly simplifies its storage and transport and contributes to a cost reduction. Large LNG storage tanks and containers with a wall thickness of up to 50 mm are being built all over the world [2]. Quenched and tempered 9%Ni steel is the most suitable material for cryogenic applications down to -196°C where mainly high impact absorbed energy is required [3, 4, 5].

Welding is the most important joining technology in the fabrication of LNG transportation and storage facilities. Therefore, understanding the factors affecting the quality of the welded joints is of considerable importance for maintaining its mechanical properties. Currently, these facilities are fabricated using mainly conventional arc welding processes such as submerged arc welding (SAW) and gas metal arc welding (GMAW). While the GMAW can be carried out in various welding positions, an innovative vertical SAW process has been developed [6]. This welding method uses a small diameter wire and weaving technique. The deposition rate is limited to 80 g/min, which does not appear to be very efficient, especially for joining large-volume weld seams. Ni-based filler materials are continued to be the most suitable choice for welding of LNG facilities [7]. Satisfied notched impact strength of austenitic Ni-based weld metal at -196 ºC for GTAW and GMAW processes on quenched and tempered 9%Ni steel were reported [8]. It was however pointed out, that welding should be done using the lowest heat input in order to lower the mixture degree between austenitic filler metal and ferritic base metal and to prevent the deterioration of the weld metal' toughness [9]. Recent LNG storage tank projects specified a minimum Charpy impact energy of 0.75 J/mm^2 at -196 °C corresponding to 60 J on a standard Charpy impact specimen [10]. Beside high toughness the ensuring the required tensile strength is not a trivial task when using nickel-based welding consumables. This means that conventional Ni-based filler metals are unable to match safely the strength of quenched and tempered 9%Ni steel [11]. This fact is taken into account in design codes for LNG tanks by basing the maximum allowable design stresses on the strength of an under-matching Ni-based weld joint. This means that very high wall thicknesses are needed in order to guarantee the expected properties of the welded construction. This problem negatively affects both economic and quality aspects of welded structures made of 9%Ni steel. An effective solution to such problems could be the application of laser beam autogenous welding which is a high-energy density and low heat input process. High-power laser beam welding is finding increasing application for steel materials up to 50 mm in the wall thickness [12]. High-power solid-state lasers with the capability of producing deep penetration welds have opened the way for welding more nonconventional materials such as high-manganese austenitic steels [13] and duplex stainless steel [14]. Recent investigations have demonstrated that the microstructure of the weld metal and also the HAZ of 9%Ni steel are affected by the cooling rate as a function of the heat input [15]. Consequently, it is expected that the microstructure and the mechanical properties of welded joints of 9%Ni steel are affected by the type of welding process. However, this research area is being far from complete and further research works are needed, particularly for laser beam welding that has not been extensively researched. The present research work encloses results of experimental investigations of the interaction between type of welding process as well as type of the filler metal and the achievable mechanical properties of the weld joints on steel grade X8Ni9+QT640 for cryogenic service containing 9% nickel. The results obtained contribute to the development and conversion in the industrial practice a new laser beam based welding technology for the automated manufacturing of LNG facilities. The effect of laser-beam and hybrid-laser-arc (HLAW) welding parameters as well as the type of the filler metal on microstructure and mechanical properties of the heat treated 9%Ni steel was experimentally investigated.

2. Experimental Setup

The welding tests were performed with a 20 kW Yb fiber laser YLR 20000 of IPG, with a wavelength of 1064 nm and a beam parameter product of 11.2 mm x mrad in flat position. An optical fiber of 200 µm was used to transmit the laser radiation. The laser optics BIMO of HIGHYAG with a magnification factor of 2.8 was used. The focal length of the optics was 350 mm and the focus diameter of the laser beam was 0.56 mm. The Qineo Pulse 600A welding unit of Cloos was used as an arc welding power source. The HLAW tests were carried out with an arc leading orientation with an angle of 25° between torch and laser beam. The distance between the wire tip and the laser beam axis on the workpiece was defined as 4 mm. A negative focus position of the laser beam relative to the workpiece surface of -3 mm have been selected. The laser head and the GMAW torch were mounted on the robot arm. Specimens with machined edges and dimensions of 250x100x14.5 mm^3 were prepared for laser autogenous as well as for HLAW square butt welds. The weld joints were accurately aligned, clamped and held firmly using fixture to prevent distortion. Figure 1 demonstrates the experimental setup.

a) 

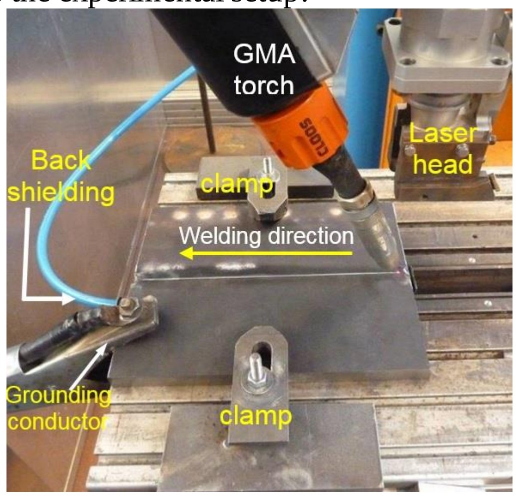
b) 

Figure 1 Laser and laser-GMA hybrid welding system used for experiments: (a) laser head and GMA torch are mounted on a 6-axis welding robot and (b) no gap square butt joint alignment, clamping and back shielding preparation

Two types of solid filler wires, the commonly used austenitic filler wire ENiCrMo-3 (AWS A5.11) with a diameter of 1.2 mm as well as an experimentally produced ferritic filler wire Boehler Tht 11TT (Company specification) with 1.0 mm diameter containing 11%Ni were used for the HLAW trials. The used base metal is a commercial 9% Ni quenched and tempered steel grade ASTM A553 Type 1 (EN10028-4 X8Ni9+QT640, heat treatment variant with minimum tensile strength of 640 MPa) with 14.5 mm plate thickness. The average measured mechanical properties of the base metal were 717 MPa tensile strength, 197 J impact absorbed energy at -196°C and 252HV hardness. All materials used and their chemical compositions are shown in Table 1.

Table 1. Chemical composition of base material and filler wires, shown in wt%

Material/Element	C	Mn	Si	P	S	Cr	Ni	Mo	Cu	Fe
plates X8Ni9+QT640	0.07	0.39	0.18	0.006	0.001	0.02	8.86	0.02	0.01	bal.
wire ENiCrMo-3	0.03	0.2	0.25	-	-	22	bal.	9	-	<1.0
wire Tht 11TT	0.013	0.4	-	-	-	0.045	11.3	-	-	bal.

A gas mixture of argon + 18%CO_2 as well as argon + 30%He with a flow rate of 25 l min^{-1} served as shielding gas for HLAW tests. Argon was used as a process gas for laser welds and as a back shielding.

4. Results and Discussion

The 14.5 mm thick plates of X8Ni9+QT640 could be butt welded with the appropriate parameter sets in good quality. Table 2 summarizes the welding parameters used for the tests.

Table 2. Welding parameters for single-pass laser and hybrid laser-arc welds

t in mm	joint preparation	welding process	filler material	P_l in kW	v_w in m min^{-1}	v_{wire} in m min^{-1}	U in V	I in A
14.5	I-butt	laser	-	18	2	-	-	-
		HLAW	ENiCrMo-3, ∅1.2 mm	16...18	2.6...3	11...14	30...33	330...350
		HLAW	Tht 11TT, ∅1.0 mm	16...17	2.5...2.8	8...16	28...32	275...315

After welding, both laser beam and laser hybrid welds were visually inspected to test external weld defects. Accepted welds were subjected to a radiographic test (RT) to verify internal weld defects. After the radiographic examination, the welded joints were examined by metallography.

Outer appearance of the face and root sides as well as RT films of autogenous laser welded joint, HLAW weld with the filler wire ENiCrMo-3 and HLAW weld with the filler wire Tht 11TT is shown in Figure 2, Figure 3 and Figure 4, accordingly.

Results of both visual inspection and RT of laser and all HLAW welded joints showed full penetration and soundness of welds where no unacceptable external or internal welding defects were observed. This is mainly due to proper selection of welding conditions implemented in all cases.

Figure 5 shows macrographs of the cross sections taken from autogenous laser weld (Figure 5a), HLAW weld produced using filler wire ENiCrMo-3 (Figure 5b) and HLAW weld produced using filler wire Tht 11TT (Figure 5c).

It is noteworthy that the development of the weld is essentially symmetrical about its center for all laser and HLAW welded joints. The macroscopic investigations confirmed the soundness of the welded joints where no unacceptable internal welding defects such as lack of fusion or microcracks were found. The laser weld is evenly formed, indeed, with a continuous undercut on the top with a depth of approximately 0.5 mm (Figure 5a). Such a material loss using the laser welding of thick walled steel plates occurs because an evaporation of the base material as well as a partly drop out of the liquid metal on the root-side. HLAW welding has resulted in a complete joint penetration free from under-filling due to the addition of filler wire (Figure 5b, c).

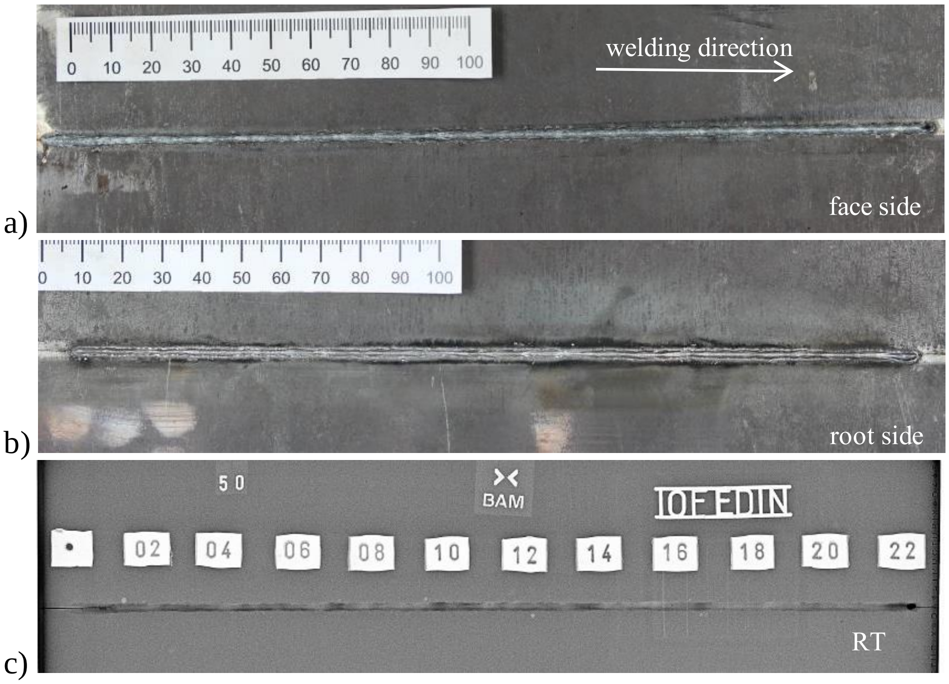


Figure 2 Photographs of (a) face side, (b) root side, (c) RT film of autogenous laser welded joint produced using 18 kW laser power, 2 m/min welding speed and 25 l/min argon shielding.

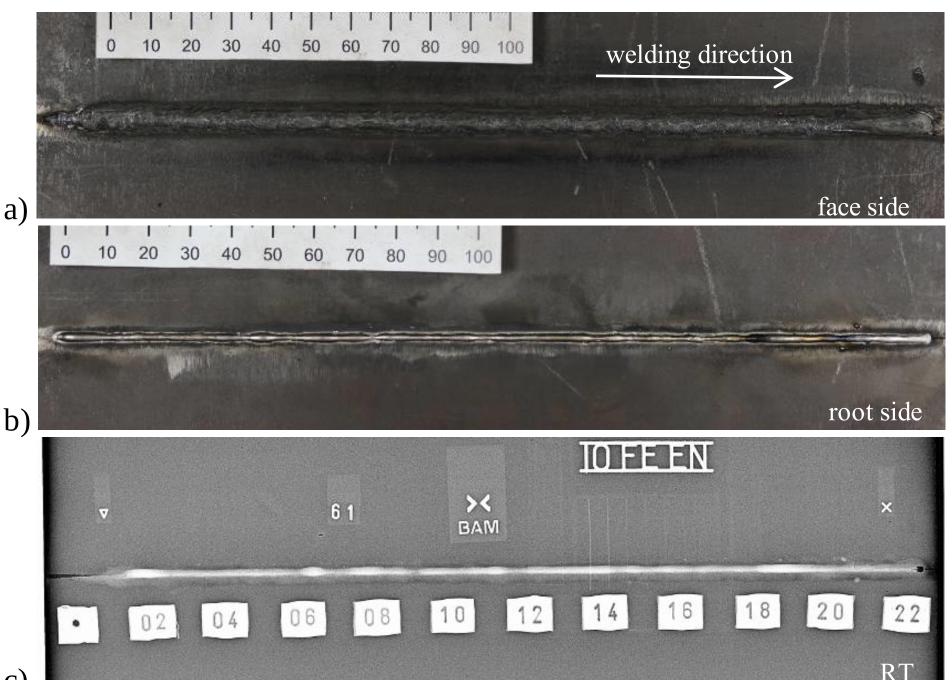
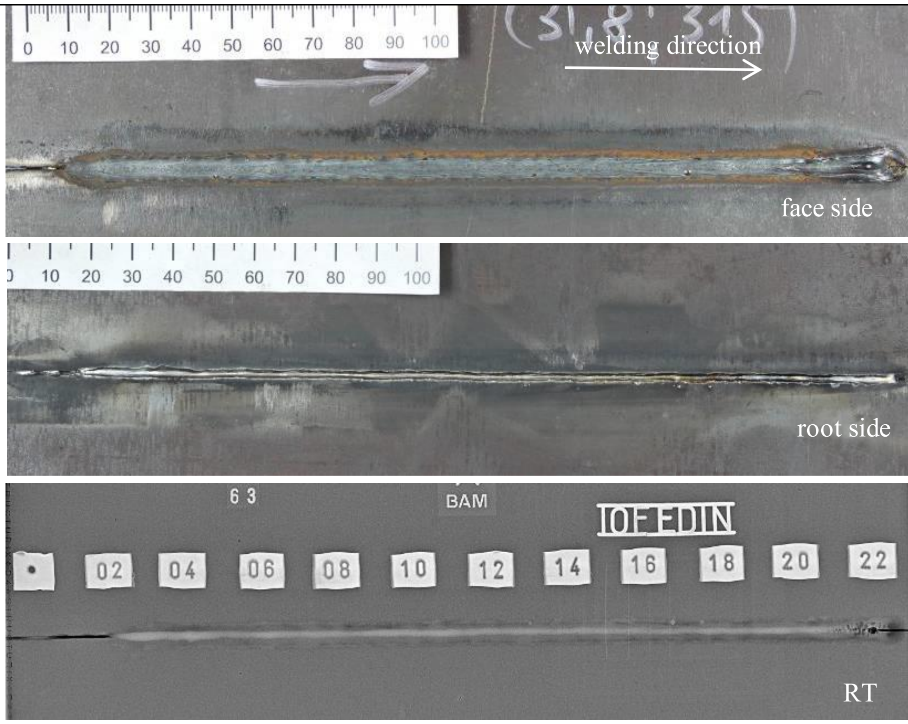


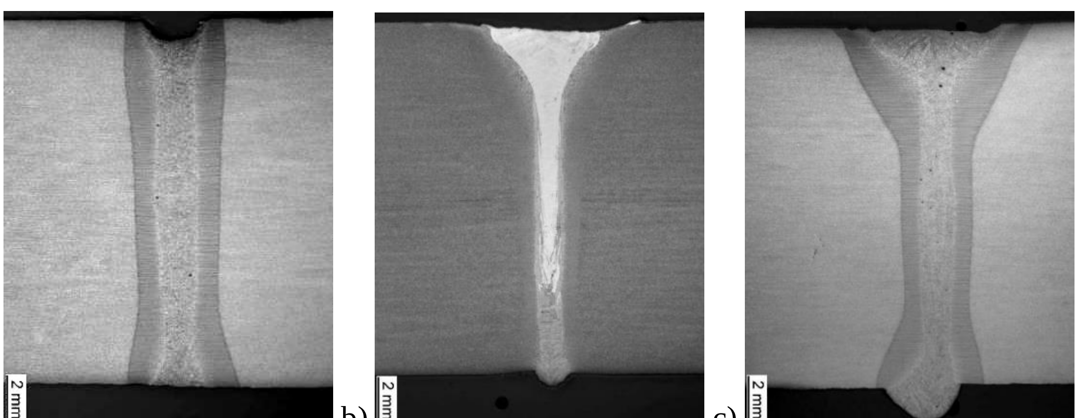
Figure 3 Photographs of (a) face side, (b) root side, (c) RT film of HLAW joint produced using 17.5 kW laser power, 2.6 m/min welding speed, 12 m/min wire feeding rate (ENiCrMo-3) and

25 l/min argon+30%He shielding.



a) b) c)

Figure 4 Photographs of (a) face side, (b) root side, (c) RT film of HLAW joint produced using 17 kW laser power, 2.8 m/min welding speed, 16 m/min wire feeding rate (Bohler Tht 11TT) and 25 l/min argon+18%CO_2 shielding.



a) b) c)

Figure 5 Macrographs of cross sections taken from (a) autogenous laser welded joint, (b) HLAW joint produced using filler wire ENiCrMo-3 and (c) HLAW joint produced using filler wire Bohler Tht 11TT

Macroscopic examinations showed typical characteristic of laser and HLAW welds where a slight taper configuration fusion zone was obtained that means the fusion zone interface is a smooth curve with no inflection. The fusion zone of laser and HLAW welds is remarkably narrower than the base metal thickness. Weld bead depth/width ratios of 5.0 and 3.1 were obtained for laser beam and HLAW welds, which are much higher than that of conventional arc welding that, in general, is lower than 1.0. This is one important feature for laser beam and HLAW welds and is related to the lower heat input as well as the higher energy density of the welding processes.

The corresponding micrographs of the weld metal (WM) for the laser weld as well as HLAW welds the are shown in Figures 6a, b and c.

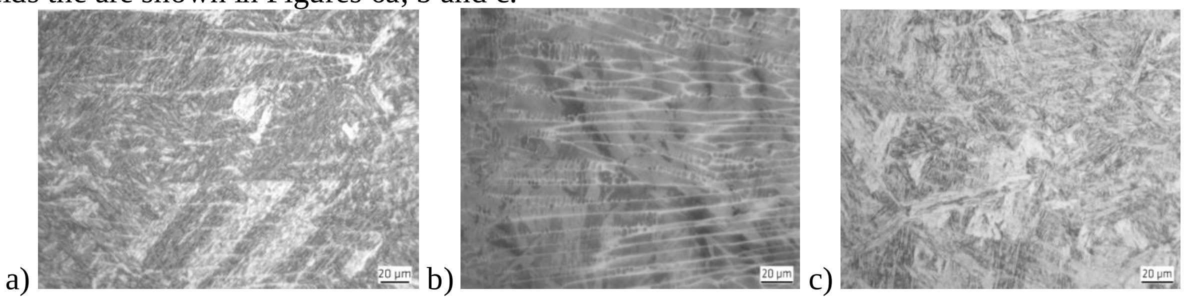


Figure 6 Optical micrographs of weld metal for (a) autogenous laser welded joint, (b) HLAW joint produced using filler wire ENiCrMo-3 and (c) HLAW joint produced using filler wire Bohler Tht 11TT

The noticeable feature is the highly directional nature of the microstructure of weld metal. The weld metal of both autogenous laser weld (Figure 6a) and HLAW weld obtained using Boehler Tht 11TT, which is 11% Ni ferritic wire (Figure 6c), exhibits fine martensitic microstructure including dendritic grains and large amounts of blocks and packets nucleated from prior-austenite grain boundaries. This is related to solidification of the weld metal at higher cooling rate as a result of lower heat input compared with that of conventional arc welding. The weld metal of HLAW weld obtained using solid wire ERNiCrMo-3 (Figures 6b) exhibits fine dendritic austenitic structure due to again the high cooling rate as a result of low heat input.

The EBSD phase maps of the base metal (Figure 7a), laser weld heat affected zone (HAZ) (Figure 7b) and laser WM (Figure 7c) show that about 81% - 96% of the sampled areas is martensite. The retained austenite content (green points in the phase maps) is about 3.5% for all examined areas. The undetected area (zero solution) reached the max. value of 15% in the HAZ.

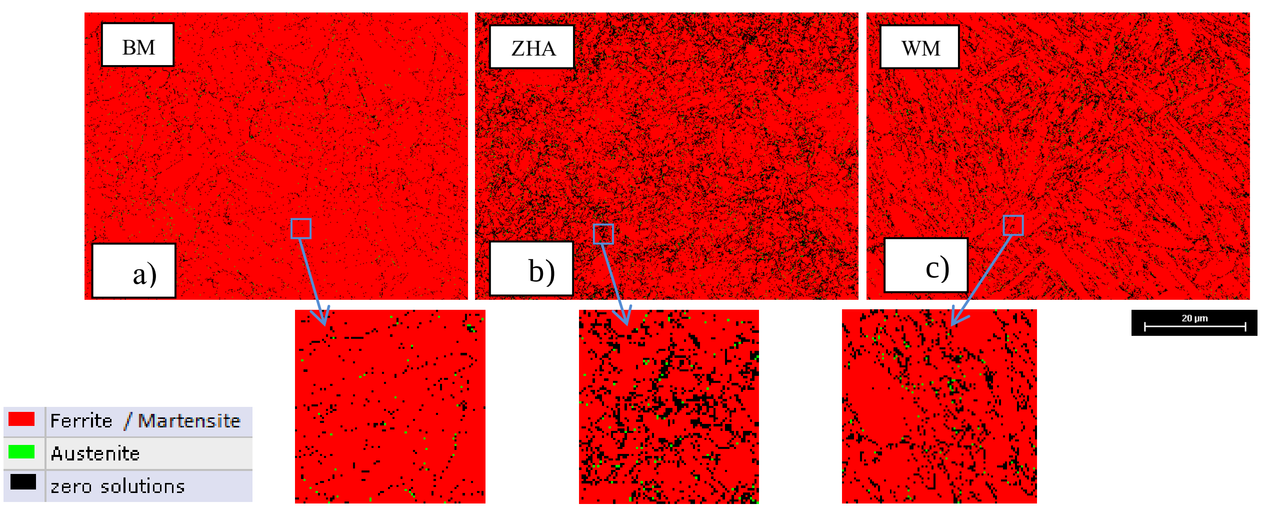
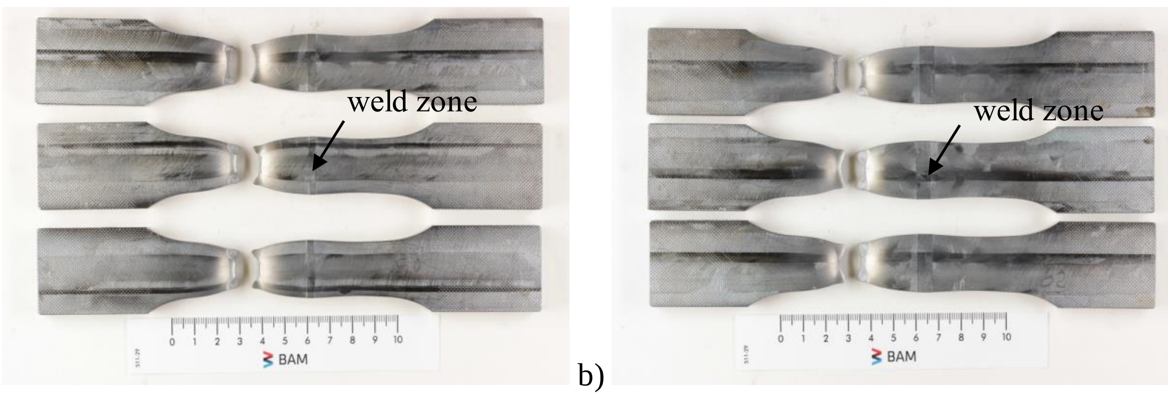


Figure 7 EBSD phase maps showing phase composition of the base metal (a), laser weld HAZ (b) and laser WM (c)

A visual comparison of macrographs in Figure 5 demonstrates that the penetration of the austenitic filler material ERNiCrMo-3 is not homogeneous through the weld thickness (Figure 5b). The EDX measurements showed average Ni concentration 25% at the weld top, 22% in the weld middle and 12% at the weld root for the HLAW welds produced using austenitic solid wire ERNiCrMo-3. On the other hand, the average Ni concentration across the HLAW weld produced using ferritic wire Boehler Tht 11TT (Figure 5c) is about 9% and has quite uniform character in the weld cross section.

Tensile tests were done according to DIN EN ISO 4136. Examples of tensile test fractured specimens of laser beam welded joints are shown in Figure 8a. The tensile test fractured specimens in Figure 8b are representative to HLAW welds made using either the austenitic filler metal ERNiCrMo-3 or the ferritic filler metal Boehler Tht 11TT. The both laser as well as laser-hybrid welds passed the tensile test. The failure stress of 720±3 MPa with a fracture location in the base material was achieved for all samples tested.



a) b)

Figure 8 Example of tensile test fractured specimens of (a) laser beam welded joint, (b) HLAW welds

The Charpy V-notch test was carried out according to DIN EN ISO 148-1 for weld metal of laser and HLAW welds -196°C. The V-notch was located at the middle of weld metal. Results of impact test are shown in Figure 9.

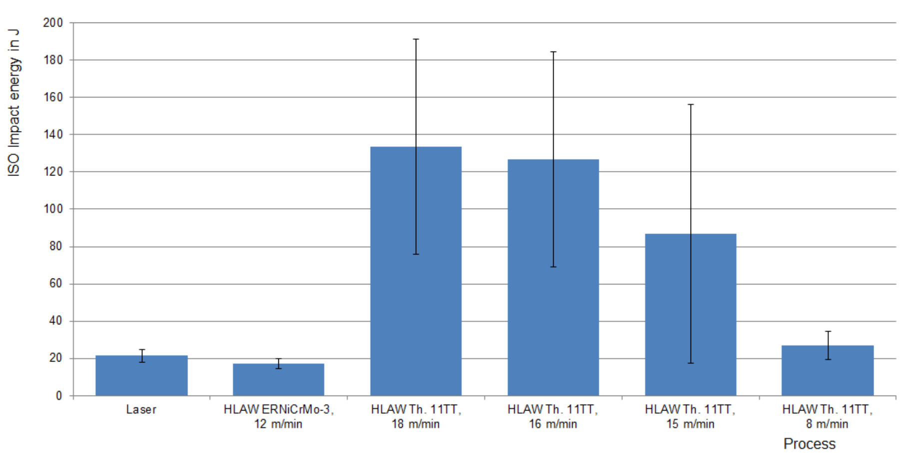


Figure 9 Impact absorbed energy at test temperature -196°C for laser beam welds as well as HLAW welds made using different filler metals with different wire feeding speeds.

For laser and HLAW welds made using ferritic filler metal Boehler Tht 11TT the impact absorbed energy (134±58 J) is much higher than that of both laser (21±5 J) and HLAW welds made using austenitic filler metal ERNiCrMo-3 (17±3 J). This is related to small weld zone size as well as uniform Ni content similar to that of the base metal through the weld cross section of the HLAW weld.

There is a correlation between Charpy values and wire feed speed. The highest toughness values 134±58 J at -196°C were obtained for the laser power of 17.5 kW, welding speed of 2.5 m/min and wire feeding speed of 18 m/min. The welding heat input for this parameter combination was 0.66 kJ/mm. A reduction of the wire feeding speed to 16 m/min corresponding to the welding heat input of 0.63 kJ/mm resulted in the lowing of Charpy toughness to 126±57 J. A process with very low wire feeding speed of 8 m/min and with a heat input of 0.5 kJ/mm led to the reducing the Charpy toughness under acceptance level of 40 J. The weld metal toughness in this case reached 27± 7 J, which is close to the laser weld toughness.

5. Conclusion

The welding process type as well as the filler metal type played important roles in obtaining satisfactory welded joints of 14.5 mm thick plates of 9%Ni steel. A stable and reproducible welding process with a sound weld seam formation could be obtained for laser and HLAW welds. The addition of experimentally produced ferritic filler wire Boehler Tht 11TT played a considerable role in maintaining the impact toughness of HLAW welded joints. This filler material is similar to the base metal and provides a homogeneous microstructure with uniform distribution of Ni through the weld seam. The micro alloying elements of the filler metal resulted in the formation of a very fine-grained nickel martensite microstructure that provided sufficient Charpy values.

Acknowledgement

The welding experiments were carried out within the joint innovative project (support code of DLR Project Management Agency, Germany 01DH14012 - Egypt GERF ID5111) between Central Metallurgical Research and Development Institute (CMRDI) of Egypt and Fraunhofer IPK of Germany. The project is supported by the Science and Technology Development Fund (STDF) of the Arab Republic of Egypt and the Federal Ministry of Education and Research (BMBF) of the Federal Republic of Germany. The authors would like to thank voestalpine Böhler Welding Germany GmbH (Department Development Covered Electrodes and Fluxes) for the providing of welding consumables for the welding trials.

References

1. Park, J. Y., Lee, J. M., Kim, M. H., 2016. An investigation of the mechanical properties of a weldment of 7% nickel alloy steels, Metals, 6(285), 1-10.
2. Furuya, H.; Kawabata, T.; Takahashi, Y.; Kamo, T.; Inoue, T.; Okushima, M.; Ando, R.; Onishi, K. Development of Low-Nickel Steel for LNG Storage Tanks. In Proceedings of the 17th International Conference & Exhibition on Liquefied Natural Gas, Houston, TX, USA, 16–19 April 2013.
3. Bourges, P., Malingraux, M., 2008. Fabrication and Welding of Thick Plates in 9% Ni Cryogenic Steel. INDUSTEEL Co., 2008.

4. Hoshio, M., Saitoh, N., Muraoka, H., Saeki, O., 2004. Development of Super-9%Ni Steel Plates with Superior Low-Temperature Toughness for LNG Storage Tanks. Nippon Steel Technical Report, 380, 17-20.
5. Wu, Y., Cai, Y., Sun, D., Zhu, J., Wu, Y., 2015. Microstructure and properties of high-power laser welding of SUS304 to SA553 for cryogenic applications. Journal of Materials Processing Technology, 225 (11), 56-66.
6. Mizumoto, M., Motomatsu, R., Nagasaki, H., Iijima, T., Kobayashi, K., Mizo,Y., 2008. Development of Submerged Arc Welding in Vertical Up Position: A study on Welding Consumables for 9%Ni Steel. Journal of the Japan Welding Society, Vol. 82, 48-49.
7. KOBELCO, 2011. Kobelco’s Welding Consumables for LNG Storage Tanks Made of 9% Ni Steel.
8. El-Batahgy A. M., Zaghloul, B., 1998. GTAW Welding of Quenched and Tempered 9%Ni steel, Technical Report, Egyptian Petrochemicals Company.
9. Khourshid, A. E. F. M., Ghanem, M. A., 2013. The influence of welding conditions on mechanical properties of 9% Ni steel welded joints of Liquefied Natural Gas tank. The International Journal of Engineering And Science (IJES)Volume 2 Issue1, 179-185.
10. Strömberg, J., Pak, S. S-H., Cost Efficient LNG Storage Tank Constructed by High Productivity Welding, ESAB, Gothenburg. In Proceedings of the 13th International Conference & Exhibition on Liquefied Natural Gas, Gas Seoul, Korea, May 14-17, 2001
11. Ohkita, S., 2003. Control of strength and toughness in weld metals. Welding international, 17(9), 693-698.
12. Zhang, X., Ashida, E., Tarasawa, S., Anma, Y., Okada, M., Katayama, S., Mizutani, M., Welding of thick stainless steel plates up to 50 mm with high brightness lasers. Journal of Laser Applications, 23(2), 022002 (2011).
13. Quiroz, V., Gumenyuk, A., Rethmeier, M., 2012. Laser beam weldability of high-manganese austenitic and duplex stainless steel sheets. Welding in the World, 56(1-2), 9-20.
14. El-Batahgy, A. M., Khourshid, A. F., Sharef, T., 2011. Effect of laser beam welding parameters on microstructure and properties of duplex stainless steel. Materials Sciences and Applications, 2(10), 1443-1451.
15. Scheid, A., Félix, L. M., Martinazzi, D., Renck, T., Kwietniewski, C. E. F., 2016. The microstructure effect on the fracture toughness of ferritic Ni-alloyed steels. Materials Science and Engineering: A, 661, 96-104.