Welding of austenitic stainless steels for cryogenic LNG applications

Low Temperature Behaviour of Austenitic Weldments

Norbert Friedrich, Application Technology, Böhler Welding Austria GmbH, Austria
Gerhard Posch, Head of Research & Development, Böhler Welding Austria GmbH, Austria
Josef Tösch, Research & Development, Böhler Welding Austria GmbH, Austria
Johann Ziegerhofer, Research & Development, Böhler Welding Austria GmbH, Austria
Walter Berger, Managing Director, Böhler Welding Austria GmbH, Austria

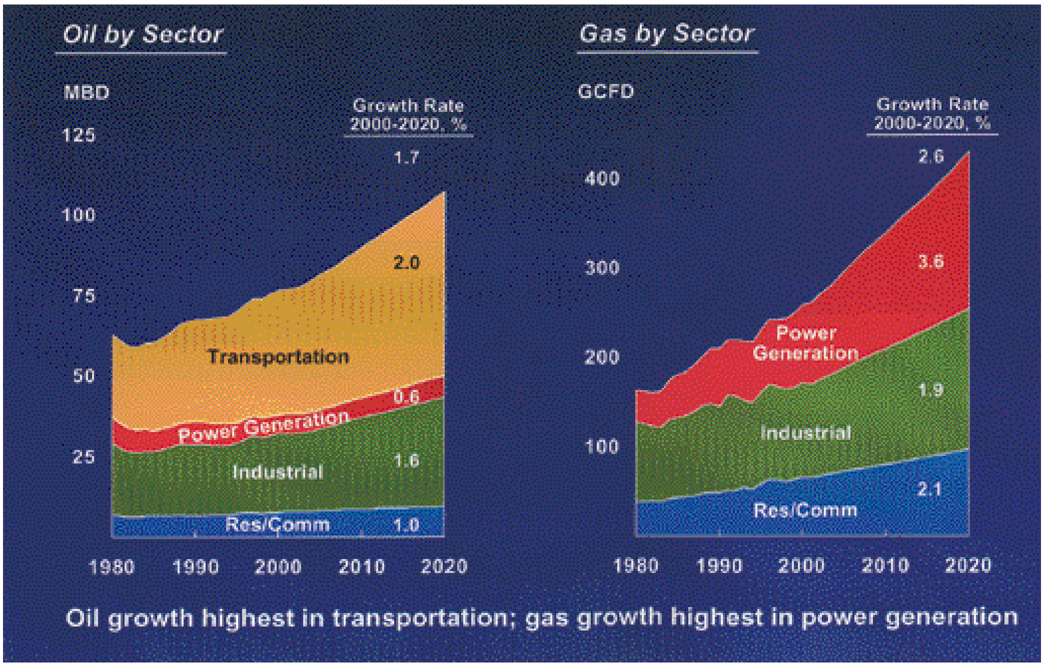
Keywords: LNG, High alloyed weldments; controlled ferrite content, cryogenic application

Abstract:

Austenitic stainless steels of type AISI 304/304L and AISI 316/316L are commonly used for the storage and distribution of liquefied natural gas (LNG). The steels have to operate at very low temperatures, which is the reason why high requirements regarding toughness and lateral expansion at -196℃ are demanded. From the metallurgical point of view, low amounts of delta ferrite in the weld metal are necessary to achieve the requirements. This paper deals with typical values for delta ferrite content and mechanical properties which can be achieved with special designed filler metals for GTAW, SMAW and FCAW. Emphasis is also given to the hot cracking susceptibility, which increases dramatically with very low delta ferrite contents.

1 Introduction

The demand for oil and gas is increasing steadily and forecasts (**Figure 1**) promote for example a gas consumption in 2020 which is about three times higher compared to 1980. To secure the supply with oil and gas new production plants, transport and storage systems have to be installed within the next decade and many plates and tubes of various materials have to be fitted together to establish the necessary tank and tubing systems. Welding plays thereby an important role.



Oil growth highest in transportation; gas growth highest in power generation

Figure 1: World oil and gas demand (forecast) [1]

Form the materials point of view, the handling of gas is a very interesting topic. Due to the high volume of gas, storage and transportation should be done with liquefied gas, because in this case the volume of the liquid is approx. 1/620 of the equivalent gas. The main "disadvantage" thereby is, that gas is liquid only at very deep temperatures and the used materials have to exhibit strong toughness requirements at very low temperatures.

In **Figure 2** typical materials which fulfil the requirements for handling liquefied natural gas (LNG) are shown.

Alloy	Type	Application
9 Ni	**9 % Ni Steel**	**Storage tanks**
304 L	**Stainless steel type AISI 304 L**	**Piping; Small vessels. Sometimes for large storage tanks**
36NiFe	**Low expansion 36 % Ni-Fe alloy**	**Sometimes for large storage tank construction. Piping in critical applications.**
Al	**Aluminium alloy 5083 (Al-4.5 % Mg) Alloy 5154 (Al - 3,5% Mg) Alloy 6000 (Al - Si)**	**Spherical or prismatic storage tanks for ship transportation of LNG. Tubing for the main cryogenic heat exchanger. Forgings such as flanges.**

Figure 2: Typical applications of established base materials used for LNG [2]

The austenitic grades, especially the austenitic weldments are the focus of this paper. It has to be mentioned that beside grade AISI 304L also type AISI 316L will be used more often in future. For joining these grades filler metal type 308L and 316L are used.
The liquefaction temperature of Methane is -163℃ (-261℉) and this fact determines the operating temperature of the LNG plant. The test temperature for mechanical properties has been set to -196℃ (-320℉) due to safety reasons but also of the easy reproducibility of this test condition.
Before setting up the requirements for LNG weldments the general mechanical properties of the austenitic steel and the main influences on the achieved test data have to be discussed.

2 Strength properties austenitic steels for LNG application

Strength design is primarily done using room temperature properties. The all weld metal properties at room temperature are quite similar independent of the applied welding process (**Figure 3**).

AWS	Böhler Brand	Process	$Rp_{0,2}$ $[N/mm^2]$	R_m $[N/mm^2]$	A5 [%]
ER308L	EAS 2 -IG	GTAW	**430**	**610**	**39**
ER308L Si	EAS 2 –IG (Si)	GMAW	**420**	**630**	**38**
E308L-15	FOX EAS 2	SMAW	**400**	**580**	**42**
E308L-17	FOX EAS 2-A	SMAW	**390**	**560**	**40**
EC308L	EAS 2-MC	GMAW	**350**	**540**	**40**
E308LT0-4 **E308LT0-1**	EAS 2-FD	FCAW	**380**	**560**	**40**
E308LT1-4 **E308LT1-1**	EAS 2 PW-FD	FCAW	**390**	**570**	**40**
ER308L	EAS 2-UP//BB 202	SAW	**350**	**550**	**35**

Figure 3: Mechanical properties of consumables type 308L for various welding processes

The mechanical properties are also hardly influenced by variation of the delta ferrite content and the electrode diameter as shown in **Figure 4** using for example an electrode of type E 308L-15.

Electrode type	Ø [mm]	$Rp_{0,2}$ [N/mm²]	R_m [N/mm²]	Ferrite * [FN]
E308L-15	2,5	421	603	9,5 – 10,3
E308L-15	3,2	401	550	6,4 – 7,6
E308L-15	4,0	395	547	6,3 – 7,5
E308L-15	5,0	400	551	6,9 – 7,8

***FERITSCOPE MP 30**

Figure 4: Mechanical properties all weld metal BÖHLER FOX EAS 2 (AWS E308L-15)

It is very well known that decreasing temperatures increase the strength of the austenitic steel.

Figure 5 shows some strain/stress curves for the base material at various temperatures and points out the strong effect of the temperature on the strength.

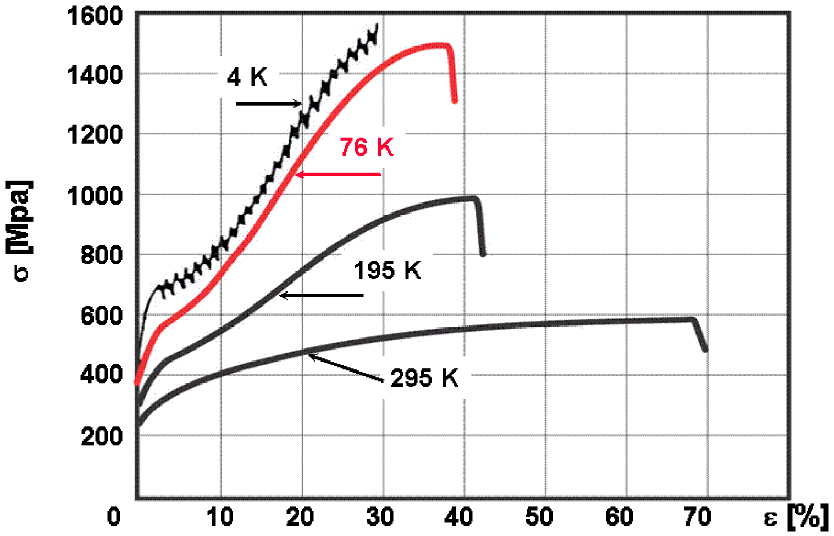


Figure 5: Tensile test specimen stress vs. strain curves of SS grade AISI 304

3 Toughness properties of austenitic steels for LNG application

As it clearly can bee seen in **Figure 5** at lower temperature the elongation, but also the toughness of the austenitic steel decreases. To establish safe LNG constructions it is necessary to set strong toughness requirements at operating temperatures. Therefore the lateral expansion and the impact energy are very useful material property data for describing low temperature toughness behaviour of the metal.

3.1 Lateral expansion and impact energy

By comparing lateral expansion and impact energy a correlation also at very low temperatures can be seen (**Figure 6**). This correlation is influenced by the welding process, type of welding consumable and slag system.

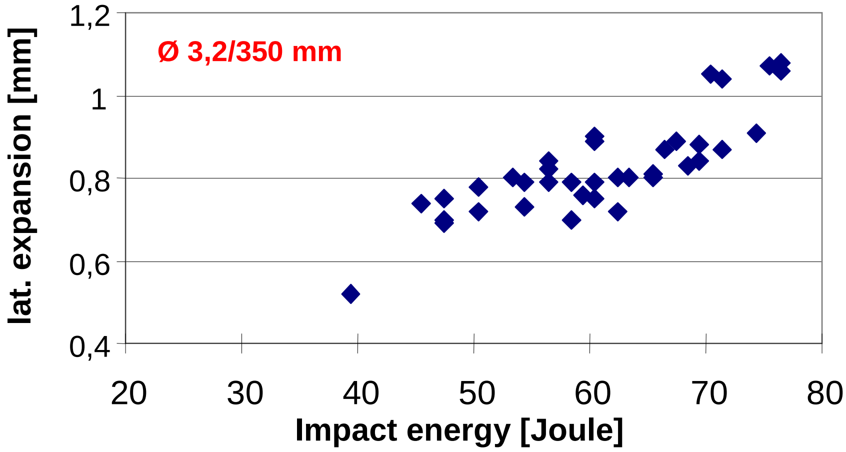


Figure 6: Relation between lateral expansion and impact energy at -196°C; consumable: BÖHLER FOX EAS 2 (E 308 L-15)

3.2 Toughness and delta ferrite content

A very important correlation can also be found between impact energy and delta ferrite content of the weld metal. At higher ferrite levels the impact toughness is significant lower compared to lower ferrite levels. As an example **Figure 7** shows this influence depending on the diameter of a stick electrode of type E308L-15 under quite extreme welding conditions.

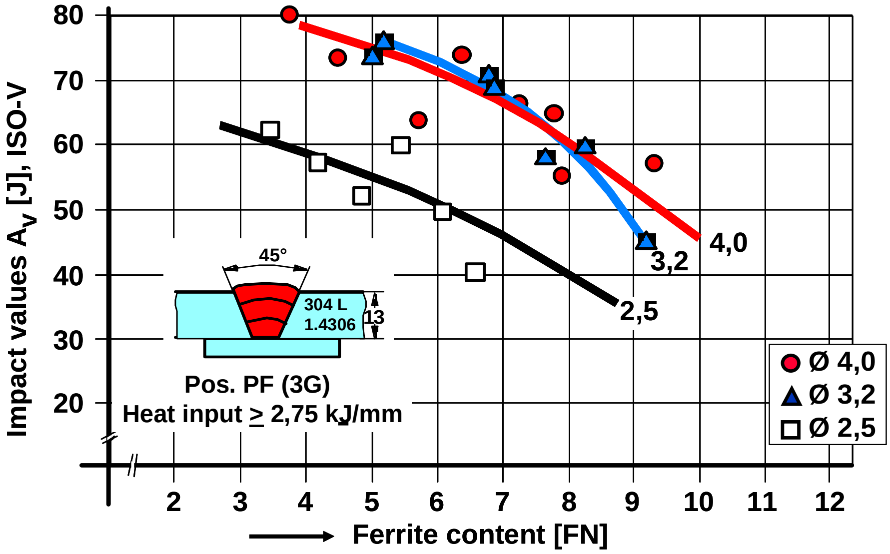


Figure 7: BÖHLER FOX EAS 2 (E308L-15); Ferrite content versus impact properties at –196°C; joint welded with very high heat input in 3G (PF)

The beneficial effect of a lower ferrite content on the deep temperature toughness described in **Figure 7** also remains at higher temperatures (**Figure 8**).

In this diagram the temperature dependence of the impact toughness can be seen. Taking the relation between impact energy and lateral expansion as described earlier into account, same considerations are also valid for the lateral expansion.

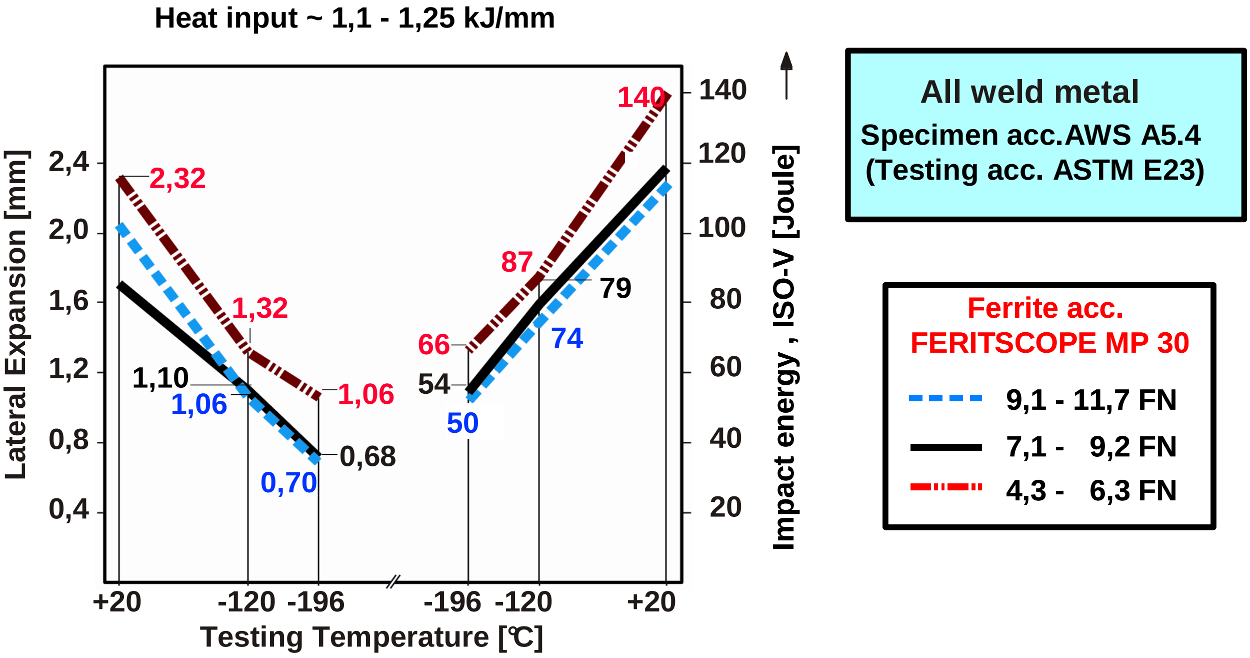


Figure 8: BÖHLER FOX EAS 2 (E308L-15): Influence of the ferrite content on the impact properties down to -196℃

As it is clearly shown, the delta ferrite content has a major influence on the deep temperature toughness of the austenitic weld metal and the relation is quite strong: The lower the delta ferrite content the higher toughness properties like impact energy and lateral expansion [3]. From this point of view, the ferrite level should be kept as low as possible to guarantee high toughness values at -196℃.
On the other hand, a minimum delta ferrite is required to prevent hot cracking at all. As a minimum level therefore 3FN has been committed for SMAW, GMAW, SAW and GTAW to guarantee crack-free joints also in case of welding procedures with high heat inputs. At ferrite levels below 3FN the hot cracking susceptibility is increased drastically, as numerous results of PVR-tests have shown (**Figure 9**).

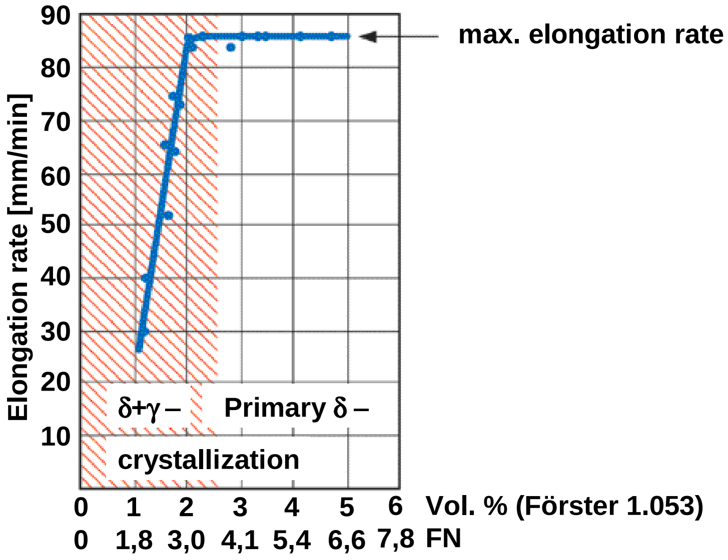


Figure 9: Ferrite content vs. hot cracking susceptibility (PVR-test) [4]

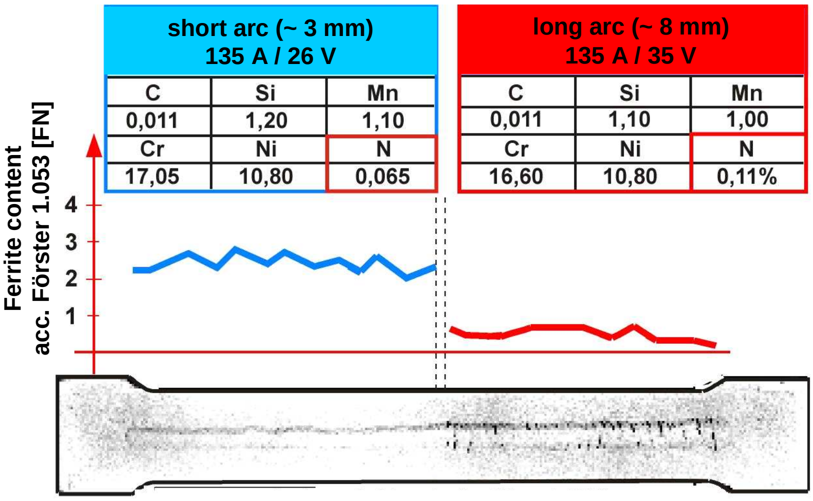
Going to the lower metallurgical limits of the delta ferrite content it is necessary to consider all additional effects which can lead to a weld metal which is below the lower limit, independent of the chemical composition of the consumable. The most important points thereby are the determination of the ferrite content and the arc, especially the arc length on the chemical composition of the weld metal.

3.2.1. Measured vs. calculated FN values

Dealing with electrodes which are designed for lowest safe FN-levels the discussion may rise if measured or based on the chemical composition calculated FN values are mandatory. As the delta ferrite content in the weld metal is a very good indication for the solidification mode of the liquid weld metal (ferritic or austentic) the actual, the measured ferrite value is therefore characteristic. Investigations have shown, that there are differences between the measured and calculated values [5] but there are also differences between results of different labs [6]. This fact should be considered by setting up the requirements for LNG projects with specified ferrite contents.

3.2.2. Influence of arc length on delta ferrite content

The metallurgical design goal for LNG consumables is to secure very low ferrite contents in the weld metal to get satisfying toughness values but also to guarantee sufficient hot cracking resistance. By reaching lowest, controlled ferrite levels in the weld metal the influence of the welder must also be taken into account. The arc length is strongly influenced by the welder.



short arc (~ 3 mm)
135 A / 26 V

C	Si	Mn
0,011	1,20	1,10
Cr	Ni	N
17,05	10,80	0,065

long arc (~ 8 mm)
135 A / 35 V

C	Si	Mn
0,011	1,10	1,00
Cr	Ni	N
16,60	10,80	0,11%

Figure 10: E308L-17: Influence of arc length on ferrite content; PVR test specimen [4]

Welding with a very long arc increases the nitrogen pick up and burn off rates of alloying elements which is responsible for a reduction of the ferrite content in the weld metal. In **Figure 10** this effect is shown using a laboratory stick electrode of type E 308L-17 with a nominal ferrite content in the weld metal of 3FN. Increasing the arc length from 3mm to 8mm the ferrite level decreases from 3FN to about 1FN [4]. In case of the very low ferrite weld metal cracks at the PVR test specimen are visible. But it has to be mentioned that basic electrodes are much more safety regarding this phenomena.

3.3 All weld metal vs. 304L-base metal joints

As earlier mentioned, for welding of the base metal of type 304L a filler of type 308L is used and the toughness values of the all weld metal are not equal to values from the joint. Comparing **Figure 8** and **Figure 11** this influence is shown by weldments with a stick electrode of type E308L-15.

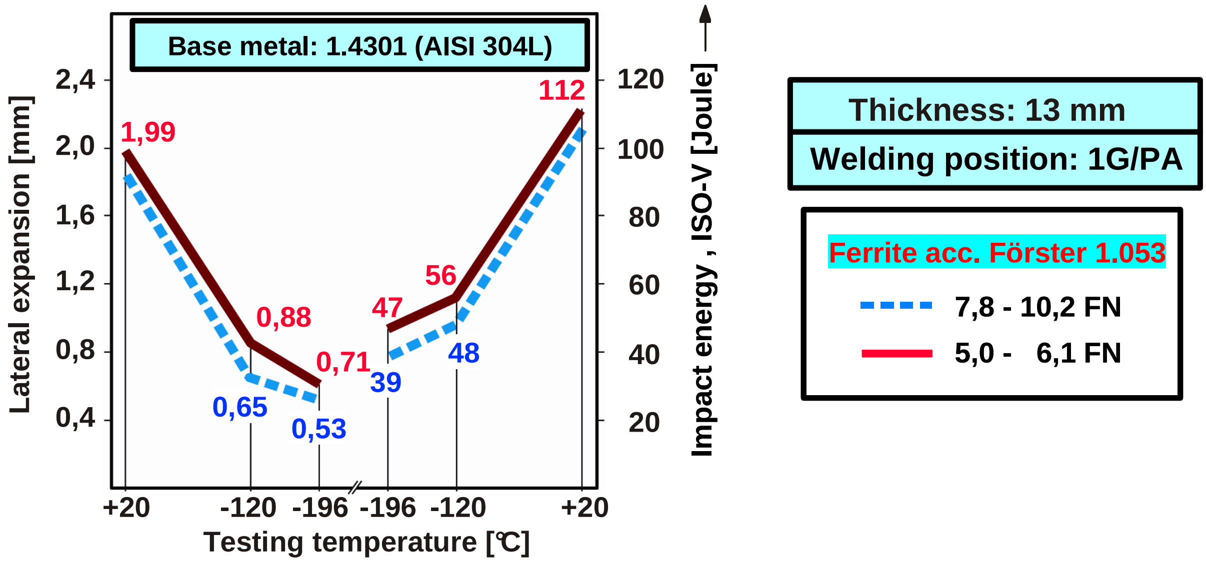


Figure 11: BÖHLER FOX EAS 2 (E308L-15): Impact energy versus ferrite content in V-joint welds

It can be seen, that at -196℃ for the low ferrite type the lateral expansion drops from 1,06 mm in the all weld metal down to 0,71 mm in the joint; similar the charpy impact energy: from 66J to 47J. This tendency is also valid for the higher ferrite grades.

3.4 Welding position

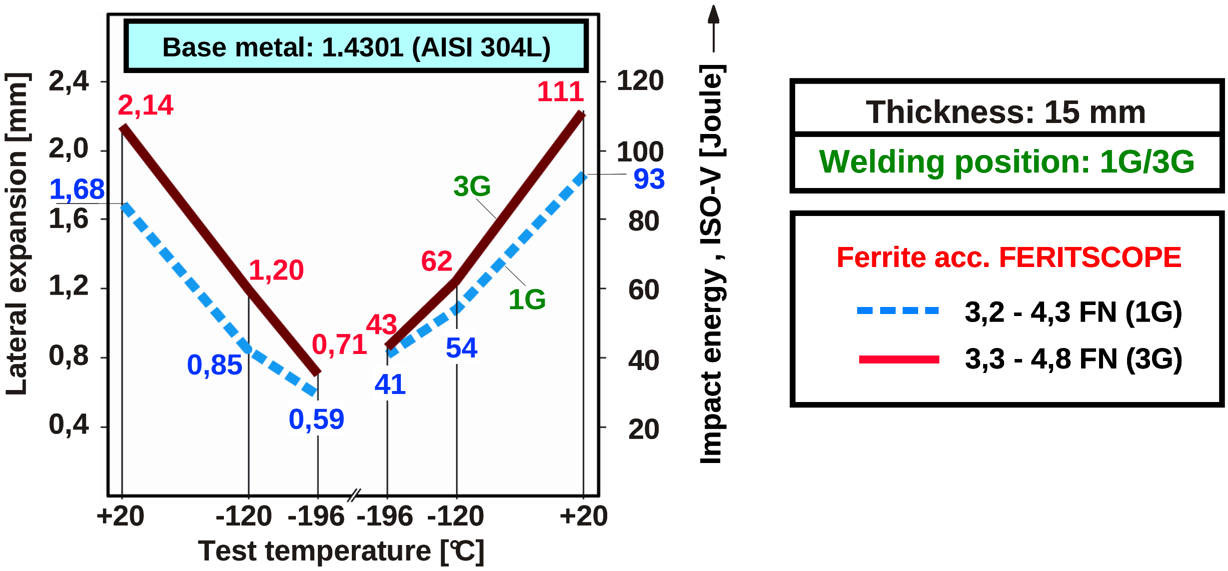
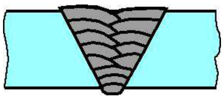
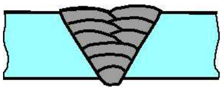
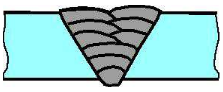


Figure 12: BÖHLER EAS2 PW-FD (LF) (E308LT1-4):
Impact energy in various welding positions: 1G/PA and 3G/PF

In **Figure 12** the influence of the welding position on the toughness properties is shown. It´s not detrimental by comparing the charpy values, more significant deviations are measured in case of the lateral expansion.

3.5 Influence of shrinkage on impact energy

A very detrimental influence was observed caused by internal stresses. If these stresses are reduced by plastic deformation (visible as shrinkage), it was not possible to improve the toughness by using an optimised bead sequence with small beads´. An example as it can be seen in the GTAW samples (**Figure 13**).

Bead sequence	Layers (Beads)	Impact energy ISO-V [Joule] average	Remarks
	**8 (13)**	**54**	**high shrinkage**
	**6 (9)**	**53**	**high shrinkage**
	**6 (9)**	**74**	**low shrinkage**

Base metal: AISI 304L; Welding position: 1G/PA; Thickness: 15 mm (Gap: 3 mm)

Figure 13: GTAW with BÖHLER EAS 2-IG; impact energy of joint welds at -196℃

3.6 Test specimen preparation

Beside the above mentioned aspects a further point has to be taken into account when discussing deep temperature toughness properties: the preparation of the test specimens. Investigations have shown, that the achieved impact tests results at very low temperatures are strongly influenced how the notch into the test specimen was made. The sharper the cutter used for preparing the notch the higher the impact values (**Figure 14**). With increasing wear of the cutter the plastic deformation at the ground of the notch increases and the measured Charpy impact value decreases.

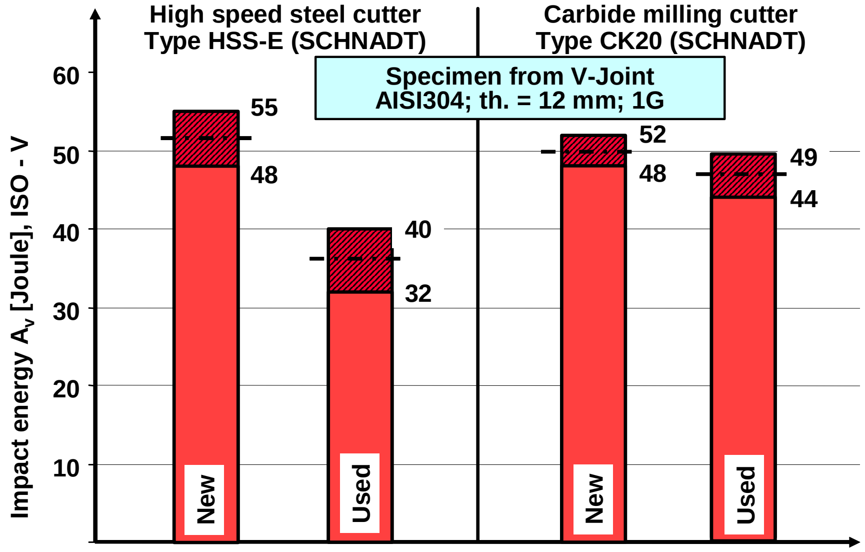


Figure 14: Influence of new and used cutters for preparing the notch on charpy test specimen on toughness values at -196°C

4 Setting up requirements for LNG stainless steels weldments

To achieve an optimum between deep temperature toughness and hot cracking susceptibility, a narrow window for the range of delta ferrite for the weld metal has to be defined as shown in **Figure 15** valid for BÖHLER FOX EAS 2 (E308L-15).

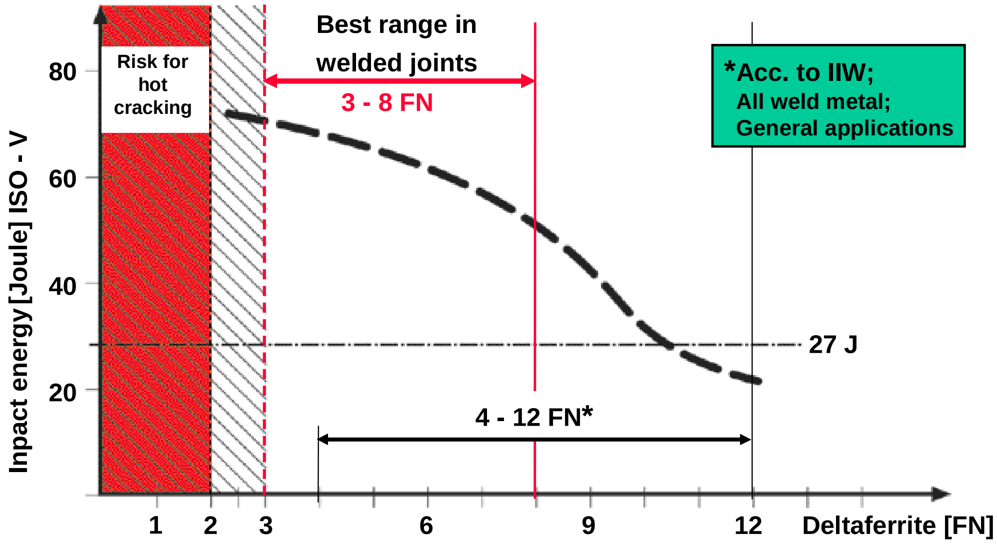


Figure 15: BÖHLER FOX EAS 2 (E308L-15); Ferrite content versus impact energy at -196°

Beside this "metallurgical" orientated requirement regarding the delta ferrite content various design codes define minimum values for toughness to secure safe constructions.

4.1 Requirements for austenitic LNG weldments

There are 2 main design codes available and they describe the toughness requirements in detail: ASME Code [7] focuses on lateral expansion and set the minimum design limit to ≥0,38mm. The comparable European Code, TÜV [8], favours the charpy impact energy. The minimum allowable value has to be ≥32J. Depending on the used design code the lateral expansion or the charpy impacts values are the characteristic material property data for selection of the filler metal.

Beside these major design codes various customer-related requirements are existing. They are often a mix of these two codes and can be extended with some further requirements regarding delta ferrite content and/or minimum heat input.

To fulfil these requirements special low ferrite electrodes for use in LNG plants were developed. **Figure 16** gives a small overview and points out the essential selection criterions as FN (measured), lateral expansion and charpy toughness at -196℃.

Böhler Brand	**AWS**	**Process**	**FN**	**Lateral expansion [mm] -196℃**	**ISO-V [J] -196℃**
EAS 2 -IG	ER308L	GTAW	**8-11**	**1,17**	**112**
FOX EAS 2	E308L-15	SMAW	**4-8**	**1,06**	**66**
EAS 2 PW-FD (LF)	E308LT1-4 E308LT1-1	FCAW	**3-6**	**0,75**	**45**
FOX EAS 4 M (LF)	E316L-15	SMAW	**5-7**	**0,60**	**67**
EAS 4 PW-FD (LF)	E316LT1-4 E316LT1-1	FCAW	**3-6**	**0,60**	**40**

Figure 16: Special designed, mostly low-ferrite filler metals for LNG applications with typical values

5 Conclusion

As it can be shown, the delta ferrite content of the austenitic weld metal has a huge influence on the toughness properties of especially at low temperatures. The lower the ferrite content the higher the toughness of the weld metal. But the reduction of the delta ferrite has its limits: a minimum ferrite level is necessary to prevent hot cracking.

Dealing with LNG applications of austenitic steels and weldments it is necessary to control the ferrite content by the chemical composition and the welding parameters to find an optimum between high toughness properties and hot cracking resistance. To develop “safe” filler metals also the influence of higher heat inputs, plastic deformation, but also the arc length on the impact values has to taken into account.

6 References

[1] Information from OMV; 2005

[2] L. Smith: “Properties of metallic materials for LNG services”; Stainless Stell World, Oct. 2001

[3] G. Holloway, Z. Zhang, A. Marshall: “Stainless Steel Arc Welding Consumables for Cryogenic Applications”; Stainless Steel World 2004; KCI Publishing BV

[4] E. Folkhard et al: “Welding Metallurgy of Stainless Steels”, Springer Verlag, Wien, 1988

[5] J. Tösch, G. Posch, J. Ziegerhofer: „Ferrite contents in stainless steel FCAW-welds“; IIW-doc. II-C 289-04

[6] J. C. M. Farrar: “The Measurement of Ferrite Number (FN) in Real Weldments”; IIW-Doc. II 1531-04

[7] Internat. Piping code ASME B31.3.

[8] VdTÜV Information Sheet “Guidelines on suitability of welding filler metals”; 1980