Is Welding Stainless Steel For LNG Applications Easy?

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Abstract
Grades 304/304L and 316/316L stainless steel base materials have a fully austenitic microstructure and therefore have very good toughness at cryogenic temperatures. Although these stainless steels are easy to weld, it is not necessarily easy to achieve good weld metal toughness at the temperatures required by LNG plant.
There are a number of options to ensure that good weld metal toughness is achieved:

- Solution annealing improves toughness but is not a practical option for most fabrications
- Use of fully austenitic weld metals. This is feasible but requires weld metal that is over-alloyed compared to the base material and the use of consumables which may not meet any national standards. It also presents problems because many specifiers insist on delta ferrite in weld metal to guarantee freedom from hot cracking
- Use of gas-shielded processes (gas tungsten arc welding, TIG/GTAW and gas metal arc welding, MIG/GMAW). TIG is a solution for root welding and also for thin wall tube, but is very slow for larger joints. MIG has only found limited use for general fabrication work and would not normally be considered for positional welding or site welding
- Use of specially designed 308L and 316L MMA/SMAW consumables capable of meeting 0.38mm lateral expansion at -196°C

For LNG applications, which have generally involved the joining of pipework, the use of specially designed 308L and 316L consumables is proving to be the favoured solution. The consistently good toughness that can be achieved by careful consumable design is supported by an extensive database of all-weld metal data. The successful application of the LNG dedicated consumables is demonstrated by reference to a number of projects that have made use of them.

Introduction

With rising demand for LNG, the construction of LNG facilities is on the increase worldwide. Various materials are selected to withstand the onerous service conditions, including aluminium, 9% nickel steel and austenitic stainless steels. The construction and fabrication of LNG facilities will inevitably involve welding pipework which usually includes 304L or 316L austenitic stainless steel that will be subject to service below -160°C or design temperatures down to -196 °C. 304L and 316L are among the most widely used corrosion resistant alloys and have the benefit of being naturally tough and resistant to catastrophic brittle failure at the lowest temperatures, unlike lower alloy ferritic steels which display a sharp and temperature-dependant ductile-brittle transition.

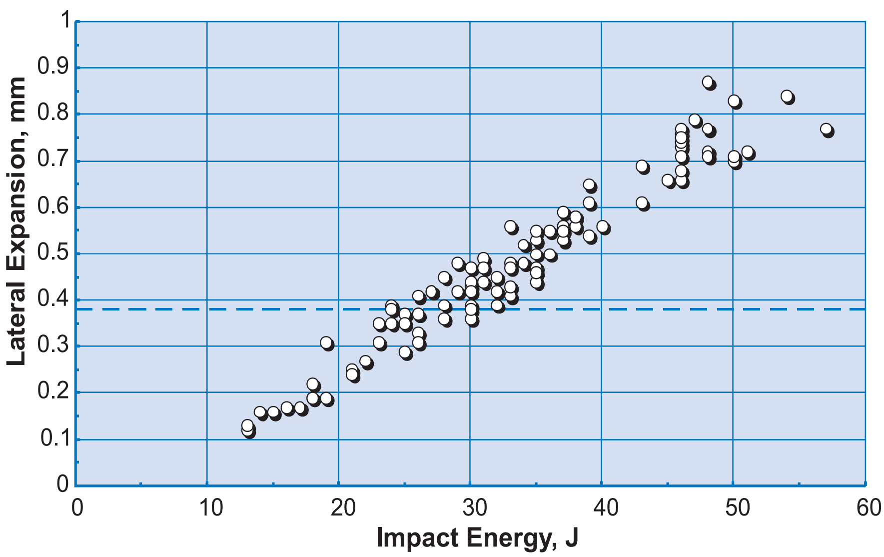

Figure 1: Correlation between impact energy and lateral expansion for E316L-16 MMA electrodes impact tested at -196°C. Data plotted is from individual Charpy specimens.

It has long been recognised that the satisfactory cryogenic toughness of weld metals for austenitic stainless steel grades 304 and 316 cannot be taken for granted. Many of the influential factors are quite well known. For example, low carbon weld metals (below 0.03-0.04%C) are always used and deliberate nitrogen additions are avoided. There are also unavoidable process-dependent influences such as the level of non-metallic inclusions which may reduce the baseline toughness, so that compensating beneficial factors need to be considered such as the choice of flux system for flux covered electrodes or submerged arc welding and the control of weld metal ferrite. The authors have recently reviewed many of these issues [1] and the present paper ex-

(1) AW = as-welded, SA = solution annealed.
(2) Minimum base material requirements:
BS EN 10088-2 grade 1.4404; UTS 530MPa, 0.2% proof stress 240MPa.
ASME A182/A240/A312 grade 316L; UTS 485MPa, 0.2% proof stress 170MPa.

Process	TIG		MMA		MMA	
AWS specification	ER316L		E316L-16		E316L-17	
BS EN specification	W 19 12 3 L		E 19 12 3 L R 3 2		E 19 12 3 L R 3 2	
Shielding	Argon		--		--	
Heat treatment (1)	AW	SA	AW	SA	AW	SA
Tensile strength, MPa (2)	605	603	591	564	591	553
0.2% proof stress, MPa (2)	466	311	471	314	461	326
Elongation, %: 4d	41	44	44	50	53	52
5d	37	40	41	48	48	50
Reduction of area, %	62	50	58	59	60	52
Impact properties -196°C:						
- impact energy, J	64	99	17	44	21	40
- lateral expansion, mm	1.03	1.58	0.26	0.78	0.30	0.67

Table 1: Solution annealed (1050°C/1 hour + WQ) versus as-welded all weld metal properties.

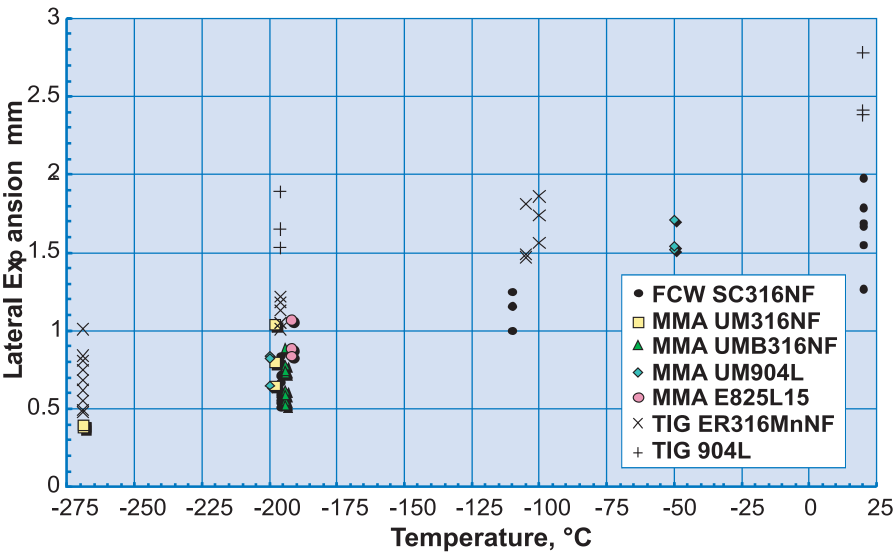

Figure 2: Charpy transition curve for a range of fully austenitic weld metals. They all show >0.5mm lateral expansion at -196°C.

might be examined to assess the percent ductile shear fracture, and some specifiers require this to be reported. However, in austenitic welds, the mixture of cleavage facets and areas of shear on the fracture surface means that Charpy fracture appearance cannot be assessed by the convenient visual criteria of ASTM E23, so test houses will usually decline to report it.

The most commonly specified toughness requirement is based on Charpy lateral expansion. The requirement for 0.38mm lateral expansion at -196°C, which can be found in the ASME Code (eg ASME B31.3 for process piping), is frequently quoted even for projects that are not being fabricated to ASME Code requirements. Although 0.38mm lateral expansion is probably the most widely specified criterion, some European projects may have a Charpy energy requirement. For example, projects carried out under the scope of TÜV sometimes specify a minimum Charpy energy of 40J/cm^2, corresponding to 32J on a standard Charpy impact specimen. For a given set of data and test temperature there is normally a linear relationship between lateral expansion and impact energy, Figure 1. Weld metal data are presented to show the relationship between Charpy energy and lateral expansion, however, this paper focuses on the previous overview with the results of new tests.

Toughness requirements

Design temperatures encountered for austenitic stainless steels used in LNG facilities may vary but for simplicity and ease of testing, Charpy impact tests are normally carried out at -196°C because this test temperature is conveniently obtained by cooling in liquid nitrogen. Toughness is proportional to the impact energy absorbed by fracture and lateral expansion is a measure of the Charpy test specimen deformation or fracture ductility.

In principle, the Charpy specimen

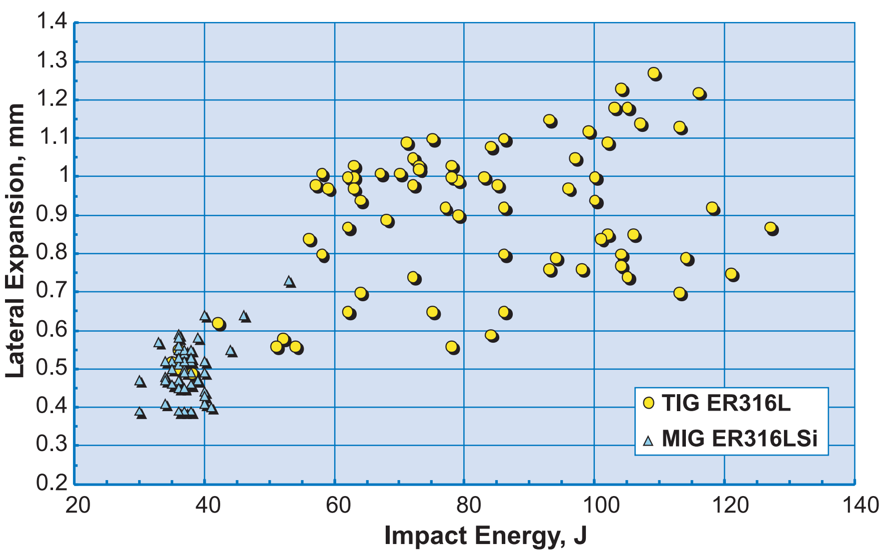

Figure 3: Correlation between impact energy and lateral expansion for ER316L TIG and ER316LSi MIG, impact tested at -196°C. Data plotted is for individual Charpy specimens.

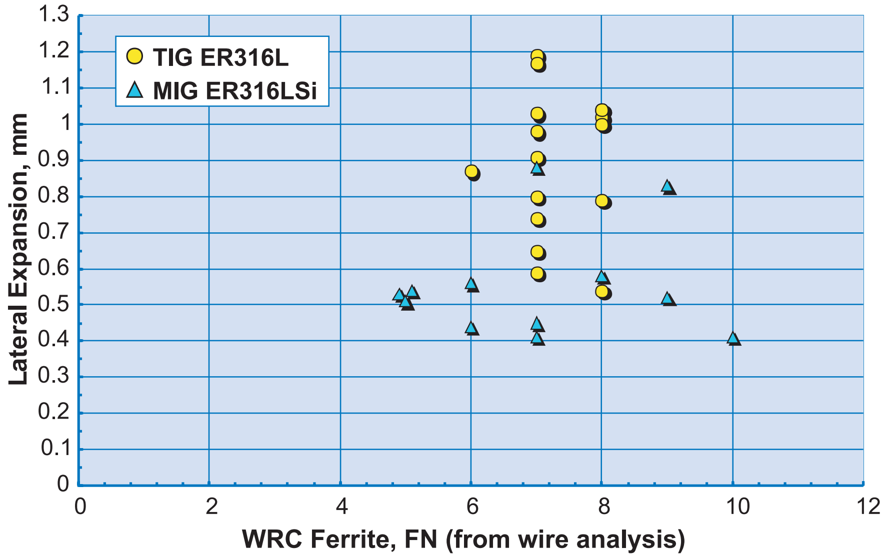

Figure 4: Correlation between ferrite (WRC ferrite calculated from the wire analysis) and lateral expansion for ER316L TIG and ER316LSi MIG tested at -196°C. Data plotted is based on the average of a set of Charpy specimens.

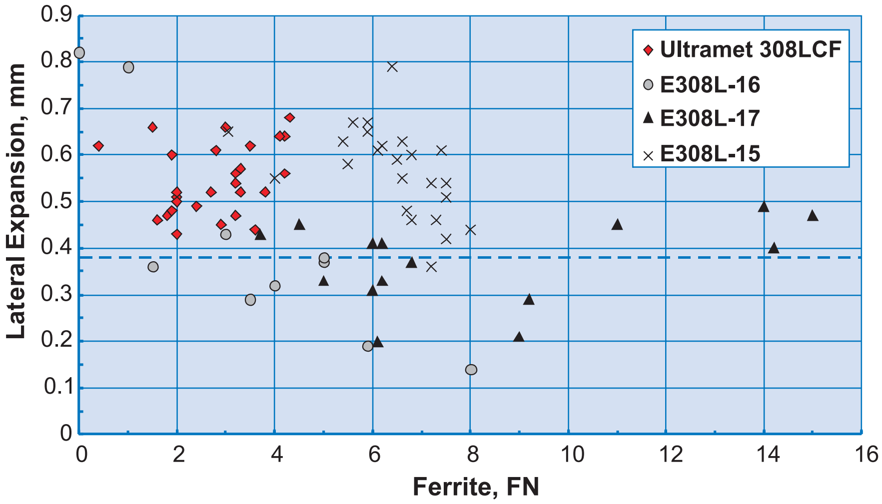

Figure 5: Effect of weld metal ferrite on lateral expansion (tested at -196°C) for a range of 308L consumables. Data from a variety of sources.

ses on the -196°C design requirement of 0.38mm lateral expansion.

Solution annealing

Solution annealing, heat treatment at 1050°C followed by water quenching, is one method of producing higher toughness weld metal. Experience has shown, for example, that an "off-the-shelf" rutile type E316L MMA electrode giving as-welded impact energy of only 10-25J and 0.10-0.28mm lateral expansion at -196°C would be restored to 32-40J and 0.50-0.70mm lateral expansion after solution annealing, Table 1. In addition to improving toughness, there will also be a reduction in yield (proof stress) and ferrite content of the weld metal. As-welded 0.2% proof stress values always overmatch base metal but heat treatment brings the proof-to-tensile ratio close to the annealed base material value, while normally still meeting the base material strength requirement.

Solution annealing has a number of practical disadvantages: it is difficult to carry out on large fabricated components; on thin material there is a danger of distortion; complex fabricated components may also distort, and it is not really practical or economic to carry out a solution annealing heat treatment on a pipeline. However, in the foundry such heat treatments are more appropriate and often specified for welds applied to castings.

Although solution annealing will provide the necessary toughness required for LNG applications it is not an option that provides a practical solution for pipework.

Process		TIG	MMA	FCAW	SAW
Consumable		ER308LCF	Ultramet 308LCF	Supercore 308LCF	ER308LCF + LA491
AWS specification		ER308L	E308L-16	E308LT1-4	ER308L (wire)
BS EN specification		W 19 9 L	E 19 9 L R 3 2	T 19 9 L P M 2	S 19 9 L (wire)
Shielding		Argon	--	Argon-20%CO_2	LA491 flux
Tensile strength, MPa		598	583	544	552
0.2% proof stress, MPa		431	452	393	398
Elongation, %:	4d	53.5	52.5	50	48.5
	5d	47.5	47	47.5	45
Reduction of area, %		78	52	54	55
Impact properties -196°C:					
- impact energy, J		84	32	36	45
- lateral expansion, mm		1.21	0.49	0.72	0.69

Table 2: Representative all-weld metal mechanical properties for the Metrode 308L 'CF' consumable range.

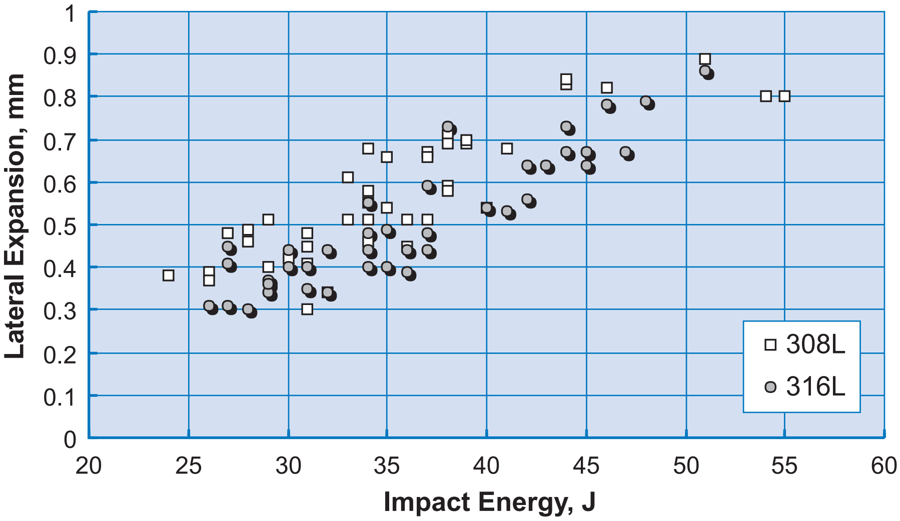

Figure 6: Correlation between impact energy and lateral expansion for a series of basic coated 308L (E308L-15) electrodes and a series of basic coated 316L (E316L-15) electrodes impact tested at -196°C. Data plotted are from individual Charpy specimens.

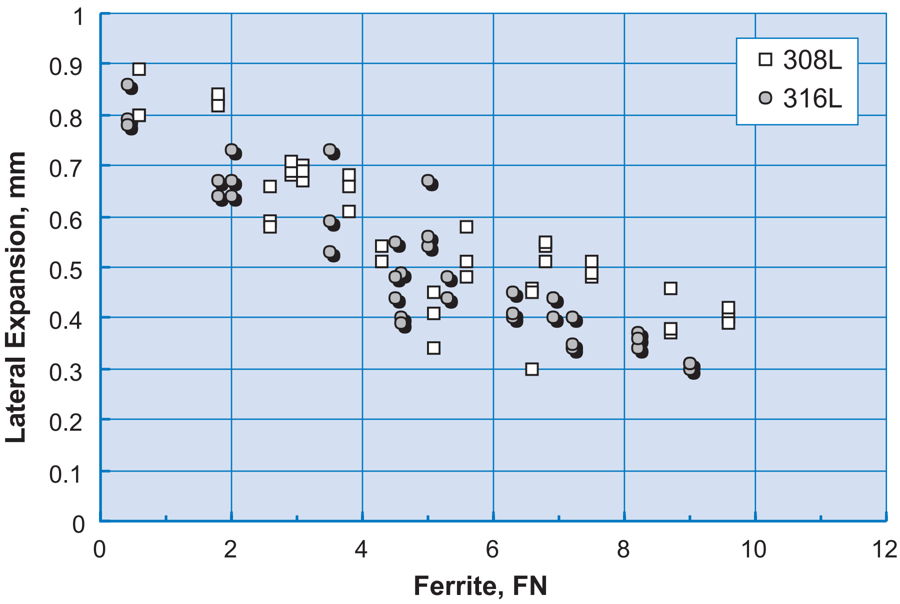

Figure 7: Correlation between ferrite and lateral expansion from -196°C impact tests. Data is from the same series of 308L and 316L basic coated electrodes plotted in Figure 6. Data plotted are from individual Charpy specimens.

Fully austenitic stainless steel weld metals

There are a number of fully austenitic low carbon weld metals, all of which provide very good impact properties at cryogenic temperatures; in fact some of the fully austenitic stainless steel weld metals will maintain useful toughness down to -269°C, Figure 2.

The fully austenitic stainless steel weld metals will be more highly alloyed than the standard 308L or 316L compositions, and this will add to the cost. It also means using a weld metal which although suitable for the application does not have the same analysis as the base material and in some circumstances it may not meet an AWS or EN specification. Some compositions may not be readily available for all welding processes. Experience has also indicated that many specifiers do not allow fully austenitic weld metal compositions but require weld metal containing delta ferrite to guarantee freedom from hot cracking.

Although fully austenitic weld metals will comfortably meet the toughness requirements of LNG applications there are a number of disadvantages in their use which means they are not the ideal solution.

Gas shielded welding processes

The gas-shielded arc welding processes - TIG and MIG - produce welds with a low level of microscopic non-metallic inclusions, leading to inherently good toughness at all temperatures. Excellent cryogenic impact properties can be achieved consistently without special control measures, using standard commercially available ER308L/ER308LSi and ER316L/ER316LSi wires. Figure 3 shows the relationship between impact energy and lateral expansion for 316L; with the TIG process comfortably meeting 0.38mm lateral expansion and in the tests carried out to date the MIG process

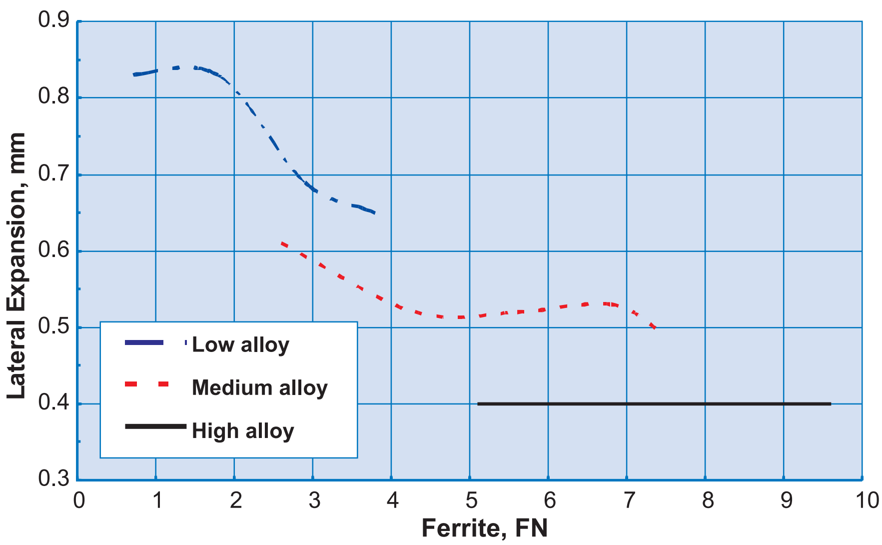

Figure 8: Correlation between ferrite and lateral expansion for E308L-15 electrodes impact tested at -196°C. The low, medium and high alloy levels refer to total alloying content of the weld deposit but all compositions fall within the AWS A5.4 E308L-15 analysis range.

also meets a minimum 0.38mm lateral expansion. With the gas-shielded processes there does not appear to be the same dependence of toughness on ferrite content that has been seen for the flux shielded processes, Figure 4. This graph is based on the predicted ferrite content of the wire calculated from the wire analysis so it is possible that the weld ferrite content would show more of a correlation with toughness.

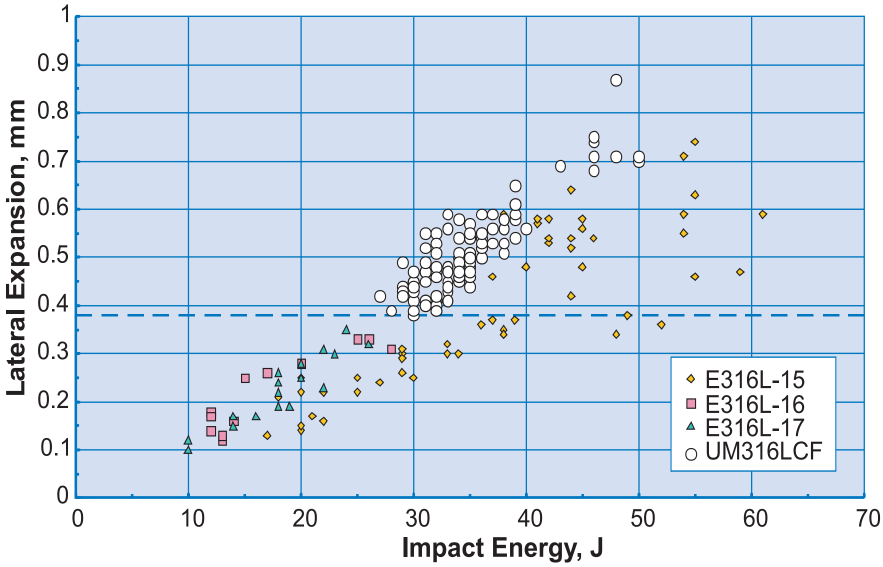

Figure 9: Correlation between impact energy and lateral expansion for 316L MMA electrodes. The advantage of the controlled ferrite consumable being clearly demonstrated. Data plotted is from individual Charpy specimens.

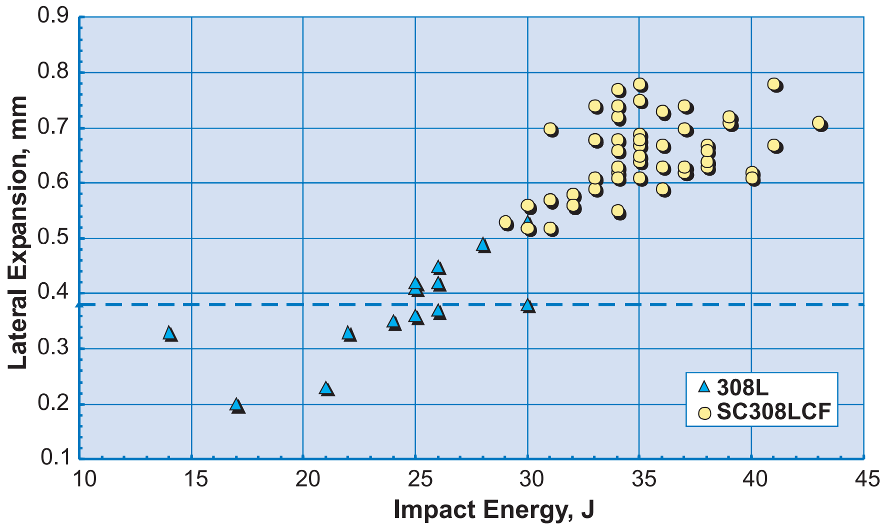

Figure 10: Correlation between impact energy and lateral expansion for 308L flux cored wires impact tested at -196°C. The controlled ferrite version (SC308LCF) consistently meets 0.38mm lateral expansion. Data plotted is from individual Charpy specimens.

The gas-shielded processes, TIG and MIG, can meet the impact requirements and have an important role to play in fabrication. But if the welding process options are restricted to TIG and MIG then there will be unnecessary restrictions imposed on the fabricator. The ability to use flux shielded processes (MMA, FCAW and SAW) would provide the fabricator with the scope to use whichever process was preferred for a particular application. However, the non-metallic inclusion level is unavoidably higher with the flux-shielded processes - MMA, FCAW and SAW - and consequently these 308L/316L consumables require additional metallurgical controls to ensure that welds will achieve the required cryogenic toughness.

Specially designed 308L and 316L consumables

Previous work has been published examining the effect of ferrite content on the toughness of 308L and 316L weld metals and the general trend is demonstrated by Figure 5 which shows that, up to a certain point, as ferrite increases the toughness is reduced. The region beyond

Process		TIG	MMA	FCAW	SAW
Consumable		ER316LCF	Ultramet 316LCF	Supercore 316LCF	ER316LCF +
AWS specification		ER316L	E316L-16	E316LT1-4	ER316L (wire)
BS EN specification		W 19 12 3 L	E 19 12 3 L R 3 2	T 19 12 3 L P M 2	S 19 12 3 L (wire)
Shielding		Argon	--	Argon-20%CO_2	SA FB 255 AC
Tensile strength, MPa		605	565	546	563
0.2% proof stress, MPa		466	461	410	402
Elongation, %:	4d	41	51.5	42	48.5
	5d	37	46.5	38.5	44
Reduction of area, %		62	63	44	67
Impact properties -196°C:					
- impact energy, J		105	33	34	32
- lateral expansion, mm		1.17	0.46	0.55	0.49

Table 3: Representative all-weld metal mechanical properties for the Metrode 316L 'CF' consumable range.

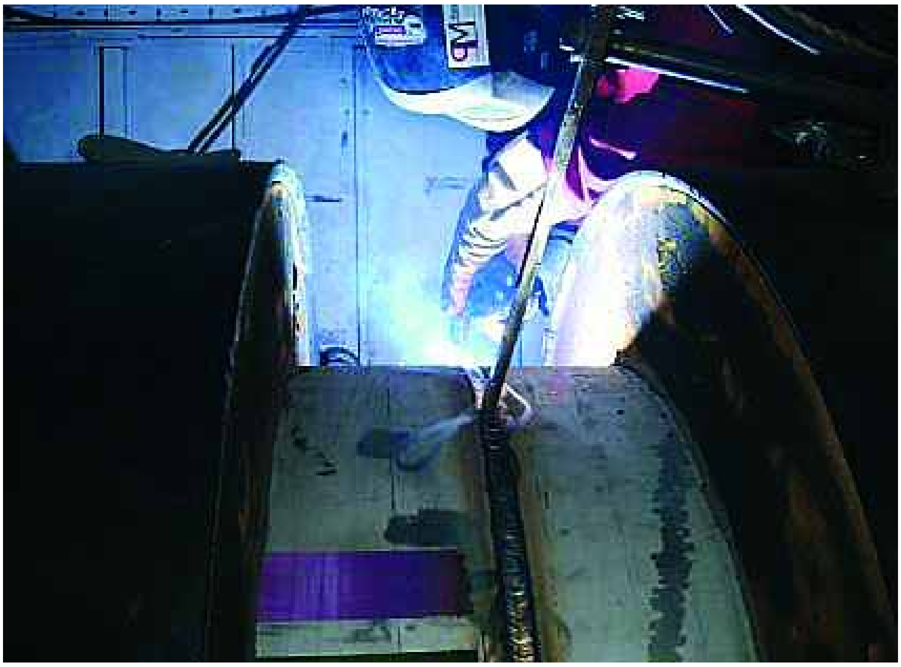

Figure11: Gas shielded flux cored arc welding, controlled ferrite 308L, being used for the first time during construction of the Grain-LNG importation facility on the Isle of Grain, UK. Photograph courtesy of P M Associates UK Ltd.

not be guaranteed with a ferrite content above ~4.5FN. However, if the data are further divided it can be shown that it is not only the ferrite content of the weld deposit that affects toughness but also the alloy level, Figure 8. In Figure 8 it can be seen that for weld metals having the same ferrite content the lower alloyed deposit will tend to produce the best toughness.

The trends that are demonstrated by these data have been used to manufacture commercial, controlled ferrite, MMA and flux cored wire consumables, Tables 2 and 3. The consistency of the impact properties that can be achieved by using controlled ferrite consumables is demonstrated by the all-weld metal data plotted in Figures 9 and 10, which show the advantage in con-

this point, where some recovery of toughness occurs, is not the subject of this paper and the authors are not aware that specifiers are yet prepared to acknowledge this effect.

To investigate the trend up to ~10FN further, two series of MMA welding consumables were produced: one E308L and one E316L. Both used the same design of basic flux coating (AWS A5.4 'EXXXL-15', EN 1600 'E XXX L B'). Basic flux systems are commonly considered to offer better toughness than rutile types. The two series of consumables were designed to cover a range of ferrite contents from ~0.5FN to ~10FN by varying the %Cr/%Ni ratio of the weld metals, but aiming to stay within the AWS and EN analysis ranges. All of the data from these tests are presented in Figure 6, showing that it is possible to get a wide range of impact properties from weld metals conforming to recognised national standards. The data covered a range of ~0.3-0.9mm lateral expansion and ~25-55J, with the 308L tending to produce slightly higher values than 316L.
When the lateral expansion is plotted against ferrite content, Figure 7, it can be seen that for these data, that 0.38mm lateral expansion can-

Figure 12: Isle of Grain importation terminal showing the pipeline connecting the jetty to the storage tanks.

trolling ferrite and alloy level when compared to standard commercial consumables, closing the gap between rutile and basic electrodes.

Applications of controlled ferrite consumables

Many tonnes of Ultramet 308LCF/316LCF electrodes have been used on projects all round the world and numerous successful weld procedures have been carried out. Most of the projects these electrodes were used on were pipelines and process pipework, all of which had stringent low temperature toughness requirements.

The Ultramet 316LCF MMA electrode was originally designed in the early 1990's to satisfy the cryogenic toughness requirements of Mobil/ Ralph M Parsons for the Scottish Area Gas Evacuation (SAGE) project terminal at St Fergus, Scotland. More recently, tonnage quantities of the controlled ferrite 'CF' MMA consumables have been used in Kazakhstan on the Karachaganak Project. There have also been significant quantities of cryogenic pipework welded with the 'CF' consumables on the natural gas to liquids plant of the Mesaieed Q-Chem petrochemical complex in Qatar.

The first commercial use of the Supercore 308LCF flux cored wire was for the Isle of Grain LNG terminal in the UK. The flux cored wire was used in the fabrication of a three mile pipeline in 915mm (36inch) diameter, 10mm (0.4inch) wall thickness, 304L stainless steel, see Figures 11 and 12. Productivity was optimised by root welding with the pulsed-MIG process and joint filling with Supercore 308LCF flux cored wire, a combination which also met the other project criteria with respect to toughness. Table 4 shows examples of selected weld procedure tests for the Grain project.

Conclusions

Is welding stainless steel for LNG applications easy? Just over 25 years ago a classic review of and presentation of test data for the cryogenic toughness of austenitic stainless steel MMA weld metals concluded that "Dual weld metal requirements for 3FN minimum and 0.38mm minimum lateral expansion at -196°C are at odds and sharply limit the choice of welding filler metal compositions conforming to the requirements of AWS A5.4..." [2]. Those same requirements are frequently called for today, but with improvements in consumable design and manufacture based on careful investigative testing of otherwise vulnerable weld metals, it is possible to say "Yes, welding stainless steel for LNG applications is easy" - assuming the correct consumables have been selected. ■

References

[1] Holloway, G B; Zhang, Z & Marshall, A W. "Stainless steel arc welding consumables for cryogenic applications" Paper P0449, Stainless Steel World 2004 Conference, Houston, USA.

[2] Szumachowski, E R & Reid, H F "Cryogenic toughness of SMA austenitic stainless steel weld metal: Part II - Role of nitrogen" Weld.J, 58 (2), Feb 1979, p34s-44s.

Contractor	P M Associates UK Ltd	Ralph M Parsons		
Project	Grain-LNG importation facility, Isle of Grain, UK	ExxonMobil SAGE terminal, St Fergus, Scotland		
Material	304L 36in Schedule 10S	316L 6in Schedule 40	316L 10in Schedule 40	316L 8in Schedule 160
Root welding process and consumable.	MIG ER308LSi	TIG Metrode ER316LCF		
Filling process and consumable.	FCAW Supercore 308LCF	TIG Metrode ER316LCF	MMA Ultramet 316LCF	MMA Ultramet 316LCF
Transverse tensile strength, MPa	621, 621	557, 595	561, 589	526, 554
Weld metal ferrite, FN	--	4-6	3-4	2-4
Weld impact properties - 196°C:	10x7.5mm	10x5mm	10x7.5mm	10x10mm
- impact energy, J	32, 29, 34 (32)	81, 85, 78 (81)	34, 33, 38 (35)	58, 55, 56 (56)
- lateral expansion, mm	0.81, 0.70, 0.73 (0.75)	1.67, 1.87, 1.98 (1.84)	0.72, 0.64, 0.66 (0.67)	0.48, 0.46, 0.6 (0.52)
HAZ impact properties - 196°C:	10x7.5	10x5	10x7.5	10x10
- impact energy, J	107, 74, 70 (84)	124, 134, 130 (129)	103, 206, 206 (172)	186, 180, 150 (172)
- lateral expansion, mm	1.44, 1.02, 1.04 (1.17)	2.17, 2.18, 2.14 (2.16)	1.28, 2.18, 2.45 (1.97)	1.64, 1.72, 1.9 (1.78)

Table 4: Representative mechanical properties for the Metrode 'CF' consumables from weld procedure tests.