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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 materials and welding consumables suitable for use at various nominal temperatures are shown in Table 1. The construction and fabrication of LNG facilities will inevitably involve welding pipework and this article is concerned with the specialist area of arc welding consumables for joining 304L and 316L austenitic stainless steels that will be subject to service or design temperatures down to –196 °C. These steels 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. The characteristic mechanical properties of welds produced by different welding processes are described and the specific weld metal controls required to achieve consistent low temperature toughness are explained. A dedicated range of controlled ferrite (CF) consumables manufactured by Metrode is presented and some of the applications for which they have been used are highlighted.

Toughness requirements

Design temperatures encountered for austenitic stainless steels used in LNG facilities may vary but for simplicity and ease of testing, Charpy toughness tests are normally carried out at -196°C because this is an easily achieved, and convenient, test temperature obtained by cooling in liquid nitrogen. The standard Charpy impact specimen is 55mm long and 10 x 10 mm in section with a V-notch to initiate a fracture path when the specimen is struck with a pendulum striker. Toughness is proportional to the impact energy absorbed by fracture and lateral expansion is a measure of the specimen deformation or fracture ductility.

The most commonly specified toughness requirement is based on Charpy lateral expansion. The requirement for 0.38 mm 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 0.38 mm lateral expansion is probably the most widely specified criterion, some European projects do have a Charpy energy requirement. For example, projects carried out under the scope of TÜV sometimes specify a minimum Charpy energy of 40 J/cm^2, corresponding to 32 J on a standard Charpy impact specimen. Weld metal data showing the relationship between Charpy energy and lateral expansion are presented, but discussion in this article assumes that the design requirement is 0.38 mm lateral expansion at -196°C.

The welding processes – where they are used

There are five main arc welding processes:

- gas tungsten arc welding (GTAW) or tungsten inert gas (TIG) welding
- gas metal arc welding (GMAW) or metal inert gas (MIG) welding
- shielded metal arc welding (SMAW) or manual metal arc (MMA) welding
- flux cored arc welding (FCAW)
- submerged arc welding (SAW).

Each of the processes has areas and applications where it excels and the following briefly describes the strengths of each process.

The GTAW process is used for root welding pipes and tubes, but is also used for completing joints in smaller diameter thinner wall pipe. The GTAW process is very controllable and produces high integrity weld metal making it an excellent choice for applications requiring careful control or where weld integrity is more important than productivity.

The GMAW process using solid wire has not found widespread use for critical fabrication work and although it is capable of achieving good cryogenic toughness many of the applications where GMAW could be used are now being welded with flux cored wires, and this is the option Metrode would recommend.

The SMAW process is still widely used for many applications because of its simplicity and adaptability. The process requires relatively simple equipment and does not require a shielding gas, making it an attractive process for site welding. The success of the process is dependent, not only on the characteristics of the electrode, but also the skill of the welder; so electrodes with good operability and welder appeal are of great benefit.

The gas-shielded FCAW process has found significant use in areas where SMAW was traditionally used but where a continuous wire process can provide a valuable productivity advantage. The gas-shielded FCAW process is similar to GMAW but uses a tubular cored wire in place of the solid wire. The cored wire can provide a number of advantages including positional capability, scope to vary chemical analysis of the weld deposit, and excellent weld appearance. The flux cored wires can offer productivity advantages over SMAW electrodes in applications involving pipes of diameter above ~200 mm and (depending on actual diameter) wall thickness greater than ~9.5-12.5 mm.

The SAW process is not normally used for general pipework or for site welding but is a highly productive process for joining thick sections that can be manipulated so that welding can be carried out in the flat position. This could apply to longitudinal seams in tanks or vessels, or to circumferential joints that can be rotated. SAW would not normally be used for material less than ~15 mm thick or less than ~200 mm in diameter.

The welding processes – toughness

The gas-shielded arc welding processes - GTAW and GMAW - 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.

However, the non-metallic inclusion level is unavoidably higher with the flux-shielded processes - SMAW, FCAW and SAW - and consequently these 308L/316L consumables require additional metallurgical controls to ensure that welds will achieve the required cryogenic toughness. Three areas in particular are important: ferrite content, alloy control, and in connection with SMAW and SAW, the type of flux. Each of these areas will be discussed separately.

Ferrite

While the typical microstructure of 304L/316L parent material is fully austenitic, it is considered essential for their weld metal compositions to be balanced to solidify with some ferrite (expressed as ferrite number, FN) to ensure resistance to hot cracking. However, it has long been recognised that the accepted ferrite levels normally applied to flux-shielded welding processes may not be compatible with satisfactory cryogenic toughness. Various standards specify ferrite limits for austenitic stainless steel weld metals. For example, the appendix to

American Welding Society (AWS) specification A5.4 for stainless steel SMAW electrodes describes the relevant issues and recommends 3FN maximum or fully austenitic welds and a basic flux system in preference to rutile (see later). API 582 Guidelines require 3FN minimum, although it is noted that for cryogenic service lower FN may be required.

It has been found that it is possible to achieve the 0.38 mm lateral expansion requirement by controlling the weld metal ferrite of SMAW electrodes and flux cored wires in the range 2-5FN. This is well illustrated with average data for both standard 308L/316L and the new Supercore 308LCF/316LCF flux cored wires shown in Figure 1. The benefit of the CF wires is very evident, with all of the specimens for the CF types exceeding 0.38 mm lateral expansion when tested at -196°C. Although this graph is for flux-cored wires, a similar trend is found for rutile SMAW electrodes.

A particular concern with austenitic weld metals having low ferrite levels is the risk of hot cracking. Most codes and specifications that specify a minimum ferrite do so to maximise hot cracking resistance, and at a typical ferrite of ~3FN the Metrode CF consumables might be considered to be at some risk. However, numerous weld procedure tests and projects have been completed with the CF consumables described here and no such problem has been reported. The reason for this is that despite the low ferrite, the composition is controlled to achieve a Cr:Ni ratio which produces a desirable crack-resistant primary ferrite solidification mode.

Alloy control

By controlling the weld metal ferrite in the range 2-5FN and simultaneously balancing the Cr:Ni equivalent ratio to eliminate any potential risk of hot cracking, the deposit composition of 'CF' SMAW electrodes and flux cored wires becomes restricted to the 'lean' area of their respective weld metal specification ranges. One consequence of this is that with 316L types molybdenum is preferably controlled in the range 2.0 – 2.5%. This means that the Ultramet 316LCF SMAW electrode and Supercore 316LCF flux cored wire conform to the relevant AWS specifications (2.0-3.0%Mo), but not the relevant BS EN specifications which require 2.5 – 3.0%Mo.

Flux type

With CMn and low alloy ferritic steels, it is traditionally accepted that the best impact properties using SMAW electrodes are achieved with fully basic flux systems. With austenitic stainless steels the effect is less pronounced, although it has long been recognised and reported that SMAW electrodes with basic flux coverings (AWS *E3XX-15* types) give somewhat better results than rutile (AWS *E3XX-16/17*) coatings. Data for general purpose E316L-15/16/17 SMAW electrodes and Ultramet 316LCF are plotted for comparison in Figure 2. It can be seen that the basic, E316L-15, electrodes give higher impact energy for a given lateral expansion but what Figure 2 clearly shows is that the basic flux system alone is no guarantee of achieving 0.38 mm lateral expansion at -196°C.

By concluding that it is necessary to control both composition and ferrite content whatever flux type is used (*E3XXL-15/16/17*), the Metrode commercially manufactured CF electrodes, Ultramet 308LCF and Ultramet 316LCF use a rutile flux system (eg. Ultramet 316LCF in Figure 2) to take advantage of the better operability and welder appeal.

Solid wire is usually specified for the SAW process, so there is much less scope for the kinds of alloy control which allow SMAW and FCAW to be optimised for cryogenic toughness; this makes it even more important to select the correct flux. The approach that Metrode has found to be most successful is the use of a fluoride-basic agglomerated flux, Metrode LA491. This flux has consistently produced the best cryogenic impact properties when tested with both 308L and 316L wires.

Weld procedure

Having selected the correct consumables, the weld procedure then needs to be optimised. Contrary to the usual trend with low alloy steel welds, the best toughness is obtained in austenitic welds when the number of weld runs deposited in the joint is minimised. This can be demonstrated by a series of submerged arc welds produced in 20 mm plate with heat inputs ranging from 1.0 kJ/mm (27 runs) up to 2.7 kJ/mm (only 10 runs). These welds showed an increase in toughness, from 0.30 mm lateral expansion (28 J) up to 0.48 mm (46 J), with increasing heat input. The reason for the improvement in toughness is not clear, but it is suspected that the reduction in the number of runs deposited reduces the strain ageing effect and hence improves the impact properties.

Many authorities do not allow this effect to be taken advantage of when welding stainless steels for aqueous corrosion applications because of concerns about the potentially adverse influence of high heat input on corrosion performance. However, published work has shown no detrimental effect on joint performance in 304L/316L stainless steel with interpass temperatures up to 300 °C and heat inputs as high as 2.9 kJ/mm. For LNG service the corrosion requirement is minimal and there should be no detrimental effects on performance with heat inputs up to ~2.5 kJ/mm.

The practical application of this is that in order to achieve good cryogenic toughness it is not necessary to use low heat inputs and controlled stringer bead welding techniques; in fact it is beneficial to use higher heat inputs and larger weld beads. This means that when welding with SMAW electrodes or flux cored wires it is possible to use a full width weave without having a detrimental effect on toughness. The use of a wide weave can be particularly helpful when welding positionally because it helps with weld pool control and is far quicker for joint filling. The selection of welding parameters should be based on joint configuration, material thickness and component size; with any proposed parameters being proven by a weld procedure qualification test.

Metrode consumables and certification

Although commercial GTAW wires without special selection should typically meet the toughness requirements demanded for LNG applications, Metrode also provide dedicated GTAW wires, ER308LCF and ER316LCF, with measured and certified ferrite content.

Ultramet 308LCF and Ultramet 316LCF are rutile all-positional SMAW electrodes suitable for fixed pipework with excellent operability and welder appeal. The Supercore 308LCF and Supercore 316LCF consumables are all-positional rutile flux cored wires that operate equally well with either Ar-20% CO_2 or 100% CO_2 shielding gas, and can be used on fixed pipework.
The Metrode 'CF' SMAW electrodes and flux-cored wires are specifically designed and manufactured to consistently meet the stringent demands of cryogenic applications; they are not batch selected standard all-purpose stainless steel consumables. The consumables are batch Charpy impact tested at –196 °C with an acceptance criterion of 0.38 mm minimum lateral expansion. The BS EN 10204 3.1.B batch certification includes weld deposit analysis, measured ferrite content and Charpy impact properties at –196°C.

As explained, it is unwise to assume that any SAW wire-flux combination will meet requirements. For this reason Metrode supply selected ER308LCF and ER316LCF solid wires that have been batch-tested with LA491 flux specifically for LNG applications. Testing comprises a Charpy impact test at –196 °C, with an acceptance criterion of 0.38 mm minimum lateral expansion, and the result forms part of the BS EN 10204 3.1.B certification for each batch of wire.

Tables 3 and 4 summarise the representative all-weld metal mechanical properties of Metrode welding consumables that are designed and pre-tested for LNG pipework and other applications requiring high cryogenic toughness.

Applications

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 SMAW 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' SMAW 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 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 by P M Associates UK Ltd on the Grain-LNG importation facility built by Skanska at the Isle of Grain in the UK. The productivity of the joints at the Grain-LNG importation facility was optimised by root welding with the Lincoln STT process and joint filling with Supercore 308LCF flux cored wire; a combination which also met the other project criteria with respect to toughness, see Figures 3 and 4. Table 4 shows examples of selected weld procedure tests for the Grain project.

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Biographies

The authors all work for Metrode Products Ltd; Graham Holloway is the Technical Support Engineer, Adam Marshall is Chief Metallurgist and Zhuyao Zhang is Senior R&D Engineer. Metrode Products Ltd is a privately owned company which was founded in 1963, and is now the UK's leading manufacturer and supplier of alloyed welding consumables.

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Table 1 Low temperature alloys and associated welding consumables.

Temperature °C	Alloy	GTAW/GMAW	SMAW		FCAW
-50	CMn	Metrode 1Ni *ER80S-Ni1*	Tufmet 1Ni.B *E8018-C3*		Metcore DWA 55E *(E81T1-Ni1)*
-60	CMn (+Ni)	Metrode 2Ni *ER80S-Ni2*	Tufmet 2Ni.B *E8018-C1*		-
-75	3%Ni	Metrode 2Ni *ER80S-Ni2 (ER80S-Ni3)*	Tufmet 3Ni.B *E8018-C2*		-
-101	3/5%Ni	20.70.Nb *ERNiCr-3*	Nimrod 182KS / AKS *ENiCrFe-2/3*		-
-196	9%Ni	62-50 / HAS C276 *ERNiCrMo-3/4*	Nimrod NCM6 *ENiCrMo-6*		-
-196	304/304L	Metrode ER308LCF *ER308L*	Ultramet 308LCF *Modified E308L-16*	Ultramet B308LCF *Modified E308L-15*	Supercore 308LCF *Modified E308LT1-4*
-196	316/316L	Metrode ER316LCF *ER316L*	Ultramet 316LCF *Modified E316L-16*	Ultramet B316LCF *Modified E316L-15*	Supercore 316LCF *Modified E316LT1-4*
-269	304L/316L	ER316MnNF *EN: E 20 16 3 Mn L*	Ultramet 316NF *EN: E 18 15 3 LR*	Ultramet B316NF *EN: E 18 15 3 L B*	Supercore 316NF *EN: T 18 16 5 NLR*

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

Process	GTAW	SMAW	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) SA FB 255 AC (flux)
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 3 Representative all-weld metal mechanical properties for the Metrode 316L 'CF' consumable range.

Process	GTAW	SMAW	FCAW	SAW
Consumable	ER316LCF	Ultramet 316LCF	Supercore 316LCF	ER316LCF + LA491
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) SA FB 255 AC (flux)
Shielding	Argon	--	Argon-20%CO_2	LA491 flux
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 4 Grain LNG project: Example of weld procedure data using controlled ferrite consumables

Contractor	P M Associates UK Ltd
Project	Grain-LNG importation facility, Isle of Grain, UK
Material	304L 36in Schedule 10S
Root welding process and consumable.	Lincoln STT GMAW LNM 304Si
Filling process and consumable.	FCAW Supercore 308LCF
Transverse tensile strength, MPa	621, 621
Weld metal ferrite, FN	--
Weld impact properties -196°C:	10x7.5mm
- impact energy, J	32, 29, 34 (32)
- lateral expansion, mm	0.81, 0.70, 0.73 (0.75)
HAZ impact properties -196°C:	10x7.5
- impact energy, J	107, 74, 70 (84)
- lateral expansion, mm	1.44, 1.02, 1.04 (1.17)

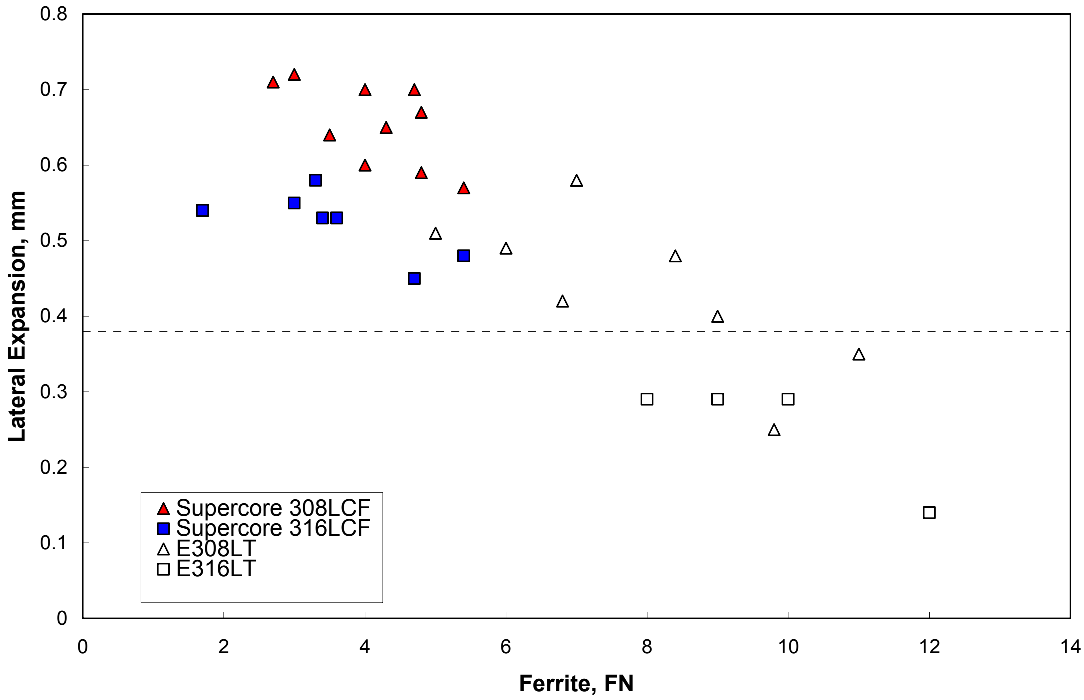

Figure 1 ***Effect of weld metal ferrite on lateral expansion at -196°C for flux cored wires. The superiority of the specially designed CF wires is clearly shown.***

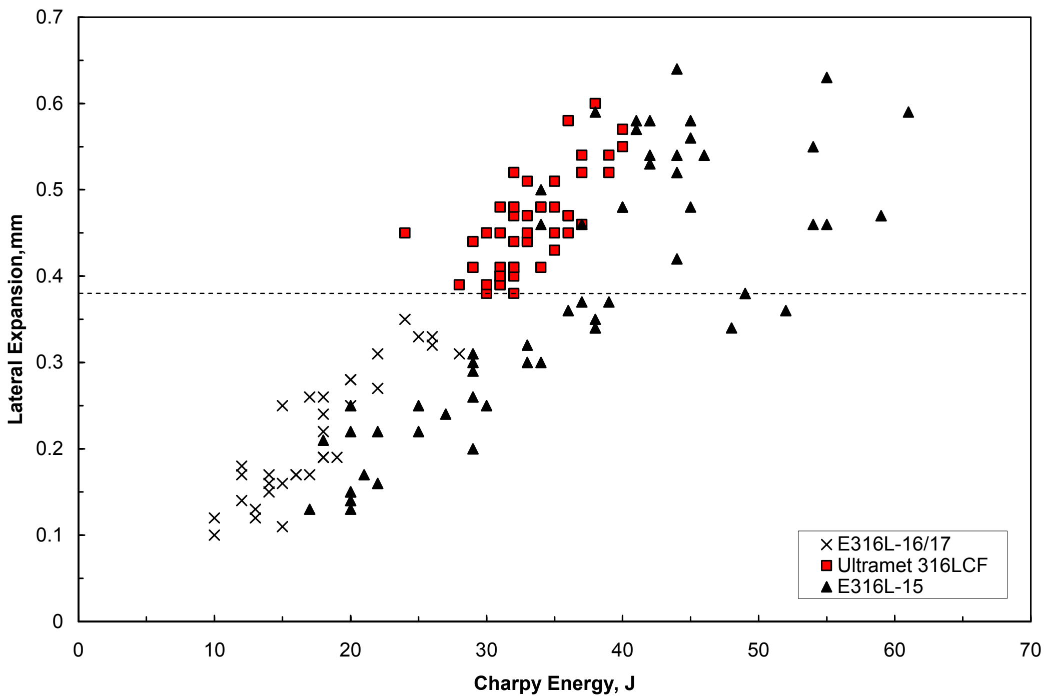

Figure 2 ***All-weld metal -196°C impact properties for 316L SMAW electrodes showing the effect of different coating types. All the data for Ultramet 316LCF meets the 0.38mm lateral expansion requirement.***

Figure 3 ***Gas shielded flux cored wire, Metrode Supercore 308LCF, being used for the first time during the construction of the Grain-LNG Importation facility on the Isle of Grain, UK.***

Figure 4 ***Construction of the Grain-LNG Importation facility on the Isle of Grain, UK; utilising the STT process for the first time in the UK on an LNG plant.***