STAINLESS STEEL CONSUMABLES FOR LNG APPLICATIONS

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Stainless Steel Consumables For LNG Applications

"How to achieve good cryogenic toughness in stainless steel welds"

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1 Introduction

Liquefied natural gas (LNG) is becoming more important in the world fuel market and with increasing demand the construction of LNG facilities is on the increase. LNG facilities make use of various materials for the onerous conditions that they will be subject to, including concrete, aluminium, 9% nickel steel and austenitic stainless steels. This technical profile covers the specialist area of arc welding consumables for joining 304L/316L stainless steel that will be3 subject to service temperatures down to -196°C (-320°F). For each welding process (GTAW, GMAW, SMAW, FCAW and SAW) typical mechanical properties are given and the specific weld metal controls required to achieve consistent low temperature toughness are explained. The dedicated range of controlled ferrite 'CF' consumables manufactured by Metrode is also described and some of the applications for which they have been used are highlighted.

2 What is LNG and why is it important?

Natural gas is composed primarily of methane (CH4) but may also contain heavier hydrocarbons (ethane, propane, butane) in addition to carbon dioxide, oxygen, nitrogen, sulphur compounds and water. Before liquefaction some of the non-methane components, such as water and carbon dioxide, must be removed to prevent the formation of solids when the gas is cooled to –161°C (-258°F). The result of this is that LNG is mainly methane, although the actual composition varies depending on the source, Table 1. Once in the form of LNG the liquid is odourless, colourless, non-corrosive and non-toxic, although LNG vapour can cause asphyxiation in an enclosed space. When it is vaporised LNG will only burn in air at concentrations of 5-15%.

Table 1 LNG composition, mole percent [1]

Source	Methane	Ethane	Propane	Butane	Nitrogen
Alaska	99.72	0.06	0.0005	0.0005	0.20
Algeria	86.98	9.35	2.33	0.63	0.71
Baltimore Gas & Electric	93.32	4.65	0.84	0.18	1.01
New York City	98.00	1.40	0.40	0.10	0.10
San Diego Gas & Electric	92.00	6.00	1.00	-	1.00

To produce LNG natural gas has to be cooled to -161°C (-258°F) at atmospheric pressure. Liquefaction reduces the volume of natural gas by approximately six hundred times making it more economic to transport, Figure 1. The ability to transport gas economically over large distances is of great benefit because there are remote areas that have large natural gas reserves but no significant local demand eg. Algeria, Qatar, Nigeria and Angola. The ability to transport the gas means that it can be delivered to areas where there is greatest demand and where it is commercially advantageous eg Japan, Europe and USA. The demand for LNG has increased rapidly since 1970, Figure 2.

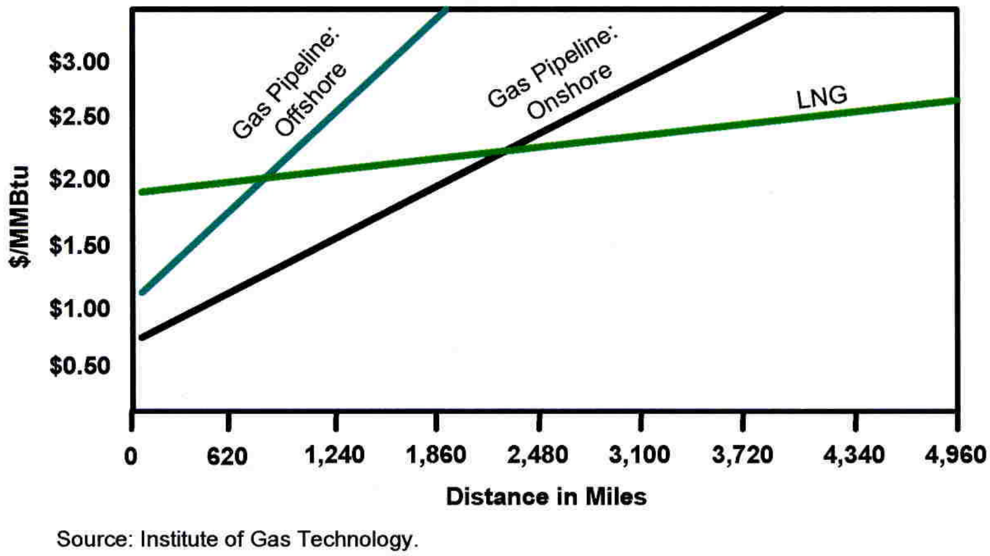


Figure 1 Comparison of costs for transportation of gas by pipeline versus LNG [2]

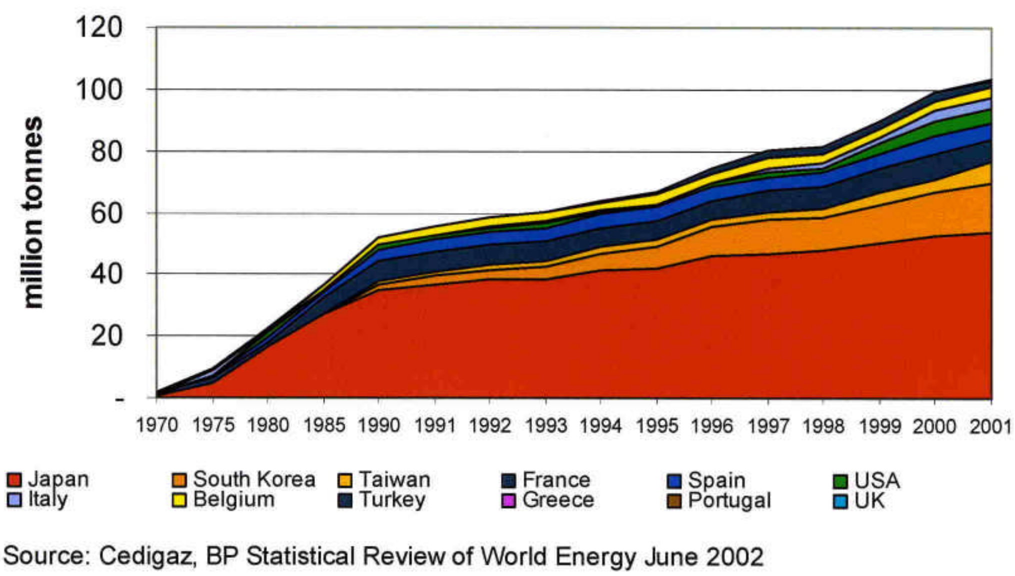


Figure 2 Worldwide growth in LNG demand since 1970 [2]

There are a number of stages in the supply of LNG: liquefaction, transport, storage and regasification. The gas from the production field has contaminants removed before liquefaction to avoid the formation of solids that may damage equipment; the contaminants may also need to be removed to meet pipeline specifications at the delivery point. Some examples of the liquefaction temperature for various gases are shown in Table 2. The liquefaction plant uses refrigerants to cool the natural gas to –161°C (-258°F). The LNG is then stored at atmospheric pressure. The storage tanks are of double-wall construction with insulation between the walls, the larger land based tanks are a distinctive cylindrical design with a domed roof Figure 3.

Table 2 Approximate liquefaction temperatures for various gases [3]

Gas	*Formula*	*Liquefaction Temperature, °C (°F)*
Butane	C_4H_{10}	0 (32)
Ammonia	NH_3	-33 (-27)
Propane	C_3H_8	-42 (-44)
Carbon dioxide	CO_2	-78 (-108)
Acetylene	C_2H_2	-84 (-119)
Ethane	C_2H_6	-88 (-126)
Ethylene	C_2H_4	-104 (-155)
Methane	CH_4	-161 (-258)
Oxygen	O_2	-183 (-297)
Argon	Ar	-186 (-303)
Nitrogen	N	-196(-320)
Hydrogen	H_2	-253 (-423)
Helium	He	-269 (-452)

Despite the insulation LNG only remains liquid because it is stored as a boiling cryogen (it is a very cold liquid at its boiling point for the pressure it is stored at). In much the same way that boiling water stays at the same temperature owing to evaporation, a cryogen (eg LNG) will stay at near constant temperature if kept at constant pressure. This is called autorefrigeration.

The LNG can be transported using LNG tankers, many of which can be readily identified because of the spherical/Moss design containment system, Figure 4. A typical LNG carrier, about 275m long, can transport ~130,000m3 of LNG, which provides about 75 million m3 of natural gas on regasification.

Figure 3 LNG terminal & storage tanks

Figure 4 LNG tanker

When the LNG tanker arrives at the receiving terminal the LNG is pumped, in its liquid state, into storage tanks similar to those used at the liquefaction plants. When there is a demand for gas the LNG is pumped at high pressure through a regasification plant where it is warmed in a controlled environment. The vaporised gas is then regulated to the correct pressure and can be fed into a gas pipeline system for delivery to the end user.

Natural gas liquids (NGL's) are not the same as LNG. NGL's are predominantly the heavier hydrocarbons (ethane, propane and butane) that liquefy more readily than methane and for most LNG used in the USA and Europe the NGL's are removed. For LNG sent to Japan, Korea, and some other Asian Countries, the NGL's are left in because the LNG heat content specification is higher in these countries than USA or Europe.

3 Materials

The storage and distribution of various gases, including liquefied natural gas (LNG), requires materials that have good mechanical properties, particularly toughness, at low temperatures. Gases are generally stored as liquids at low pressure and this requires that the materials used for storage tanks and pipework are capable of withstanding the low temperatures encountered with liquefied gases.

The most important criterion for service at cryogenic temperatures is normally toughness, and it is important that the weld metals used are capable of achieving good toughness. Large land based storage tanks are normally fabricated from 9% nickel steel and ship's storage tanks of aluminium but pipework for distribution etc is often made from austenitic stainless steel. The welding consumables for 9% nickel steels and 304L/316L austenitic stainless steels are tested down to -196°C (-320°F). For applications down to -269°C (-452°F), 304/316 austenitic stainless steel (welded with fully austenitic stainless steel consumables) or aluminium are used. The materials and welding consumables suitable for use at various nominal temperatures are shown in Table 3.

Table 3 Low temperature alloys and associated welding consumables

Temperature °C (°F)	*Alloy*	*GTAW/GMAW*	*SMAW*		*FCAW*
-50 (-58)	CMn	Metrode 1Ni ER80S-Ni1	Tufmet 1Ni.B E8018-C3		Metcore DWA 55E (E81T1-Ni1)
-60 (-76)	CMn (+Ni)	Metrode 2Ni ER80S-Ni2	Tufmet 2Ni.B E8018-C1		-
-75 (-103)	3%Ni	Metrode 2Ni ER80S-Ni2 (ER80S-Ni3)	Tufmet 3Ni.B E8018-C2		-
-101 (-150)	3/5%Ni	20.70.Nb ERNiCr-3	Nimrod 182KS / AKS ENiCrFe-2/3		-
-196 (-320)	9%Ni	62-50 / HAS C276 ERNiCrMo-3/4	Nimrod NCM6 ENiCrMo-6		-
-196 (-320)	304/304L	Metrode ER308LCF ER308L	Ultramet 308LCF Modified E308L-16	Ultramet B308LCF Modified E308L-15	Supercore 308LCF Modified E308LT1-4
-196 (-320)	316/316L	Metrode ER316LCF ER316L	Ultramet 316LCF Modified E316L-16	Ultramet B316LCF Modified E316L-15	Supercore 316LCF Modified E316LT1-4
-269 (-452)	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

As explained already, many different alloys are selected for LNG applications. This technical profile covers austenitic stainless steels, 304/304L and 316/316L, and the relevant weld metals 308L and 316L [4-9]. The use of fully austenitic weld metals (eg. BS EN 18 15 3 L types) is not covered here, although these fully austenitic weld metals have excellent toughness at -196°C (-320°F) and useful properties down to -269°C (-452°F).

4 Toughness requirements

Design temperatures encountered for austenitic stainless steels used for gas storage may vary but for simplicity and ease of testing, Charpy toughness tests are normally carried out at -196°C (-320°F) because this is an easily achieved, and convenient, test temperature obtained by cooling in liquid nitrogen.

The most commonly specified requirement is based on Charpy lateral expansion. The requirement for 0.38mm (0.015inch or 15mils) lateral expansion at -196°C (-320°F), which can be found in the ASME Code eg ASME B31.3 for process piping [10], is frequently quoted even for projects that are not being fabricated to ASME Code requirements. Although 0.38mm (0.015inch) 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 [11] sometimes specify a minimum Charpy energy of 40J/cm2, corresponding to 32J (24ft-lb) on a standard (10x10mm) Charpy specimen. Weld metal data showing the relationship between Charpy energy and lateral expansion are presented, but discussion in this technical profile assumes that the design requirement is 0.38mm (0.015inch) lateral expansion at -196°C (-320°F).

5 Welding processes

The following sections consider the five major arc welding processes: GTAW, GMAW, SMAW, FCAW and SAW. The main applications for each process are covered and the typical properties, and specific controls required to achieve good toughness are described.

5.1 Gas-shielded processes

The gas-shielded welding processes – gas tungsten arc welding (GTAW) / tungsten inert gas (TIG) welding and gas metal arc welding (GMAW) / metal inert gas (MIG) welding - produce inherently good toughness even at cryogenic temperatures. The gas shielding provides a metallurgically clean weld metal, with low oxygen, hence low non-metallic inclusion content.

5.1.1 GTAW / TIG – Metrode ER308LCF and ER316LCF

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 (eg root runs in pipe) or where weld integrity is more important than productivity.

The GTAW process in conjunction with Metrode ER308LCF (ER308L / W 19 9 L) or Metrode ER316LCF (ER316L / W 19 12 3 L) wire produces clean weld metal and exceptional toughness even at -196°C (-320°F). Experience has shown that with both ER308LCF and ER316LCF wires it is possible to achieve typically 80J (60ft-lb) at -196°C (-320°F) and a lateral expansion of about 1.0mm (0.040inch), when using the argon shielded GTAW process. Table 4 gives the results of actual tests on 316L.

5.1.2 GMAW / MIG – Supermig 308LSi and Supermig 316LSi

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 GMAW process with Ar-2%O2, or other shielding gas with similar oxidising potential, using Supermig 308LSi (ER308LSi / G 19 9 L Si) or Supermig 316LSi (ER316LSi / G 19 12 3 L Si) wire deposits weld metal with a somewhat higher oxygen level than GTAW, but is still capable of producing ~40J (30ft-lb) at -196°C (-320°F) with a lateral expansion of about 0.5mm (0.020inch).

These excellent impact properties can be consistently achieved without special control measures, using standard commercially available ER308L/ER308LSi and ER316L/ER316LSi wires with the GTAW and GMAW processes, Table 4 gives the results of actual tests on 316L.

Table 4 Representative mechanical properties from all-weld metal joints using the gas shielded processes and 316L wire

	GTAW	*GMAW*
Consumable	Metrode ER316LCF (ER316L / W 19 12 3 L)	Supermig 316LSi (ER316LSi / G 19 12 3 L Si)
Shielding gas	Ar	Ar-2%O2
Tensile strength, MPa (ksi)	605 (88)	559 (81)
0.2% Proof stress, MPa (ksi)	466 (68)	413 (60)
Elongation, % 4d	41	50
5d	37	47
Reduction of area, %	62	73
Impact properties -196°C (-320°F):		
impact energy, J (ft-lb)	105 (77)	43 (32)
lateral expansion, mm (inch)	1.17 (0.046)	0.58 (0.023)

5.2 Flux-shielded processes

The three flux shielded processes – shielded metal arc welding (SMAW) / manual metal arc (MMA) welding, flux cored arc welding (FCAW) and submerged arc welding (SAW) – do not achieve such low oxygen content, low inclusion content weld metal, and hence give lower impact properties than the gas-shielded processes. If consistently satisfactory toughness is required at -196°C (-320°F), it is invariably necessary to provide careful control of the welding consumable because standard commercial SMAW electrodes and FCAW wires will not reliably achieve 0.38mm (0.015inch) lateral expansion at -196°C (-320°F).

5.2.1 SMAW / MMA – Ultramet 308LCF and Ultramet 316LCF

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.

As already discussed in Section 5.1, the gas shielded processes do not require any special controls to achieve 0.38mm (0.015inch) lateral expansion at -196°C (-320°F). But with the flux shielded processes, controls are required to produce 308L/316L consumables capable of achieving good cryogenic toughness. Three areas in particular are important for SMAW: ferrite content, alloy control and flux type; each of these areas will be discussed separately.

5.2.1.1 Ferrite

Various standards specify ferrite limits for austenitic stainless steels. For example, ASME III [12] requires 5FN minimum, or 3-10FN for service above 427°C (800°F); and API 582 [13] has 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 0.38mm (0.015inch) lateral expansion requirement by controlling weld metal ferrite of SMAW electrodes in the range 2-5FN.

The effect of ferrite on toughness of E308L welds is well illustrated in Figure 5, which includes data from a variety of sources. The trends shown confirm those found by others in earlier work [eg 14-16]. As can be seen, the general trend is for the lateral expansion to decrease as ferrite increases, but beyond about 8FN the lateral expansion increases again, as seen for the E308L-16/17 series in Figure 5. This increase in lateral expansion beyond about 8FN is believed to be due to a change in the ferrite morphology. The benefit of controlling ferrite in the range 2-5FN is shown by the Ultramet 308LCF series in Figure 5, where all the data for Ultramet 308LCF gave lateral expansions in the range 0.4–0.7mm (0.016-0.028inch).

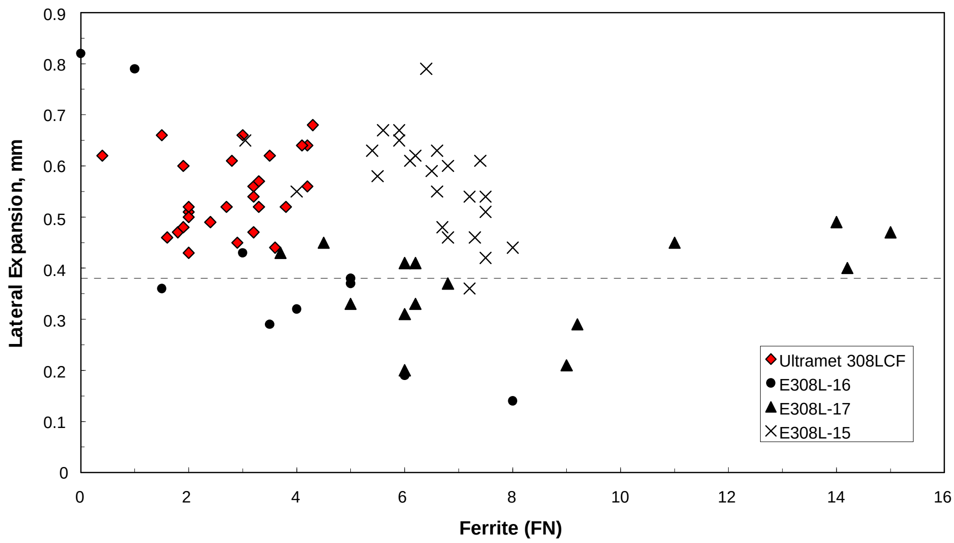


Figure 5 Weld ferrite versus lateral expansion for 308L SMAW electrodes at –196°C (-320°F). Note the superiority of Ultramet 308LCF, a specially designed rutile electrode, compared with conventional rutile E308L-16/17 types

A particular concern with austenitic consumables having low ferrite levels is the risk of solidification cracking or microfissuring. Most codes and specifications that specify a minimum ferrite do so to maximise resistance to hot cracking, and at a typical ferrite of ~3FN the controlled ferrite (CF) consumables might be considered to be at risk. However, numerous weld procedures and projects have been carried out with the Ultramet 308LCF and Ultramet 316LCF SMAW consumables described here and no solidification cracking, or microfissuring problems, have ever been encountered. The reason for this is that despite the low ferrite, the composition is controlled to achieve a Cr:Ni ratio which produces a desirable primary ferrite solidification mode. The robust resistance to cracking can also be demonstrated by superimposing the controlled ferrite electrode composition range on the Suutala diagram, as shown for Ultramet 308LCF in Figure 6 [17].

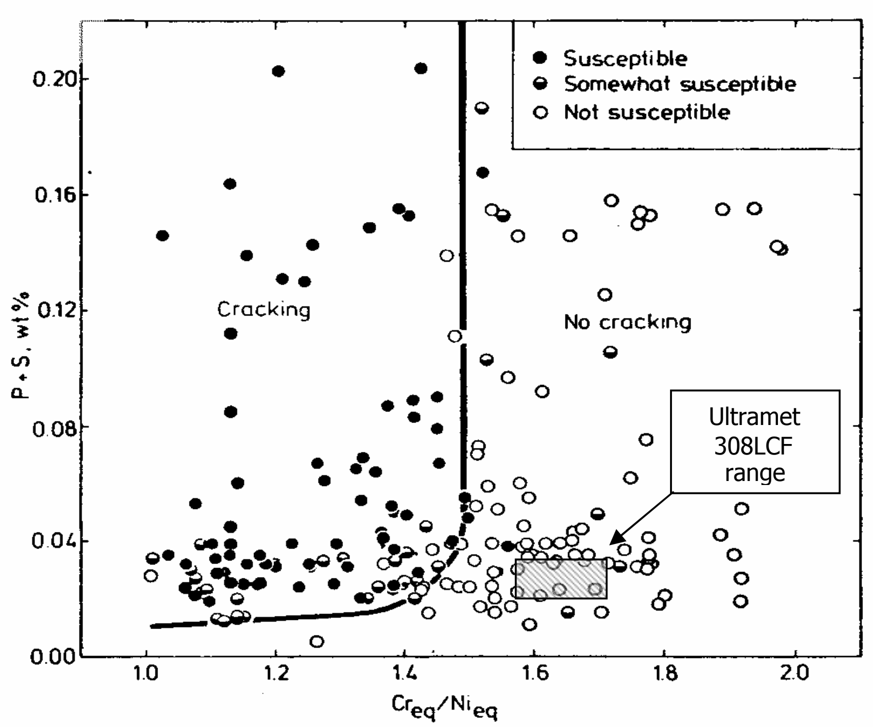


Figure 6 Suutala diagram [17] with the Ultramet 308LCF SMAW electrode composition range superimposed. The Ultramet 308LCF composition range is well in the"'no cracking" region of the Suutala diagram.

5.2.1.2 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 Ultramet 308LCF and Ultramet 316LCF electrodes becomes restricted to the 'lean' area of their respective weld metal specification ranges. One consequence of this is that with Ultramet 316LCF molybdenum is preferably controlled in the range 2.0 – 2.5%. This means that the Ultramet 316LCF controlled ferrite SMAW electrode conforms to the AWS specification (2.0-3.0%Mo for E316L-16 [4]), but not the BS EN specification E 19 12 3 L R [7] which requires 2.5 – 3.0% Mo. Although not reviewed here, excellent cryogenic toughness and resistance to hot cracking at low FN levels is also displayed by the 'lean 316' type 16.8.2 consumables [18]. The analysis of representative batches of Ultramet 308LCF and Ultramet 316LCF are shown in Table 5.

Table 5 Deposit analysis from representative batches of Ultramet 308LCF and Ultramet 316LCF

	C	*Mn*	*Si*	*S*	*P*	*Cr*	*Ni*	*Mo*	*Cu*	*N*	*O*
Ultramet 308LCF	0.023	0.77	0.58	0.014	0.022	18.9	9.6	0.04	0.04	0.112	0.064
Ultramet 316LCF	0.021	0.81	0.61	0.012	0.022	17.3	11.4	2.23	0.04	-	-

5.2.1.3 Electrode flux coating

With CMn and low alloy steels, it is traditionally accepted that the best impact properties are achieved using SMAW electrodes with fully basic flux systems. With austenitic stainless steels the effect is less pronounced, although it has long been recognised and reported that electrodes with basic flux coverings such as 'lime-fluorspar' E3XX-15 types give somewhat better results than rutile E3XX-16/17 coatings [14-16].

The data for standard 'general purpose' E316L-15/16/17 and Ultramet 316LCF are plotted for comparison in Figure 7. It can be seen that the basic type, E316L-15, electrodes give higher impact energy for a given lateral expansion (apparently a larger effect than reported by previous workers). Consequently, Figure 7 indicates that for E316L-16/17 electrodes a lateral expansion of 0.38mm (0.015inch) is assured by about 32J (24ft-lb), whereas E316L-15 electrodes require about 40J (30ft-lb). What Figure 7 clearly shows is that the basic flux system alone is no guarantee of achieving 0.38mm (0.015inch) lateral expansion.

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 controlled ferrite electrodes, Ultramet 308LCF and Ultramet 316LCF, use a rutile flux system (eg. E316L-16CF/Ultramet 316LCF in Figure 7) to take advantage of the best operability and welder appeal.

Basic coated electrodes, Ultramet B308LCF (E308L-15) and Ultramet B316LCF (E316L-15), are also available for those applications where basic coated electrodes are specified. The basic coated electrodes may have some benefit for the most demanding positional pipework but for most applications the rutile electrodes have proved to be satisfactory.

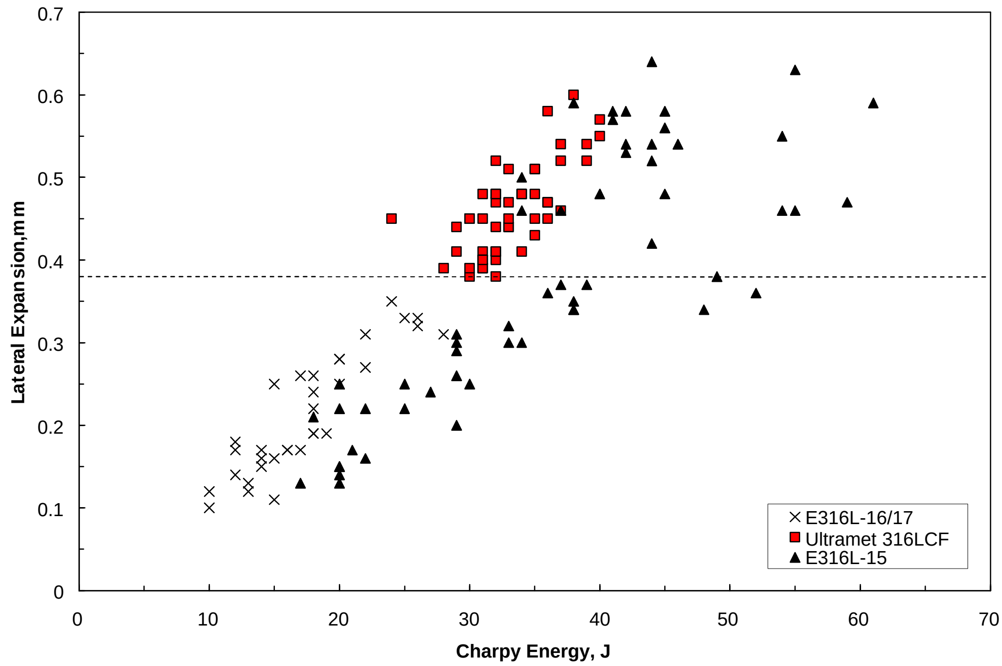


Figure 7 All-weld metal -196°C (-320°F) impact properties for 316L SMAW electrodes showing the effect of different coating types. (Data plotted are for individual Charpy specimens)

5.2.2 Gas shielded FCAW – Supercore 308LCF and Supercore 316LCF

The flux cored arc welding process has found significant use in areas where SMAW has traditionally been used but where a continuous wire process can provide a valuable productivity advantage. The flux cored wires can offer productivity advantages over SMAW electrodes in applications involving material over ~200mm (8inch) diameter and greater than ~12.5mm (0.5inch) thickness. The Supercore 308LCF (E308LT1-4) and Supercore 316LCF (E316LT1-4) consumables are all-positional rutile flux cored wires that operate equally well with either Ar-20%CO2 or 100%CO2 shielding gas. The wires are based on a rutile flux system suitable for all-positional pipe welding. The controls required to ensure good toughness are discussed further in the next section.

5.2.2.1 Ferrite

As with the SMAW electrodes, ferrite also has a pronounced effect on the toughness of flux cored wire weld deposits at -196°C (-320°F). This is illustrated with average data for both standard 308L/316L and the new 308LCF/316LCF types in Figure 8. The toughness data are plotted separately for 308L and 316L in Figures 9a and 9b showing individual Charpy energy versus lateral expansion values at -196°C (-320°F) for standard wires and controlled ferrite wires. The benefit of the controlled ferrite type wires is very evident, with all of the specimens for the controlled ferrite types exceeding 0.38mm (0.015inch) lateral expansion at -196°C (-320°F).

As can be seen in Figure 9a, some of the results for standard 308L wire also reached the 0.38mm (0.015inch) lateral expansion requirement, but none except the Supercore 308LCF achieved 32J (24ft-lb) or 40J/cm^2. With the 316L flux cored wires the only results that meet the 0.38mm (0.015inch) requirement are those for the controlled ferrite wire, Supercore 316LCF. An example of the microstructure of a vertical-up weld deposited using Supercore 308LCF is shown in Figure 10.

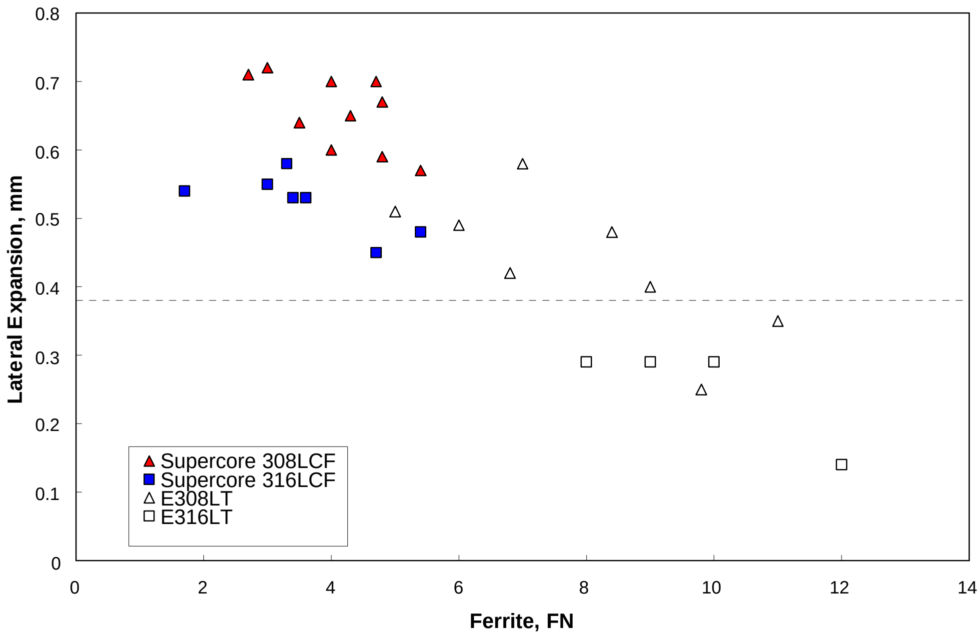


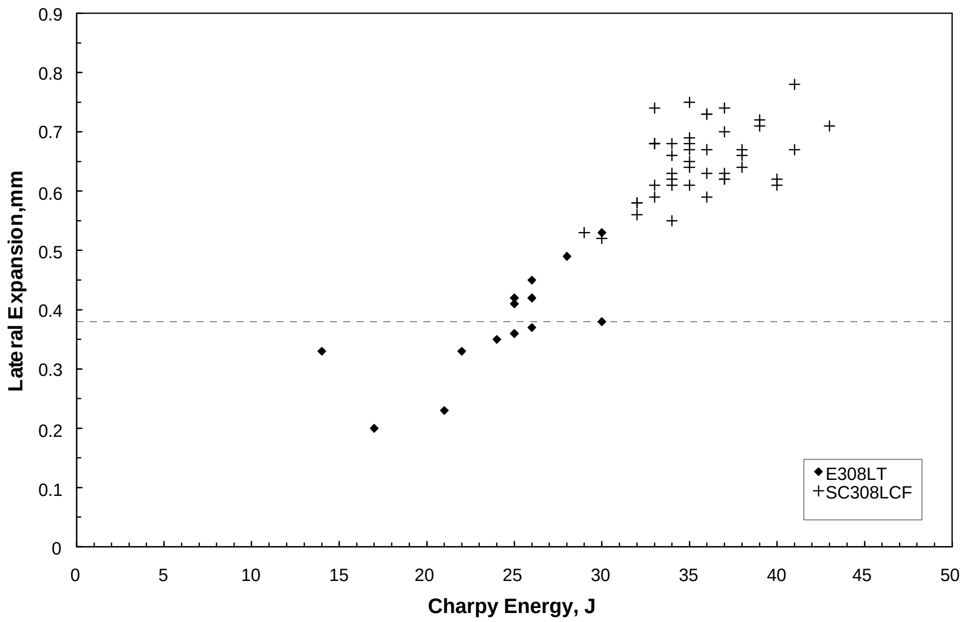
Figure 8 ***Effect of weld metal ferrite on lateral expansion at -196°C (-320°F) for flux cored wires. The superiority of the specially designed 'CF' wires is clearly shown. (Data plotted are based on average lateral expansion from a set of Charpy specimens)***

5.2.2.2 Alloy control

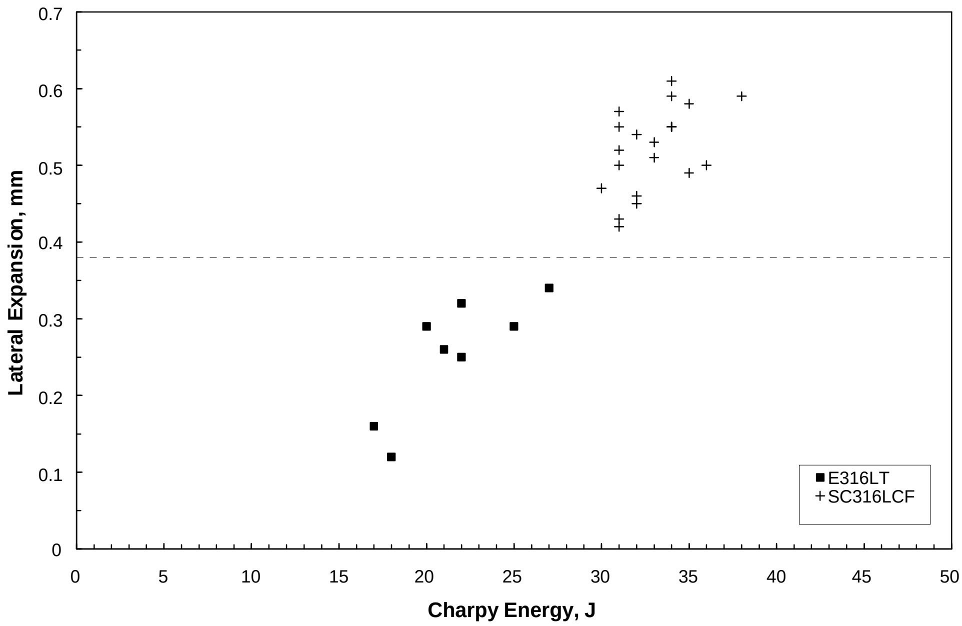
The experience gained over many years of manufacturing controlled ferrite SMAW electrodes has now been applied to flux cored wires. The compositional and ferrite aims for the Supercore 308LCF and Supercore 316LCF flux cored wires are similar to the equivalent SMAW electrodes. This means that the wires conform to E308LT1-4 and E316LT1-4 with a ferrite aim of 2-5FN. As with the SMAW electrodes, the Supercore 316LCF flux cored wire conforms to the AWS specification E316LT1-4 [6] but not necessarily to the EN specification T 19 12 3 L P [9], which requires 2.5-3.0% Mo. The analysis of representative batches of Supercore 308LCF and Supercore 316LCF are shown in Table 6.

Table 6 Deposit analysis of representative batches of Supercore 308LCF and Supercore 316LCF.

Wire	Gas	C	Mn	Si	S	P	Cr	Ni	Mo	Cu	N	O
308LCF	Ar-20%CO_2	0.030	1.42	0.62	0.012	0.020	18.3	10.6	0.05	0.04	0.032	0.089
316LCF	Ar-20%CO_2	0.028	1.38	0.57	0.013	0.024	18.1	12.5	2.02	0.05	-	-



(a)



(b)

Figure 9 All-weld metal impact properties for flux cored wire deposits at -196°C (-320°F) clearly showing the better toughness obtained with the CF wires. (Data plotted are for individual Charpy specimens):
(a) 308L data including Supercore 308LCF
(b) 316L data including Supercore 316LCF

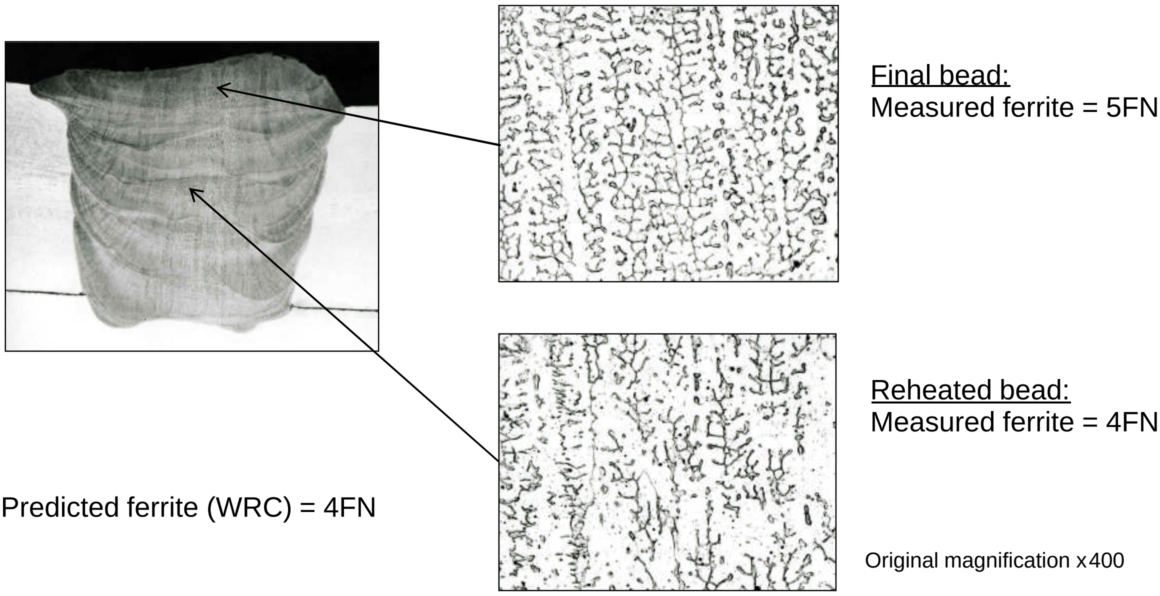


Figure 10 Microstructure of a vertical-up weld deposited with Supercore 308LCF flux cored wire using Ar-20%CO2, in 12.5mm (0.5inch) 304L plate

5.2.3 Submerged arc welding – ER308LCF and ER316LCF wires and LA491 flux

The submerged arc welding 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 ~15mm (0.6in) thick or less than ~200mm (8in) in diameter.

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 best results are likely to be obtained by the use of flux with no chromium compensation (to avoid excessive ferrite), coupled with attention to heat input, as discussed in Section 6. Higher flux basicity will support chromium transfer and thus produce a weld deposit higher in ferrite, but metallurgically cleaner, than more acid fluxes and either approach probably has its protagonists. The approach that Metrode has found to be most successful is the use of the fluoride-basic agglomerated flux Metrode LA491 (SA FB 255 AC). This flux has consistently produced the best cryogenic impact properties when tested with both 308L and 316L wires; see Table 7 for comparison with other Metrode fluxes.

Table 7 Effect of flux on impact properties of 316L sub-arc welds produced with the same batch of wire and same welding procedure (~1.5kJ/mm)

Flux	*Basicity Index*	*Ferrite, FN*		*-196°C (-320°F) Properties*	
		Measured, mid-section/final bead	*WRC*	*Charpy energy, J (ft-lb)*	*Lateral expansion, mm (inch)*
SSB	2.2	6 / 9	8	21 (15)	0.31 (0.012)
L2N	1.3	5 / 7	9	32 (24)	0.45 (0.018)
LA491	2.7	6 / 7	10	36 (27)	0.54 (0.021)

Unlike the SMAW and FCAW processes, which are certified with a deposit analysis, the submerged arc deposit analysis will vary from that of the wire depending on the flux that is used. The LA491 flux is neutral, with little Mn loss and minimal Si pick-up, there is also very little change in Cr, Ni and Mo; see Table 8 for representative wire and deposit analyses.

Table 8 Analysis of 316L submerged arc deposits produced with ER316LCF wire and LA491 flux

Wire		C	Mn	Si	S	P	Cr	Ni	Mo	Cu	N	O
ER316LCF	*Wire*	0.011	1.71	0.44	0.010	0.019	18.5	11.5	2.51	0.04	-	-
	Deposit	0.022	1.68	0.53	0.008	0.022	18.8	11.3	2.49	0.05	0.056	0.050
ER316LCF	*Wire*	0.014	1.51	0.38	0.012	0.013	18.4	11.6	2.60	0.10	-	-
	Deposit	0.025	1.44	0.48	0.010	0.014	18.1	11.4	2.41	0.10	-	-

6 Weld procedure

An improvement in Charpy properties with increasing heat input and reduced number of weld runs has been reported previously [19-20]. This finding was confirmed by a series of three submerged arc welds produced with heat inputs from 1.0 up to 2.7KJ/mm and these welds showed an increase in toughness with increasing heat input, Table 9. The reason for the improvement in toughness is not certain, but it is suspected that the reduction in the number of runs deposited reduces the strain ageing effect and hence improves the impact properties. Most authorities do not allow this effect to be taken advantage of when welding stainless steels for wetted corrosion applications because of concerns over the effect the high heat inputs may have on corrosion performance.

For LNG service the corrosion requirement is minimal and there should be no detrimental effects on performance with heat inputs up to ~2.5kJ/mm. The selection of welding parameters should be based on joint configuration, material thickness and component size. TWI work [21] showed no detrimental effect on joint performance in 304L/316L with interpass temperatures up to 300°C (575°F) and heat inputs up to 2.9kJ/mm (74kJ/inch).

Table 9 Effect of heat input/number of runs on impact properties of 316L sub-arc welds produced with the same batch of wire and SSB flux in 22mm (0.9inch) thick plate

*Heat input, kJ/mm **	*Number of runs in joint*	*Ferrite, FN*	*-196°C (-320°F) Properties*	
			Charpy energy, J (ft-lb)	*Lateral expansion, mm (inch)*
1.0	27	5	28 (21)	0.30 (0.012)
1.8	17	7	34 (25)	0.42 (0.017)
2.7	10	7	46 (34)	0.48 (0.019)

* Heat input altered by varying travel speed with current and voltage constant at 300A and 30V

The beneficial effect of increased heat input can also be seen with SMAW electrodes. The larger diameter electrodes, on average, produce higher impact properties, Figure 11. This could be attributed to the larger diameter electrodes being deposited using a higher heat input hence producing larger weld beads with fewer runs per joint.

The tests carried out to date have not shown the FCAW process to be so dependent on heat input, number of weld runs, welding position or shielding gas; this is shown in Table 10 where results of tests carried out on the same batch of wire are given.

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.

Table 10 Effect of welding position and shielding gas on the impact properties of Supercore 308LCF controlled ferrite flux cored wire at -196°C (-320°F).

Shielding gas	*Welding position*	*Heat input, kJ/mm*	*Bead sequence*	*-196°C (-320°F) Properties*	
				Charpy energy, J (ft-lb)	*Lateral expansion, mm (inch)*
Ar-20%CO_2	1G (PA)	1.1	2 bead per layer	38 (28)	0.64 (0.025)
100%CO_2	1G (PA)	1.0	2 bead per layer	33 (24)	0.68 (0.027)
Ar-20%CO_2	3G (PF)	1.2	2 bead per layer	32 (24)	0.57 (0.022)
Ar-20%CO_2	3G (PF)	1.8	Full width weave	36 (27)	0.67 (0.026)
100%CO_2	3G (PF)	1.1	2 bead per layer	36 (27)	0.64 (0.025)

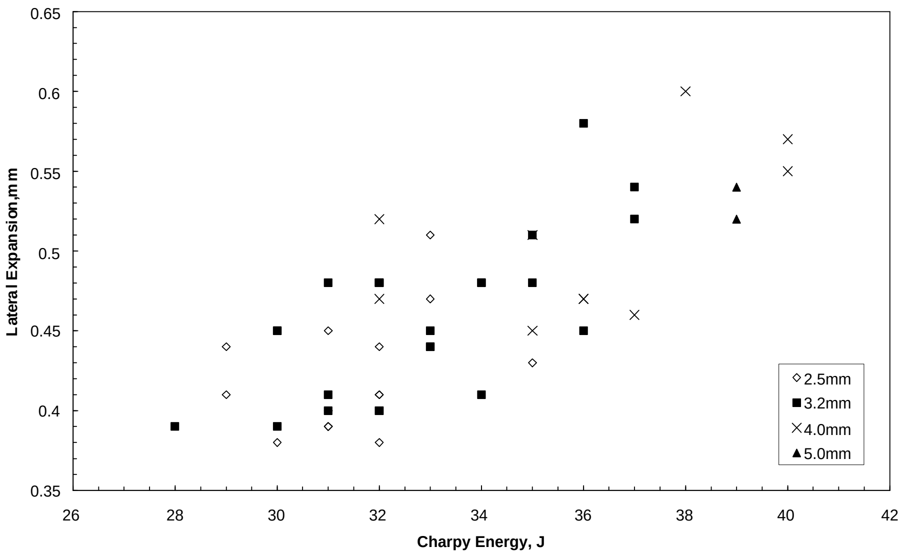


Figure 11 All-weld metal impact energy versus lateral expansion at –196°C (-320°F) for Ultramet 316LCF SMAW electrode. (Data plotted is for individual Charpy specimens)

7 Metrode consumables and certification

Table 11 summarises the Metrode consumables that are designed for LNG pipework and other applications requiring good cryogenic toughness [22].

Table 11 Metrode 'CF' consumables for stainless steel LNG applications

Process	*Metrode 308L Consumable*	*Metrode 316L Consumable*
GTAW	ER308LCF (ER308L)	ER316LCF (ER316L)
SMAW	Ultramet 308LCF (E308L-16)	Ultramet 316LCF (E316L-16)
	Ultramet B308LCF (E308L-15)	Ultramet B316LCF (E316L-15)
FCAW	Supercore 308LCF (E308LT1-4)	Supercore 316LCF (E316LT1-4)
SAW	ER308LCF (ER308L) LA491 flux (BS EN SA FB255)	ER316LCF (ER316L) LA491 flux (BS EN SA FB255)

7.1 Metrode GTAW wires

Metrode offers ER308LCF (ER308L) and ER316LCF (ER316L) solid GTAW wires, which are specifically selected to offer ferrite control of 3-8FN and are batch certified with wire analysis and deposit ferrite content measured with a Fischer Ferritescope.

7.2 Metrode SMAW electrodes

Ultramet 308LCF (E308L-16) and Ultramet 316LCF (E316L-16) are rutile ('16' type coatings) all-positional electrodes suitable for fixed pipework with excellent operability and welder appeal. Ultramet B308LCF (E308L-15) and Ultramet B316LCF (E316L-15) are basic ('15' type coatings) all-positional electrodes suitable for fixed pipework.

The Metrode electrodes are specifically designed and manufactured to consistently meet the stringent demands of cryogenic applications; they are not batch selected standard all-purpose stainless steel electrodes.

The electrodes are batch impact tested at –196°C (-320°F) with an acceptance criterion of 0.38mm (0.015inch) 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 (-320°F). Table 12 shows typical properties of Ultramet 308LCF and Ultramet 316LCF weld deposits.

Table 12 Representative mechanical properties from all-weld metal joints using Ultramet 308LCF and Ultramet 316LCF

Consumable	*Ultramet 308LCF*	*Ultramet 316LCF*
Specification, AWS A5.4	E308L-16	E316L-16
Specification, BS EN 1600	E 19 9 L R 3 2	(E 19 12 3 L R 3 2)
Tensile strength, MPa (ksi)	583 (85)	565 (82)
0.2% Proof stress, MPa (ksi)	452 (66)	461 (67)
Elongation, % 4d	52.5	51.5
5d	47	46.5
Reduction of area, %	52	63
Impact properties -196°C (-320°F):		
impact energy, J (ft-lb)	32 (24)	33 (24)
lateral expansion, mm (inch)	0.49 (0.019)	0.46 (0.018)

7.3 Metrode flux cored wires

The Supercore 308LCF (E308LT1-4) and Supercore 316LCF (E316LT1-4) consumables are all-positional rutile flux cored wires that operate equally well with either Ar-20%CO2 or 100%CO2 shielding gas.

The Metrode 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 wires.

Metrode's flux cored wires are batch impact tested at –196°C (-320°F) with an acceptance criterion of 0.38mm (0.015inch) lateral expansion. The BS EN 10204 3.1.B batch certification covers weld deposit analysis, measured ferrite content and Charpy toughness at –196°C (-320°F). Table 13 shows typical properties of Supercore 308LCF and Supercore 316LCF.

Table 13 Representative mechanical properties from all-weld metal joints using Supercore 308LCF and Supercore 316LCF

Consumable	*Ultramet 308LCF*	*Ultramet 316LCF*
Specification, AWS A5.22	E308LT1-4	E316LT1-4
Specification, BS EN 12073	T 19 9 L P M 2	(T 19 12 3 L P M 2)
Shielding gas	Ar-20%CO_2	Ar-20%CO_2
Tensile strength, MPa (ksi)	544 (79)	546 (79)
0.2% Proof stress, MPa (ksi)	393 (57)	410 (59)
Elongation, % 4d	50	42
5d	47.5	38.5
Reduction of area, %	54	44
Impact properties -196°C (-320°F):		
impact energy, J (ft-lb)	36 (27)	34 (25)
lateral expansion, mm (inch)	0.72 (0.028)	0.55 (0.022)

7.4 Metrode submerged arc welding consumables

In conjunction with the LA491 flux it is also beneficial to select batches of wire that show the most favourable ferrite potential. For this reason Metrode have ER308LCF (AWS ER308L) and ER316LCF (AWS ER316L) solid wires that have been selected specifically for LNG, and other cryogenic, applications. In addition to having optimised ferrite levels the ER308LCF and ER316LCF wires are also batch tested as standard in conjunction with the Metrode LA491 flux.

The testing comprises a Charpy impact test at –196°C (-320°F), with an acceptance criterion of 0.38mm (0.015inch) minimum lateral expansion, and the result forms part of the BS EN 10204 3.1.B certification for each batch of wire. Table 14 shows typical properties for ER308LCF and ER316LCF submerged-arc wires with LA491 flux.

Table 14 Representative mechanical properties from all-weld metal joints using ER308LCF and ER316LCF submerged arc welding wires and LA491 flux

Consumable	*ER308LCF*	*ER316LCF*
Wire specification, AWS A5.9	ER308L	ER316L
Wire specification, BS EN 12072	S 19 9 L	S 19 12 3 L
Flux	LA491	LA491
Tensile strength, MPa (ksi)	552 (80)	563 (82)
0.2% Proof stress, MPa (ksi)	398 (58)	402 (58)
Elongation, % 4d *5d*	48.5 45	48.5 44
Reduction of area, %	55	67
Impact properties -196°C (-320°F): *impact energy, J (ft-lb)* *lateral expansion, mm (inch)*	 45 (33) 0.69 (0.027)	 32 (24) 0.49 (0.019)

8 Applications

Numerous successful weld procedures have been carried out with the controlled ferrite SMAW electrodes, and many tonnes of Ultramet 308LCF/316LCF electrodes have been used on projects all round the world. Most of the projects that these electrodes were used on were pipelines and process pipework; some examples are given here, also see Table 15 for weld procedure data from two of these projects.

The controlled ferrite Ultramet 316LCF SMAW electrode was originally designed in the early 1990's to satisfy the requirements of Mobil/Ralph M Parsons for the SAGE (Scottish Area Gas Evacuation) project terminal at St Fergus, Scotland. The plant, run by ExxonMobil, has now been processing gas since 1992. A number of weld procedures were completed covering different welding processes and pipe sizes, an example of a procedure qualification record (PQR) run for this project is shown in Appendix 2. This procedure is for an ASME 6G / EN H-L045 joint in 200mm (8inch) diameter 23mm (0.9inch) wall thickness pipe completed with GTAW (ER316LCF) and SMAW (Ultramet 316LCF).

More recently tonnage quantities of the controlled ferrite SMAW consumables have been used in Kazakhstan on the Karachaganak Project where the contractor was CCC-Saipem. The controlled ferrite electrodes were used on 304/316 process pipework. There have also been significant quantities of pipework welded with the controlled ferrite consumables on the Mesaieed Q-Chem petrochemical complex in Qatar. The contractor was Snamprogetti and the SMAW electrodes were used on the natural gas to liquids plant (NGL-4), which will produce ethane rich gas feedstock for the ethylene plant.

Table 15 Examples of weld procedure data using controlled ferrite consumables

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.	Lincoln STT GMAW LNM 304Si	GTAW Metrode ER316LCF		
Filling process and consumable.	FCAW Supercore 308LCF	GTAW Metrode ER316LCF	SMAW Ultramet 316LCF	SMAW 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:	10x7.5mm	10x5mm	10x7.5mm	10x10mm
- 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)

The first commercial use of the Supercore 308LCF flux cored wire was for the Isle of Grain LNG terminal in the UK, which also used the SMAW electrode. The Supercore 308LCF controlled ferrite 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. The Supercore 308LCF flux cored wire was used for the filling and capping runs on top of a single root run, see Figure 12.

Figure 12 Gas shielded flux cored arc welding, Supercore 308LCF, 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

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