Stainless Steel Arc Welding Consumables for Cryogenic Applications

Authors:
G. Holloway, Z. Zhang,
A. Marshall
Metrode Products Ltd.

Keywords:
Austenitic stainless steel, cryogenic, LNG, lateral expansion, toughness, welding consumables.

Abstract

The storage and distribution of various gases including liquefied natural gas (LNG) requires materials that have good mechanical properties, particularly toughness, at low temperatures. Many different alloys are selected for LNG applications; this paper covers austenitic stainless steels, 304/304L and 316/316L, and the relevant AWS conforming weld metals, 308L and 316L. The question: what is 'good' cryogenic toughness for 308L and 316L weld metal? – is addressed. The typical toughness which can be achieved with the GTAW, GMAW, SMAW, FCAW and SAW processes and the controls that need to be imposed on the weld metal to achieve good toughness are reviewed for the various arc welding processes. The mechanical properties of austenitic stainless steel weld metals are not generally considered to be significantly affected by welding procedure but data is presented showing that weld procedure can influence cryogenic toughness. Finally, examples are presented of some of the projects around the world for which the consumables have been used.

1. Introduction

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. Some examples of the liquefaction temperatures of various gases are shown in Table 1.

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 but pipework for distribution etc is often made from austenitic stainless steel. The 9% nickel steels and 304/316 austenitic stainless steel consumables 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 2.

2. Materials

As explained already, many different alloys are selected for LNG applications. This paper covers austenitic stainless steels, 304/304L and 316/316L, and the relevant weld metals 308L and 316L [1-6]. 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). The paper is divided into four main areas:

- typical toughness requirements, the effect of different welding processes on toughness,
- how weld metals achieve the required toughness
- and, finally, the effect of weld procedure.

3. Toughness Requirements

Design temperatures encountered for austenitic stainless steels used for LNG applications 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 [7], is frequently quoted even for projects which 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 [8] sometimes specify a minimum Charpy energy of 40J/cm^2, corresponding to 32J (24ft-lb) on a standard Charpy specimen. Weld metal data showing the relationship between Charpy energy and lateral expansion is presented in this paper, but discussion assumes that 0.38mm (0.015inc) lateral expansion at -196°C (-320°F) is the design requirement.

4. Welding Process

4.1 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.

The GTAW process in conjunction with ER308L (W 19 9 L) or ER316L (W 19 12 3 L) wire produces the cleanest weld metal and exceptional toughness even at -196°C (-320°F). Experience has shown that with both ER308L and ER316L wires it is possible to achieve typically 80J (60ft-lb) at -196°C (-320°F) and a lateral expansion of 1.0mm (0.040inch), when using the argon shielded GTAW process. The GMAW process with Ar-2%O_2 or other shielding gas with similar oxidising potential, using ER308LSi (G 19 9 L Si) or ER316LSi (G 19 12 3 L Si) wire deposits weld metal with a somewhat higher oxygen level, but is still capable of producing typically 40J (30ft-lb) at -196°C (-320°F) with a lateral expansion of typically 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 3 gives the results of actual tests on 316L.

4.2 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). Note that the FCAW process referred to is not the gasless 'self-shielded' type, since ingress of air and pickup of nitrogen by the weld metal must be minimised to avoid unnecessary degradation of properties, but is the gas shielded FCAW process which is shielded by both a shielding gas and a slag cover. The controls required to ensure good toughness are discussed further in the next section.

5. Controls Required for SMAW Electrodes

As already discussed in Section 4, the gas shielded processes do not require any special controls to achieve 0.38mm (0.015inch) lateral expansion at -196°C (-320°F). With the flux shielded processes, controls are required to produce 308L/316L consumables capable of achieving good cryogenic toughness. Three areas in particular will be covered:

- ferrite content
- alloy control
- type of flux

The discussion and data presented in Sections 5.1 and 5.2 concentrates on the SMAW process but the information presented is equally applicable to FCAW as will be seen in Section 6.

5.1 Ferrite

Various standards specify ferrite limits for austenitic stainless steels. For example, ASME III [9] requires 5FN minimum, or 3-10FN for service above 427°C (800°F); and API 582 [10] 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 1, which includes data from a variety of sources. The trends shown confirm those found by others in earlier work [eg 11-13]. 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 1. 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 UM308LCF series in Figure 1, where all the points of 1-4FN gave lateral expansions in the range 0.4–0.7mm (0.016-0.028inch).

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 308L and 316L controlled ferrite 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 the 308LCF electrode in Figure 2 [14].

5.2 Alloy Control

By controlling the weld metal ferrite range to 2-5FN and simultaneously balancing the Cr:Ni equivalent ratio to eliminate any potential risk of hot cracking, the deposit composition of 308LCF and 316LCF electrodes becomes restricted to the 'lean' area of their respective weld metal specification ranges. One consequence of this is that with the 316LCF types Mo is preferably controlled in the range 2.0 – 2.5%. This means that the 316LCF controlled ferrite SMAW electrode conforms to the AWS specification of 2.0-2.5%Mo E316L-16 [1], but not the EN specification E 19 12 3 L R [4] 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 [15].

5.3 Flux Type

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 coverings [11-13]. The data for standard 'general purpose' E316L-15/16/17 and E316L-16CF are plotted for comparison in Figure 3. It can be seen that the basic type, E316L-15, electrodes gave significantly higher impact energy for a given lateral expansion (apparently a larger effect than reported by previous workers). Consequently, Figure 3 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 3 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 commercially manufactured controlled ferrite electrodes utilised a rutile flux system (E316L-16CF in Figure 3) to take advantage of the best operability and welder appeal.

6. Flux Cored Wires

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 308LCF and 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 316LCF flux cored wire conforms to the AWS specification E316LT1-4 [3] but not necessarily to the EN specification T 19 12 3 L P [6].

The wires are based on a rutile flux system suitable for all-positional pipe welding using standard Ar-20%CO_2 or 100%CO_2 shielding gas. The welding position and shielding gas have been shown to have very little influence on the Charpy properties of all-weld metal joints; this is shown in Table 4 where tests carried out on the same batch of wire are given.

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 4. The toughness data is plotted separately for 308L and 316L in Figures 5a and 5b showing individual Charpy energy versus lateral expansion values at -196°C (-320°F) for standard wires and controlled ferrite wires. The benefits of the controlled ferrite type wires is very evident, with all of the data for the controlled ferrite types exceeding 0.38mm (0.015inch) lateral expansion at -196°C (-320°F). As can be seen in Figure 5a, some of the results for standard 308L wires also reached the 0.38mm (0.015inch) lateral expansion requirement, but none except the 308LCF achieved 32J (24ft-lb) or 40J/cm^2. With the 316L flux cored wires the only results which meet the 0.38mm (0.015inch) requirement are those for the controlled ferrite wire.

7. Weld Procedure

The mechanical properties of austenitic stainless steel welds are not generally considered to be affected by welding procedure. However, a series of three submerged arc welds was produced with heat inputs from 1.0 up to 2.7KJ/mm and these showed an increase in toughness with increasing heat input, Table 5. The improvement in Charpy properties with increasing heat input and reduced number of weld runs has been reported previously [16]. 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. 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. 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 shown above. Higher flux basicity will support chromium transfer and thus higher ferrite but cleaner weld metal than more acid fluxes, and either approach probably has its protagonists.

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 6. This could again 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 or number of weld runs, see results in Table 4.

8. Applications

Numerous successful weld procedures have been carried out with the controlled ferrite SMAW electrodes, and many tonnes of electrodes have been used on projects all round the world. Most of the projects for which these electrodes were used were pipelines and process pipework; some examples are given here.

The controlled ferrite UM316LCF SMAW electrode was originally designed over 12 years ago 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 for nearly twelve years. 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 Figure 7. This procedure is for an ASME 6G / EN H-L045 joint in 200mm (8inch) diameter 23mm (0.9inch) wall thickness pipe completed with GTAW and SMAW.

More recently tonnage quantities of the controlled ferrite SMAW consumables have been used in Kazakhstan on the Karachaganak Project where the contractors were 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 contractors were 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.

The first commercial use of the flux cored wire was for the Isle of Grain LNG project in the UK, which also used the SMAW electrode. The SC308LCF controlled ferrite flux cored wire was used in conjunction with the STT GMAW process for the fabrication of a three mile long pipeline in 915mm (36inch) diameter, 10mm (0.4inch) wall thickness, 304 stainless steel. The STT process, utilising ER308LSi solid wire, was used for the root run and the controlled ferrite flux cored wire for the filling and capping runs.

9. Conclusions

The data presented show that with appropriate controls it is possible to achieve good mechanical properties, particularly Charpy toughness, at -196°C (-320°F) using 308L and 316L welding consumables conforming to the relevant AWS-ASME specifications, and without resorting to fully austenitic weld metal.
For the gas shielded processes, GTAW and GMAW, standard ER308L/ER316L wires can achieve the commonly specified requirement of 0.38mm (0.015inch) lateral expansion at -196°C (-320°F).
For flux shielded processes, SMAW and FCAW, controls have to be imposed to meet 0.38mm (0.015inch) lateral expansion at -196°C (-320°F).

Data is presented showing that when 308L/316L SMAW and FCAW consumables with rutile flux systems are made within controlled limits (particularly ferrite) they will meet the specified toughness requirement.

Although most of the results presented are from all-weld metal tests, the successful use of the controlled ferrite (CF) SMAW and FCAW consumables is demonstrated by examples of some applications and projects for which they have been used.

References:

[1] AWS A5.4-92 “Specification for stainless steel electrodes for shielded metal arc welding”.

[2] AWS A5.9-93 “Specification for bare stainless steel welding electrodes and rods”.

[3] AWS A5.22-95 “Specification for stainless steel electrodes for flux cored arc welding and stainless steel flux cored rods for gas tungsten arc welding”.

[4] BS EN 1600 -1997 “Welding consumables – Covered electrodes for manual metal arc welding of stainless and heat resisting steels – Classification”.

[5] BS EN 12072-2000 “Welding consumables – Wire electrodes, wires and rods for arc welding of stainless and heat-resisting steels – Classification”.

[6] BS EN 12073-2000 “Welding consumables – Tubular cored electrodes for metal arc welding with or without a gas shield of stainless and heat-resisting steels – Classification”.

[7] International piping code ASME B31.3 - Process piping.

[8] VdTÜV Information Sheet “Guidelines on suitability testing of welding filler metals” Welding engineering document 1153, 1980.

[9] ASME III, Division 1, Subsection NB “Rules for construction of nuclear power plant components” paragraph NB-2433.2.

[10] API recommended practice 582 “Welding guidelines for the chemical, oil and gas industries” first edition, March 2001.

[11] Siewart, T A “Predicting the toughness of SMA austenitic stainless steel welds at 77K” Weld. J, March 1986, p23-28.

[12] Szumachowski, E R & Reid, H F “Cryogenic toughness of SMA austenitic stainless steel weld metal: Part I – Role of ferrite” Weld. J, 57 (11), Nov 1978, Research Supplement p325s-333s.

[13] 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, Research Supplement p34s-44s.

[14] Kujanpää, V P “Solidification cracking – estimation of the susceptibility of austenitic and austenitic-ferritic stainless steel welds” Met. Construction, 1980, June, p282-285.

[15] Marshall, A W & Farrar, J C M “Lean austenitic type 16.8.2 stainless steel weld metal” Stainless Steel World Conference 2001, The Hague, 13-15th Nov 2001, p216-222.

[16] Karlsson, L et al “Low temperature properties of weld metals for cryogenic applications” International Conference on Applications of stainless steel, 9-11th June 1992, Stockholm, Sweden.

Tables

Gas	Liquefaction Temperature, °C (°F)	
Ammonia	-33 (-27)	
Propane	-45 (-49)	LPG
CO_2	-78 (-108)	
Acetylene	-84 (-119)	
Ethane	-88 (-126)	
Ethylene	-104 (-155)	LEG
Methane	-163 (-261)	LNG
Oxygen	-183 (-297)	
Argon	-186 (-303)	
Nitrogen	-196(-320)	
Hydrogen	-253 (-423)	
Helium	-269 (-452)	

Table 1: Liquefaction temperatures for various gases

Temp *°C (°F)*	*Alloy*	*GTAW/GMAW*	*SMAW*	*FCAW*
-50 (-58)	1%Ni	ER80S-Ni1	E8018-C3	E81T1-Ni1
-60 (-76)	2%Ni	ER80S-Ni2	E8018-C1	-
-75 (-103)	3%Ni	ER80S-Ni2/Ni3	E8018-C2	-
-101 (-150)	3/5%Ni	ERNiCr-3	ENiCrFe-2/3	-
-196 (-320)	9%Ni	ERNiCrMo-3/4	ENiCrMo-6	-
-196 (-320)	304L/316L	ER308L/ER316L	Modified E308L-16/E316L-16	Modified E308LT1-4/E316LT1-4
-269 (-452)	304L/316L	EN: E 20 16 3 Mn L	EN: E 18 15 3 LR	EN: T 18 16 5 NLR

Table 2: Low temperature alloys and associated welding consumables

	GTAW	**GMAW**
Consumable	ER316L (W 19 12 3 L)	ER316LSi (G 19 12 3 L Si)
Shielding gas	Ar	Ar-2%CO_2
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)

Table 3: Representative mechanical properties from all-weld metal joints using the gas shielded processes and 316L wire

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)

Table 4: Effect of welding position and shielding gas on the impact properties of SC308LCF controlled ferrite flux cored wire at -196°C (-320°F).

*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.*

Table 5: Effect of heat input/number of runs on impact properties of 316L sub-arc welds produced with the same wire and flux in 22mm (0.9inch) thick plate.

Figures

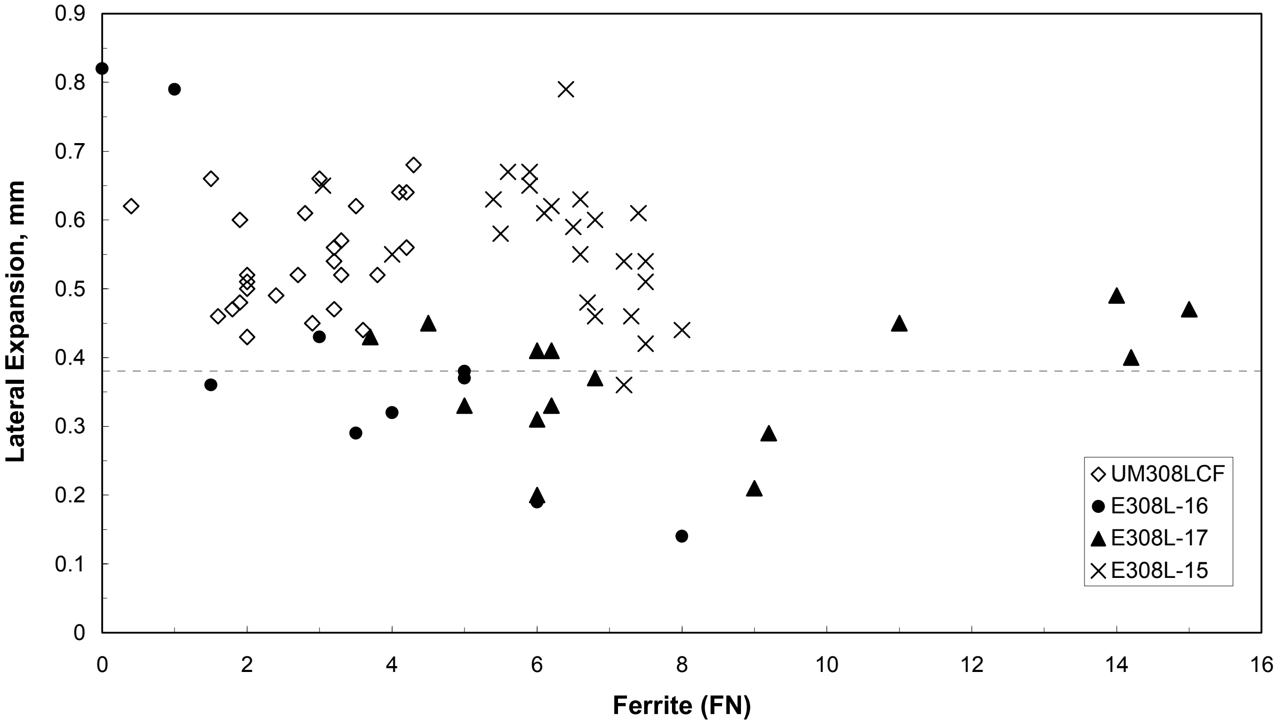


Figure 1: Weld metal ferrite versus lateral expansion for 308L SMAW electrodes at –196°C (-320°F)

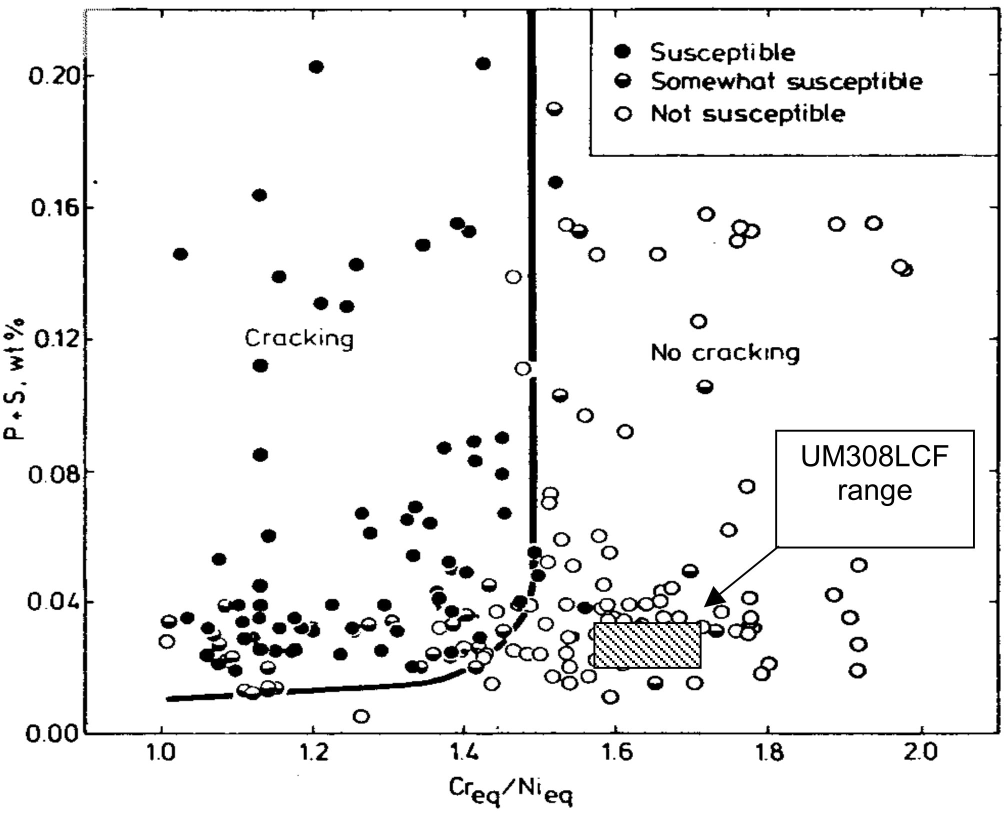


Figure 2: Suutala diagram [14] with the UM308LCF SMAW electrode composition range superimposed.

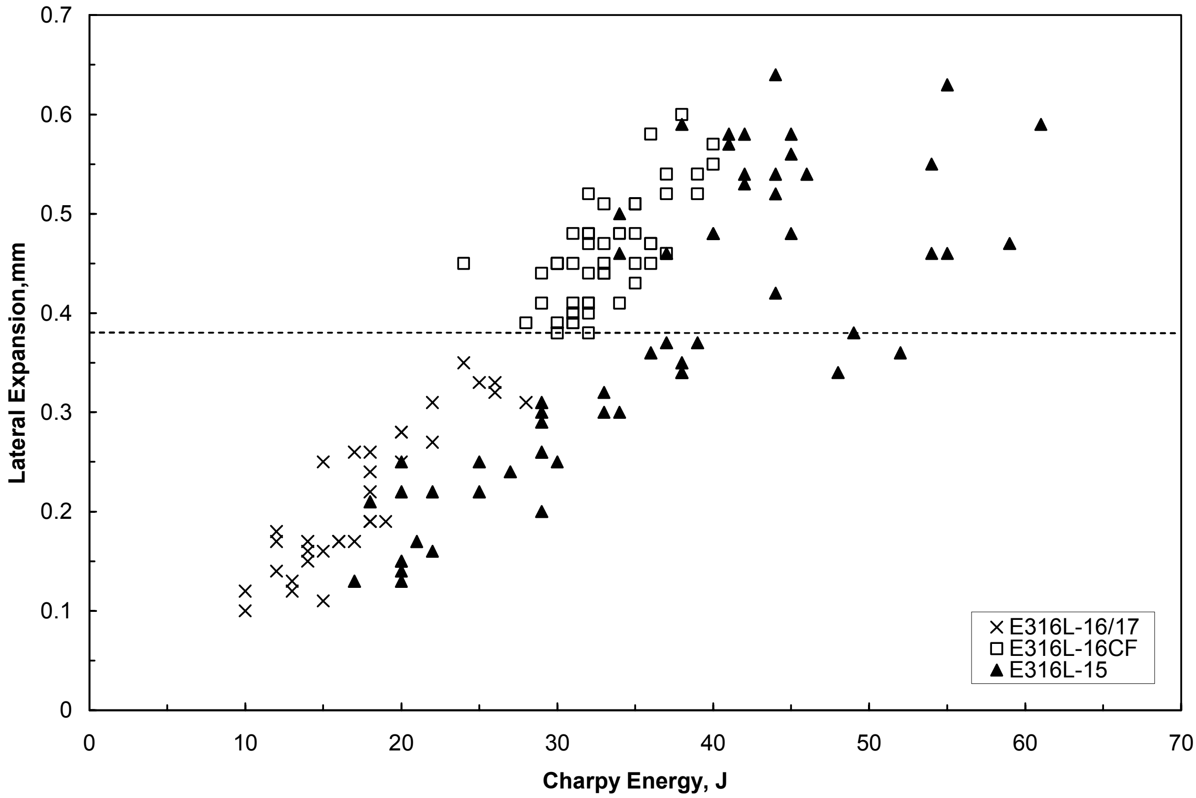


Figure 3: All-weld metal -196°C (-320°F) impact properties for 316L SMAW electrodes showing the effect of different coating types. (Data plotted are for individual Charpy specimens).

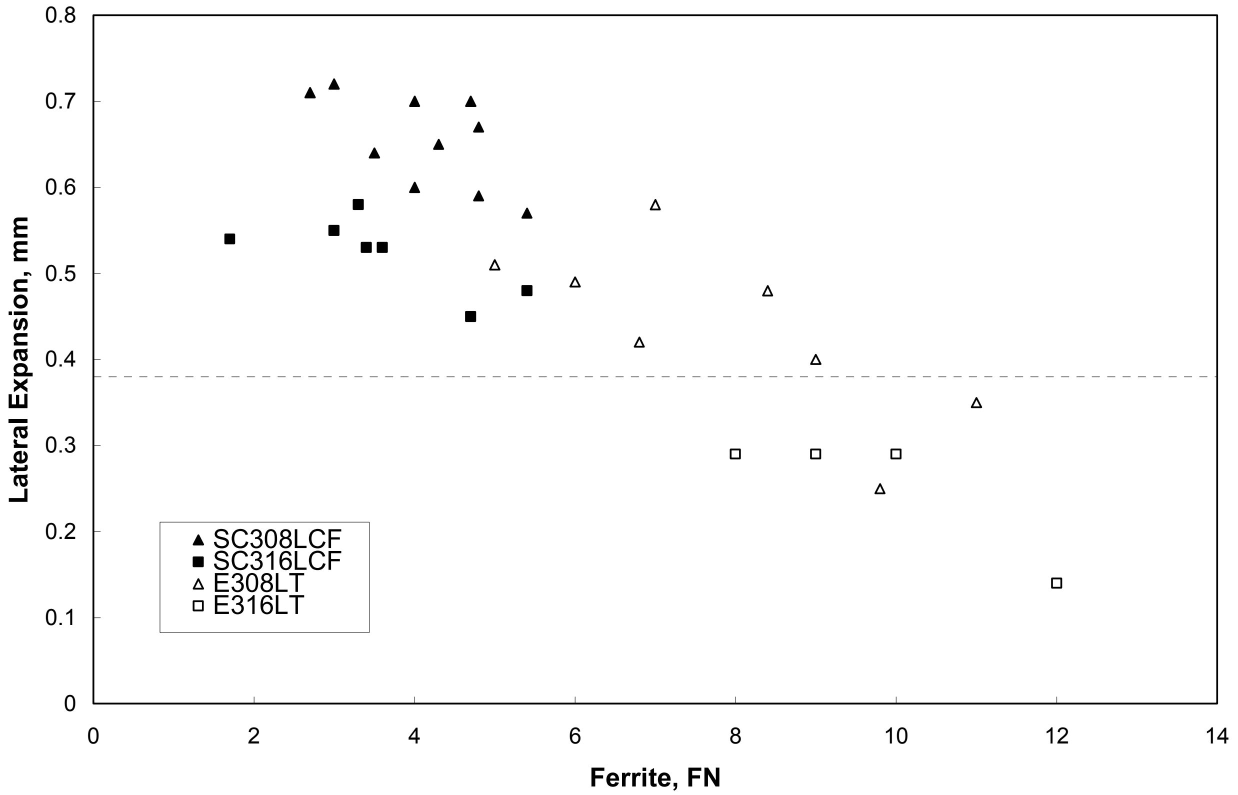
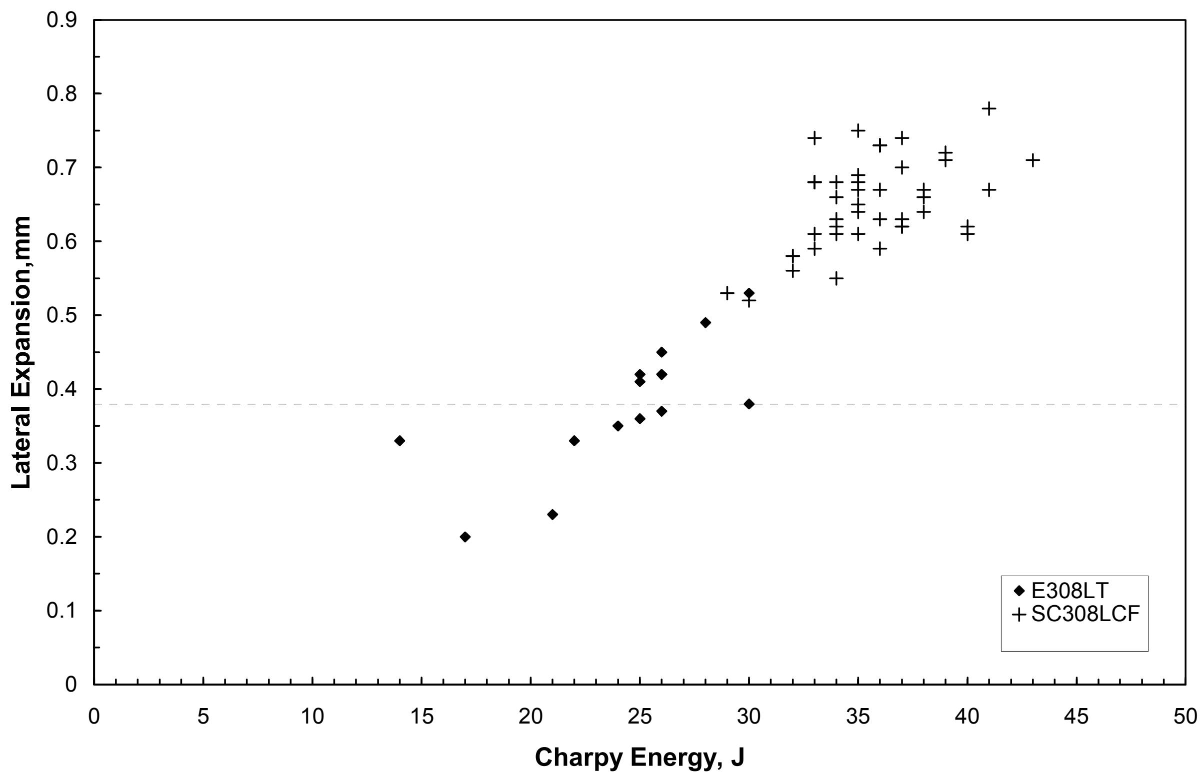
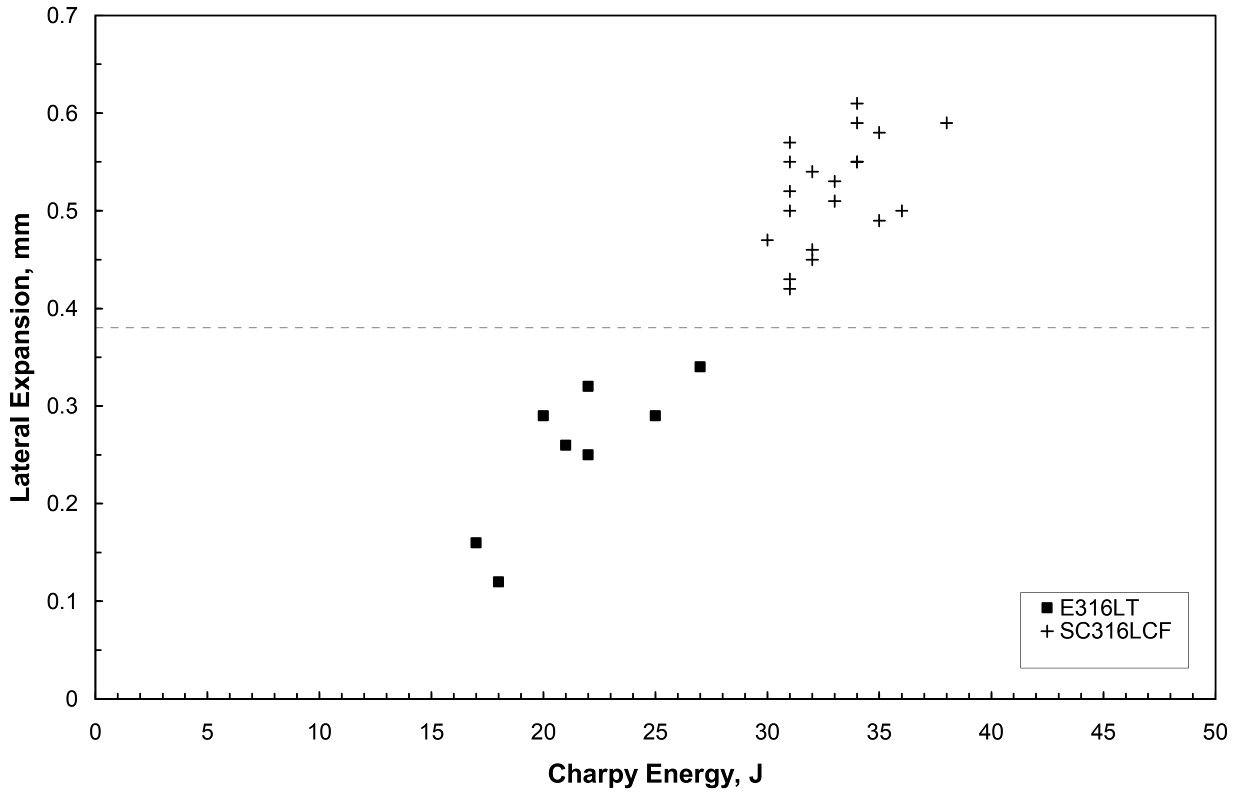


Figure 4: Effect of weld metal ferrite on lateral expansion at -196°C (-320°F) for flux cored wires. (Data plotted are based on average lateral expansion from a set of Charpy's).



(a)



(b)

Figure 5: All-weld metal impact properties for flux cored wire deposits at -196°C (-320°F): (a) E308LT (b) E316LT. (Data plotted are for individual Charpy specimens).

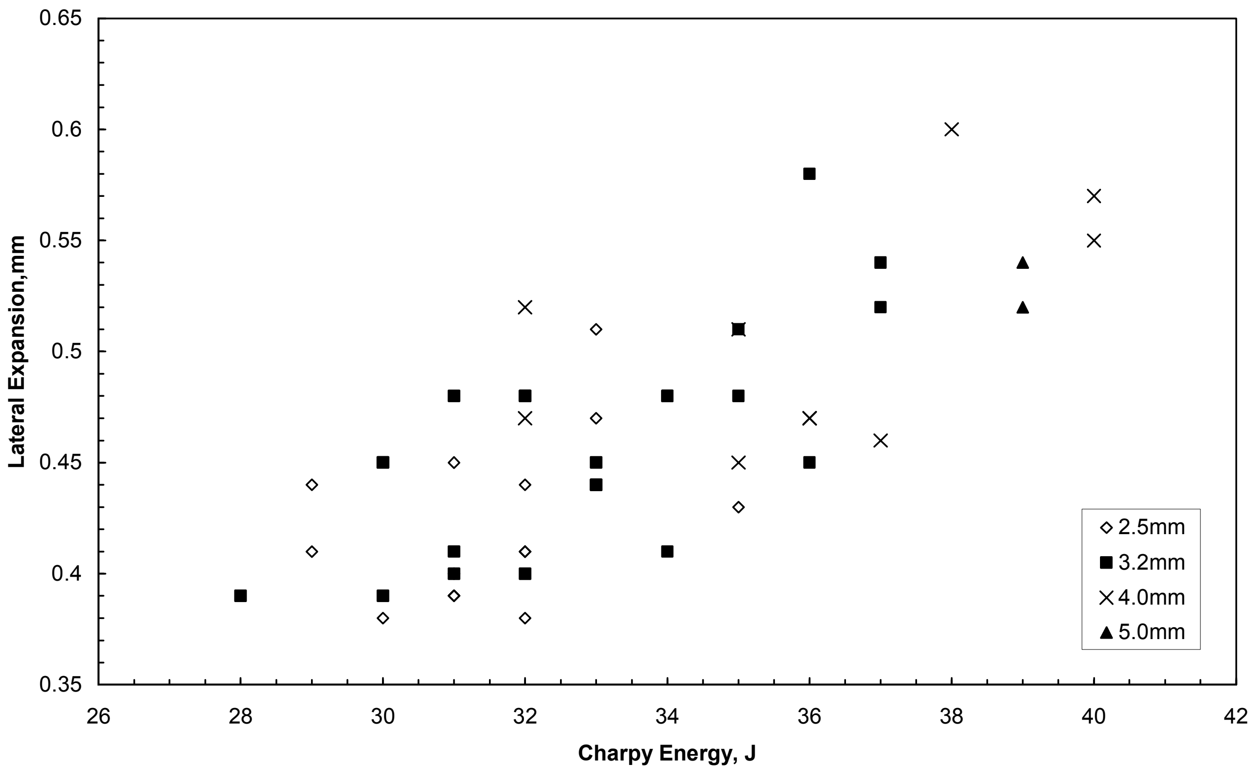
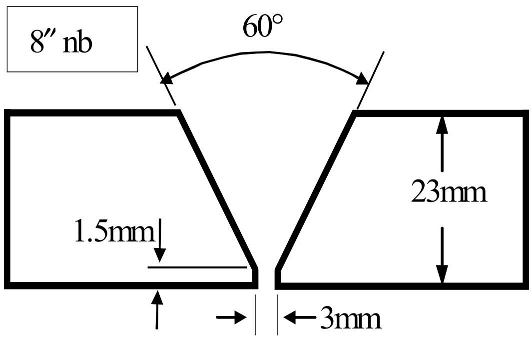


Figure 6: All-weld metal impact energy versus lateral expansion at –196°C (-320°F) for UM316LCF SMAW electrodes. (Data plotted is for individual Charpy specimens).

Weld Procedure Record

Material	ASTM A312 type 316L pipe 8 inch Schedule 160		
Filler Metal	**316S92 / Ultramet 316LCF**		
Classification	ER316L / E316L-16		
Process	GTAW / SMAW	**Gas Shield**	Ar
Current	DC- / DC+	**Position**	6G
Preheat / Interpass Temperature	15/150°C		
PWHT	None		

Weld Details



Run No	ø mm	Current Amp	Arc Volts	Travel Speed mm/min	Heat Input kJ/mm
1	2.4	90	10	50	1.3
2-4	2.5	60	23	75	1.0
Rem	3.2	80	24	80	0.9

Procedural Comments

Argon gas shield:

Torch 10 l/min

Purge 15 l/min

Analysis	C	Mn	Si	S	P	Cr	Ni	Mo	Nb	Cu	FN
SMAW 2.5mm	0.021	0.7	0.6	0.014	0.026	17.1	12.2	2.2	0.01	0.11	2
SMAW 3.2mm	0.023	0.7	0.6	0.013	0.026	17.2	12.0	2.1	0.01	0.11	3

Tensile (transverse)	Ferrite Ferritescope
526MPa 554MPa Failed in pipe.	Cap 2.3% Mid 3.8% Root 2.7%

Charpy -196°C	Cap J	Cap mm	Root J	Root mm
Weld	58	0.48	38	0.48
	55	0.46	35	0.48
	56	0.62	37	0.56
FL	70	1.18	65	1.17
	60	0.76	70	1.04
	74	0.90	92	0.99
FL + 2mm	186	1.64	138	1.52
	180	1.72	160	1.67
	150	1.99	180	1.85
FL + 5mm	296	2.81	298	2.47
	298	2.73	298	2.83
	298	2.83	298	2.66

Hardness HV (10)	PM	HAZ	Weld Metal	HAZ	PM
Cap	176	204	205-225	190	171
Root	197	225	215-235	233	193

Figure 7: Weld procedure, using 316LCF electrodes, from the SAGE project.