Lean austenitic type 16.8.2 stainless steel weld metal

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Abstract
The so-called 'lean 316' (type 16.8.2) weld metals have been available for more than 40 years, but their characteristics and virtues appear to have been either overlooked or neglected. They display an unusual combination of properties, including excellent high temperature microstructural stability, impressive resistance to hot cracking at very low ferrite (FN) levels, and very good cryogenic toughness. Thus in principle a single composition may offer robust structural properties from -196 °C to 800 °C.

This paper reviews the weld metal compositions and consumable product forms available and presents new data on thermal stability. Useful information on cryogenic toughness and hot cracking resistance is assessed, along with high temperature properties which are relevant to applications in the power generation, petrochemical and process engineering industries. Finally, the use of 16.8.2 weld metal in elevated temperature dissimilar welds is described.

1. Introduction

This paper reviews the unusual combination of properties found in nominally 16Cr-8Ni-2Mo weld metals. These properties include excellent high temperature microstructural stability, high resistance to hot cracking at very low ferrite (FN) levels, and good cryogenic toughness. Some of these characteristics and virtues appear to be largely overlooked or neglected. It is worth noting that no reference to 16.8.2 weld metal appears in Folkard's standard text on the welding metallurgy of stainless steels.[1]

Table 1 gives the AWS and recently introduced EN specification limits for SMAW (MMA) weld metal and the solid wire composition used for the GTAW/GMAW/SAW processes. These are almost equivalent except for the inexplicably higher minimum molybdenum in EN1600. For historical completeness, the specification limits are also included for the related type 17.8.2 in BS 2926, where the overall alloying level, particularly chromium, is somewhat higher. However, it is common practice to generically describe all the types listed as "lean 316 alloys".

2. Microstructure

The first published reference to 16.8.2 in 1956 describes the development by The Babcock and Wilcox Company of an electrode depositing weld metal with about 0.07C-15.6Cr-8.2Ni-1.5Mo. [2] On the Schaeffler diagram this composition was shown to be centred around the austenite 'nose' at the confluence of the Austenite + Martensite (A+M) and Austenite + Ferrite (A+F) boundaries. This area is shown on the Espy modified diagram, Figure 1, assuming 0.04-0.1 %C and constant values of 0.5 %Si-1.5 %Mn-0.05 %N. In addition to austenite, with perhaps up to 10 % ferrite, a significant region shows that martensite may be expected in the as-deposited weld metal.

However, the appendices to AWS A5.4 and A5.9 state that 16.8.2 weld metal will typically show below 5FN, and there seems to be no evidence that commercial weld metals contain martensite, although it is recognised that lean austenitic compositions will be susceptible to strain-induced martensite. Recently, these leaner compositions have been studied thoroughly by Kotecki [3] using plain Cr-Ni alloys. Kotecki's work explains the observed martensite-free microstructure of 16.8.2 and corrects the misleading predictions of previous constitution diagrams.

Figure 2 places the Figure 1 composition area for 16.8.2 (box 1) on the modified WRC diagram with Kotecki's martensite boundary zone for welds with around 1 %Mn. The lower boundary to this zone, corresponding closely to the appearance of as-deposited martensite, is touched only by the leanest corner of 16.8.2. Below this zone all 2T bend tests fail, confirming the presence of as-deposited martensite. Within the zone, bend test failures may occur because of excessive strain-induced martensite. It is clear that a deliberate level of C+N is important for controlling the WRC Nieq and the position of the leanest corner of the 16.8.2 composition box.

Very few weld metals of 16.8.2 type were included in the original WRC ferrite database and consequently the current WRC-1992 diagram cuts off at 17Creq, although Figure 2 shows that the 16.8.2 specification range extends down to 15.5Creq. Fortunately, extension of the WRC iso-ferrite lines provides satisfactory agreement between prediction and measurement, and the ferrite lines are shown extended to Kotecki's martensite boundary in Figure 2.

2.1 Heat treatment and martensite formation

The lean composition and low ferrite typically found in 16.8.2 type weld metals provide excellent microstructural stability and ductility retention for service at elevated temperature [4,5] or after stress relief PWHT. In a recent case, ferrite stability was assessed for TIG ER16.8.2, ER316H and SMAW E17.8.2 weld metal pads by exposure at 750 °C for up to 5h. Under these conditions, initial ferrite usually declines with transformation to austenite plus chromium carbides ($M_{23}C_6$), often followed by (non-magnetic) intermetallics such as sigma or chi-phase.[1,4]

Figure 3 shows the results of these tests in terms of magnetic response FN (by Magne-Gage) and compositions are given in Table 2, items A, B and C. As expected because of its high Cr and Mo content, ferrite in ER316H declined significantly and quite rapidly, followed by the leaner E17.8.2 with a smaller shift. In contrast, the apparent FN for ER16.8.2 progressively increased with exposure time at 750 °C, reaching a plateau of around 17FN after 5h at temperature.

The explanation for this unexpected behaviour is that carbide precipitation during PWHT has destabilised a proportion of the prior austenite, raising its Ms temperature and leading to some martensite transformation on cool-out to ambient. This is illustrated schematically on Figure 2 where the area marked 2 is "carbon-free" 16.8.2, shifted down towards the martensitic zone and to the left as a result of $M_{23}C_6$ removing Cr from the austenitic matrix.

A few subsequent experiments have shown that this behaviour is quite sensitive to relatively small differences in composition, and that further transformation could be obtained by additional cooling in a domestic refrigerator. For example, composition D in Table 2 gave 0.6FN (by Feritscope) in the as-welded condition, 0.3FN after PWHT 750 °C/1h and 0.6FN after refrigeration, whereas a repeat test on composition C gave 4.0FN, 4.8FN and 14.9FN respectively. Comparison of these two compositions shows that the less stable alloy C has lower WRC Nieq and a particularly low level of nitrogen. In this respect, alloy C is probably unusual. However, the SAW composition E has intermediate Nieq and this showed an increase from 1FN to 3.7FN after 750 °C/5h. Others who have worked with 16.8.2 may be familiar with this effect of PWHT (or high temperature service), but no published reports have been found. The high alloy martensite will have a low Ac1 and reversion to austenite is likely at high service temperatures, which are typically above 540 °C. The extent to which this austenite might be strengthened by a higher dislocation density inherited from the prior martensite is not known. In a detailed structural study of a GTAW ER16-8-2 weldment[6] which had been solution annealed at 1060 °C/30min then cold-straightened, no martensite was reported (nor was it sought). A higher than expected dislocation density was ascribed to the effect of cold work, but this substructural feature largely persisted after re-annealing. Ferrite level was also remarkably stable, since WRC 2FN can be calculated from the given analysis and 2 % ferrite (by QTM) survived two annealing cycles at 1060 °C. Another study [7] examined the effect of PWHT, including 800 °C/10h, on the elastic, tensile and creep anisotropy of 17.8.2 weld metal equivalent to composition B in Table 2. As in other studies of this alloy, no martensite was reported. However, with respect to all cases where some martensite might be anticipated, it must be noted that conventional optical metallography will not reveal its presence. Either special etching techniques [3] or comparative magnetic response studies are required.

2.2 Ferrite and hot cracking

The presence of ferrite, determined at room temperature, is conventionally considered to be desirable or necessary for satisfactory resistance to hot cracking in nominally austenitic weld metals. Type 16.8.2 is unusual in that hot cracking is not reported in typical commercial compositions, even though these contain little or no measured or calculated ferrite.

Using the fissure bend test, Lundin et al [8,9] found trivial microfissuring (4 microfissures in total) in two of twelve tests on two commercial batches of E16-8-2-16 with 0.7 and 1.2FN, and unlike the other standard austenitic types investigated the onset and extent of hot cracking could not be plotted against FN, see Figure 4. The accepted explanation for this is evident with reference to the WRC diagram which shows that the desirable FA primary ferritic solidification mode boundary intersects low FN levels in compositions with low Creq values. (The fissure bend test also involves bending the test pieces to 120°, and noticeably more strain-induced martensite was found by magnetic response in the E16-8-2 welds than the others.)

The hot cracking resistance of 16.8.2 may be even more robust than is apparent from the WRC diagram. The Suutala diagram [10], Figure 5, is based on coefficients for the influence of alloying on solidification mode, derived by Hammer and Svensson[11]. It shows a dramatic improvement in resistance to hot cracking at the transition to primary ferritic FA solidification at a Creq:Nieq ratio above about 1.5. The 16.8.2 compositions evaluated by Lundin et al have Creq:Nieq ratios of 1.73 and 1.67 (assuming 0.06 %N), which places them well into the 'safe' region, whereas the WRC diagram places them close to the austenite boundary and correctly predicts <1FN at room temperature. If these compositions were pushed to the Suutala Creq:Nieq=1.5 limit (eg by raising Ni), the equivalent WRC Nieq values would be about 0.5Nieq above the austenite boundary.

Clearly, further work to explore the hot cracking behaviour of these lean austenitics would be fruitful. However, the robust character of 16.8.2 weld metal is now accepted by the ASME Code Section III [12] (nuclear Class 1 components). Ferrite determination is not required for type 16-8-2 welding materials, whereas >5FN is required for all 308/316 types used up to 427 °C design temperature and 3-10FN above 427 °C.

3. Other Useful Properties

3.1 Cryogenic temperatures

The cryogenic properties of austenitic SMAW weld metals in relation to ferrite content were reported in detail by Szumachowski and Reid over 20 years ago. [13] These tests were interesting in that E16-8-2 types were included, and the performance of these leaner weld metals appeared superior to many others, especially when considering the requirement to meet a minimum charpy lateral expansion of 0.38mm (15mils in customary US units) at –196 °C. In particular, 16.8.2 types were less sensitive to the generally detrimental effect of ferrite on toughness and all the E16-8-2-15 variants with up to 10FN and no added nitrogen met requirements. At the same time, all the 16.8.2 welds had 0.04-0.055 %C, typical of commercial products designed for high temperature applications, while none of the other weld metals with ferrite and above 0.04 %C met the lateral expansion criterion. It is also known, but not reported by these authors, that 16.8.2 charpy specimens when fractured at –196 °C become noticeably ferro-magnetic as a consequence of strain-induced (or low temperature transformed) martensite being present. Evidently some martensite formation is not detrimental to fracture properties and possibly contributes transformation-induced plasticity to these welds.

The distinctive impact properties at –196 °C of SAW ER16.8.2 (Table 2, composition E) are shown compared with various batches of SAW ER308L and ER316L in Figure 6. The WRC-predicted ferrite based on analysis was 1FN and measured ferrite was 1.1FN (mid-section of weld) and 1.6FN (final bead). After PWHT at 750 °C/5h, the same weld still gave 26J and 0.52 mm lateral expansion at –101 °C, which confirms a remarkably high resistance to thermal embrittlement, despite some martensite formation coupled with carbide precipitation as described earlier.

The gas-shielded FCAW process provides another example. There is currently no national standard specification for FCAW consumables of 16.8.2 type, although they are available and also recognised by the ASME Code Section III [12] as "EXXXT-G (16-8-2 chemistry)". The data shown in Figure 7 are for normal batches not optimised for cryogenic applications, but the intrinsically superior toughness of 16.8.2 (composition F, Table 2) is obvious. Comparable FCAW properties are obtained in 316L only in fully austenitic compositions specially modified to suppress hot cracking (E316LMnT in Fig 7).

In view of the useful cryogenic properties of 16.8.2, which arise from its relative safety at intrinsically low FN levels coupled with low microsegregation and embrittlement tendency, it is surprising that no reference to its use in cryogenic applications is given in a recent review [14] or in the appendices to AWS A5.4 and A5.9. Some general guidance is given in the appendix to AWS A5.4, clauses A9.8 to A9.12.

3.2 Elevated temperature and dissimilar welds

The customary applications of 16.8.2 are for elevated temperature service, originally [2] for thick section 347H where the low stress-rupture ductility, hot cracking and in-service HAZ relaxation cracking susceptibility are aggravated by the use of matching weld metal. [2,15,16] Today it is also sometimes specified for welding 304H, in preference to 308H weld metal [17], the presence of Mo being beneficial to creep rupture ductility [15] and the low Cr+Mo restricting formation of intermetallic phases. [1,4] The ASME Code Section III [12] gives stress-rupture factors up to 650 °C for welds in 304 and 316 using 16-8-2, including the FCAW process as noted above. Under most conditions and especially at higher temperature and longer duration, type 16-8-2 has been allocated higher stress-rupture factors than 308/316 weld metals.

A thorough assessment of SMAW E16-8-2-15 welds compared with E316H for welding 316H steels has recently been presented [18] and this supports the ASME tables. All-weld metal stress-rupture data for FCAW 16-8-2 (as composition F, Table 2) have also been presented recently [17] showing that minimum base material requirements were exceeded from 650 °C up to 816 °C. This gives confidence in extending useful properties well beyond 650 °C which is important for welds in 304H used in the petrochemical processing industry.

Strictly, these are dissimilar metal welds (equivalent base material, ASTM 16-8-2, exists but does not seem to be encountered). However a more radical use of 16.8.2 for welding dissimilar materials has been presented. [19] Type 16.8.2 was chosen and successfully evaluated for welding 304 to an alloy 800 transition piece between stainless type 304 and P22 (2Cr-1Mo), see Figure 8. This was chosen on the basis of its intermediate coefficient of thermal expansion, although the presumed value is a little difficult to reconcile with the data presented by Elmer et al. [20] In Y-groove tests, and in spite of dilution effects from alloy 800 with over 30 %Ni, the microfissuring resistance of 16.8.2 was found to be slightly superior to type 182 nickel base weld metal traditionally used, although both were satisfactory.

4. Summary

The 'lean 316' or 16-8-2 family of weld metals have an unusual combination of properties which warrant further investigation and wider exploitation by industry. Corrosion performance has not been considered in this review, but structural applications range from -196 °C up to around 800 °C.

The microstructure of the weld metals consists of austenite with a small proportion of ferrite. There is no evidence of martensite in as-deposited weld metals but many compositions lie close to the martensite boundary with the resultant possibility of strain-induced martensite being formed under certain conditions.

The combination of lean composition and low ferrite lead to excellent microstructural stability and ductility retention after prolonged PWHT or elevated temperature service. There is evidence that in the leanest compositions carbide precipitation during PWHT raises the Ms temperature and leads to some martensite transformation on cooling.

The resistance to hot cracking is excellent and, even at very low ferrite levels (<2FN), virtually no fissuring is found in fissure bend tests and performance is superior to other 300 series austenitic stainless steel weld metals. This robust behaviour is now recognised by the ASME Code Section III which requires no minimum ferrite level for 16-8-2 weldments.

The cryogenic properties of the weld metal are better than most standard 316L and 308L types of weld metal, particularly so when lateral expansion rather than impact energy is used as the assessment criterion. Cryogenic toughness is retained after PWHT.

The expansion coefficient of 16-8-2 weld metal lies midway between that of alloy 800 and type 304 stainless, which offers the possibility of use as a transition joint between these two alloys. This is in addition to the more common application for the welding of thick section 347H, where the use of matching weld metal can lead to hot cracking, low stress-rupture ductility and in-service HAZ relaxation cracking. The use of 16-8-2 for welding 304 and 316 materials is now recognised by the ASME Code Section III, which allows higher stress-rupture factors for weldments than "matching" weld metals.

5. Acknowledgement

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Figures:

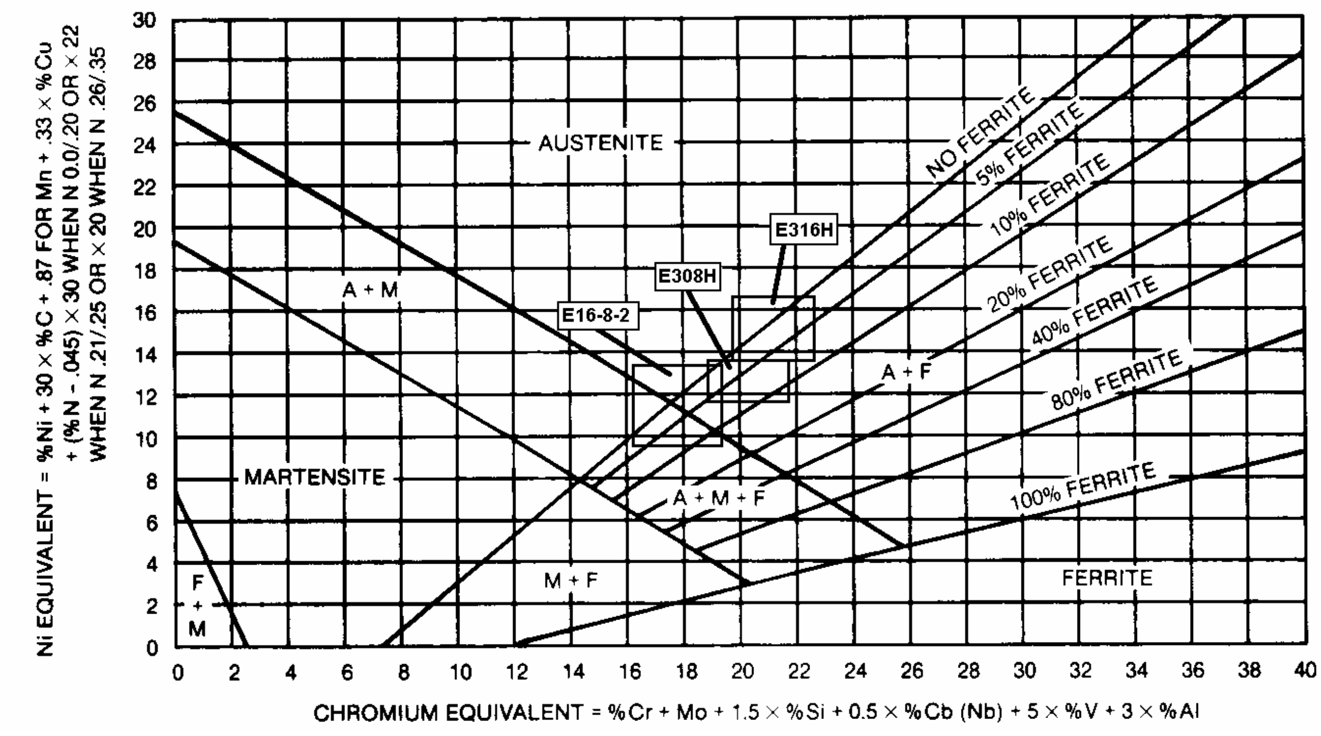

Figure 1: Espy diagram showing location of 16.8.2 with partially constrained composition limits (see text) and similarly constrained E308H and E316H

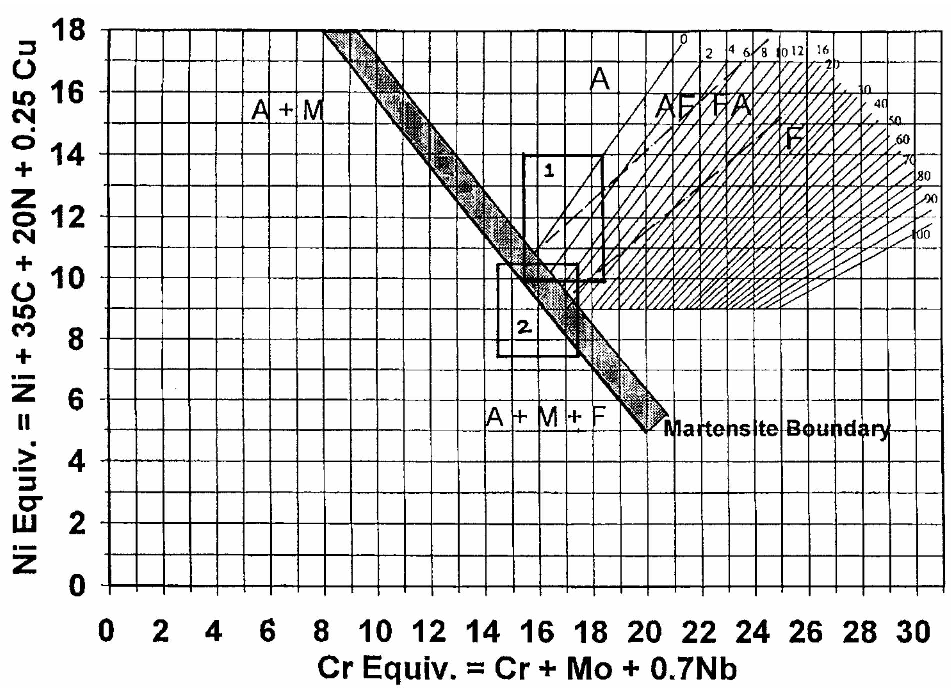

Figure 2: WRC diagram showing location of 16.8.2 weld metal (area 1) and the same with carbon and chromium removed from the matrix as $M_{23}C_6$ (area 2)

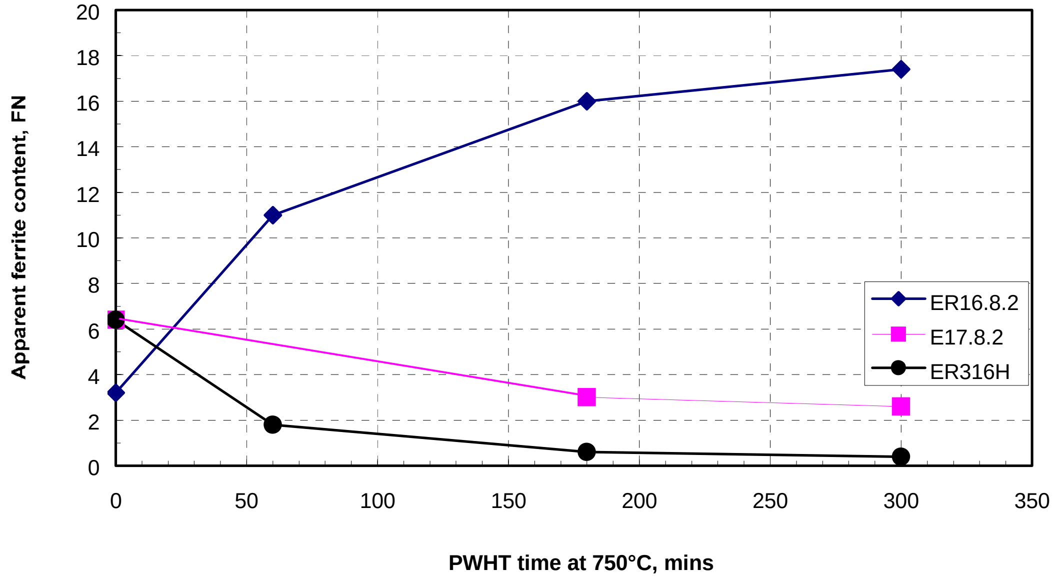

Figure 3: Effect of PWHT at 750 °C on weld metal ferrite (magnetic response) in GTAW ER16-8-2 compared with ER316H and SMAW 17.8.2

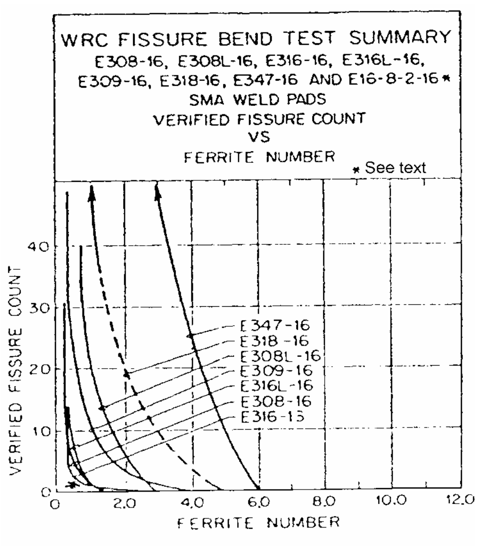

Figure 4: Comparison of the fissuring relationship for eight different austenitic stainless steel weld metals [8,9]
Note: E16-8-2-16 showed trivial fissuring and is therefore not plotted

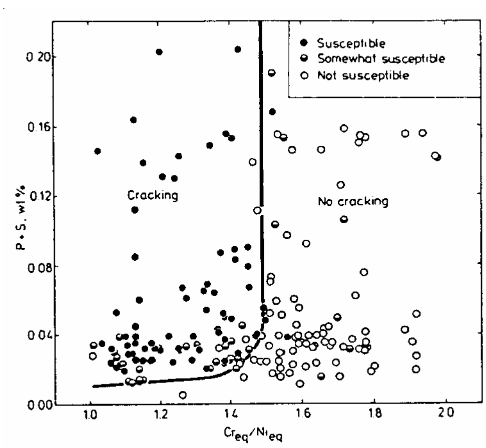

Figure 5: Suutala diagram [10] showing crack / no crack boundary at Creq:Nieq ratio of about 1.5
Creq = Cr + 1.5Si + 1.37Mo, Nieq = Ni + 0.31Mn + 22C + 14.2N

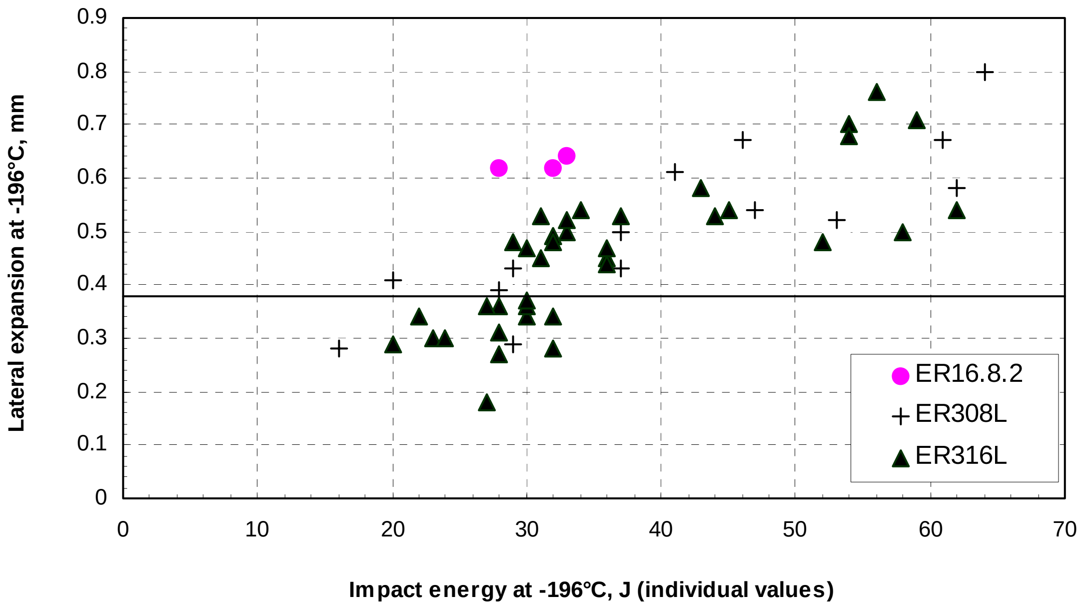

Figure 6: *Relationship between Charpy impact energy and lateral expansion of ER16.8.2, ER308L and ER316L SAW weld metals at –196 °C*

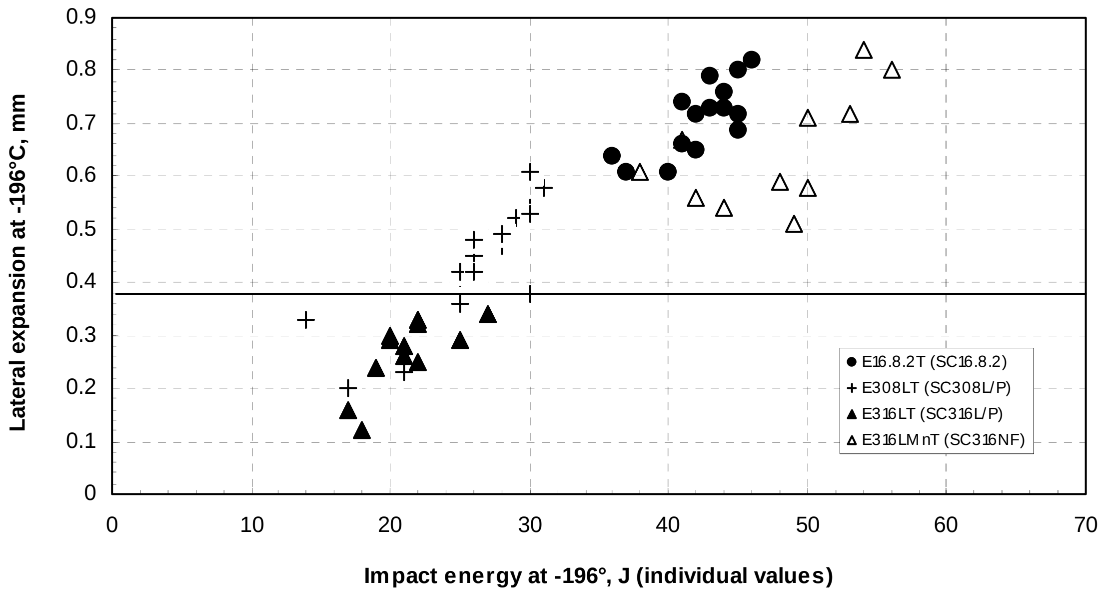

Figure 7: *Relationship between Charpy impact energy and lateral expansion of E16-8-2T, E308LT, E316LT and E316LMnT FCAW weld metals at –196 °C*

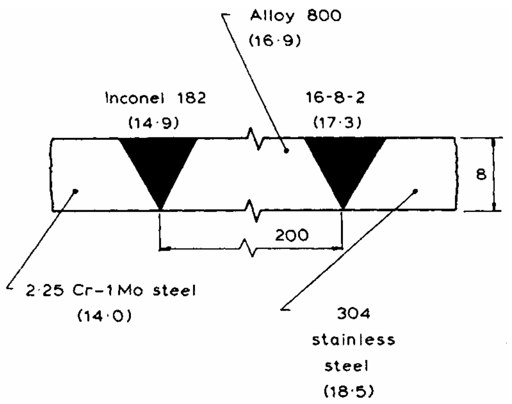

Figure 8: *Use of 16.8.2 weld metal for transition joint in protoype fast breeder reactor. Thermal expansion coefficients are shown in brackets [19]*

Tables:

	MMA E16.8.2 EN 1600	**Wire 16.8.2 EN12072**	**MMA E16-8-2 AWS A5.4**	**Wire E16-8-2 AWS A5.9**	**MMA 17.8.2 BS 2926**
C	< 0.08	< 0.10	< 0.10	< 0.10	0.06 – 0.10
Mn	< 2.5	1.0 – 2.5	0.5 – 2.5	1.0 – 2.0	0.5 – 2.5
Si	< 1.0	< 1.0	< 0.60	0.30 – 0.65	< 0.8
S	< 0.025	< 0.02	< 0.03	< 0.03	< 0.030
P	< 0.030	< 0.03	< 0.03	< 0.03	< 0.040
Cr	14.5 – 16.5	14.5 – 16.5	14.5 – 16.5	14.5 – 16.5	16.5 – 18.5
Ni	7.5 – 9.5	7.5 – 9.5	7.5 – 9.5	7.5 – 9.5	8.0 – 9.5
Mo	1.5 – 2.5	1.0 – 2.5	1.0 – 2.0	1.0 – 2.0	1.5 – 2.5
Cu	–	–	< 0.75	< 0.75	–

Table 1: Welding consumable specifications for 16.8.2 and related type 17.8.2

Batch	**Type**	**Process**	**C**	**Mn**	**Si**	**Cr**	**Ni**	**Mo**	**N**
A *	ER316H	GTAW	0.041	1.64	0.43	19.1	12.7	2.30	0.042
B *	E17.8.2	SMAW	0.071	1.79	0.22	17.4	8.6	2.13	0.072
C	ER16-8-2	GTAW	0.040	1.42	0.35	15.6	8.4	1.33	0.023
D	ER16-8-2	GTAW	0.050	1.43	0.44	15.6	8.8	1.21	0.048
E	ER16-8-2	SAW	0.050	0.89	0.77	15.4	8.4	1.16	0.047
F *	SC16-8-2	FCAW	0.045	1.17	0.53	16.1	8.9	1.13	0.050

* These are representative compositions, others are specific compositions studied.

Table 2: Weld deposit compositions for ER316H and 16-8-2 consumables referred to