THE USEFUL PROPERTIES OF LEAN AUSTENITIC TYPE 16.8.2 WELD METALS

by

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Abstract

Type 16.8.2 is the leanest of the austenitic stainless steel weld metal specifications. However, although welding consumables have been available for over 40 years, some of the alloy's unusual characteristics and virtues appear to have been either overlooked or neglected. Useful properties of this weld metal include excellent high temperature microstructural stability, impressive resistance to hot cracking at very low ferrite levels, and inherently good cryogenic toughness.

Consequently, a single composition may offer robust characteristics from –196°C up to around 800°C, for structural applications relevant to the petrochemical, process engineering and power generation industries.

This paper reviews consumable specifications and the available product forms, and illustrates how the special features of a lean composition provide high resistance to hot cracking and the possibility of unusual response to heat treatment. Useful information is presented on cryogenic toughness and stress-rupture properties. Finally, the reported use of 16.8.2 for an elevated temperature dissimilar metal weld 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 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 unexplained higher minimum molybdenum in EN1600. At present, there are no specifications for the FCAW process, although these consumables are available and also recognised by the ASME Code Section III [2] as "EXXXT-G (16-8-2 chemistry)". 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. These types as a group are often described as "lean 316 alloys".

Table 1: Welding consumable specifications

	MMA E16.8.2 EN 1600	Wire 16.8.2 EN12072	MMA E16-8-2 AWS A5.4	Wire ER16-8-2 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	–	< 0.3	< 0.75	< 0.75	–

2. Microstructure

The first published reference to 16.8.2 was in 1956 and 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.[3] The Schaeffler diagram shows that this composition is centred around the austenite 'nose' at the confluence of the Austenite + Martensite (A+M) and Austenite + Ferrite (A+F) boundaries. The composition box is shown on the Espy modified Schaeffler 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 area of the box shows that martensite may be expected in the as-deposited weld metal.

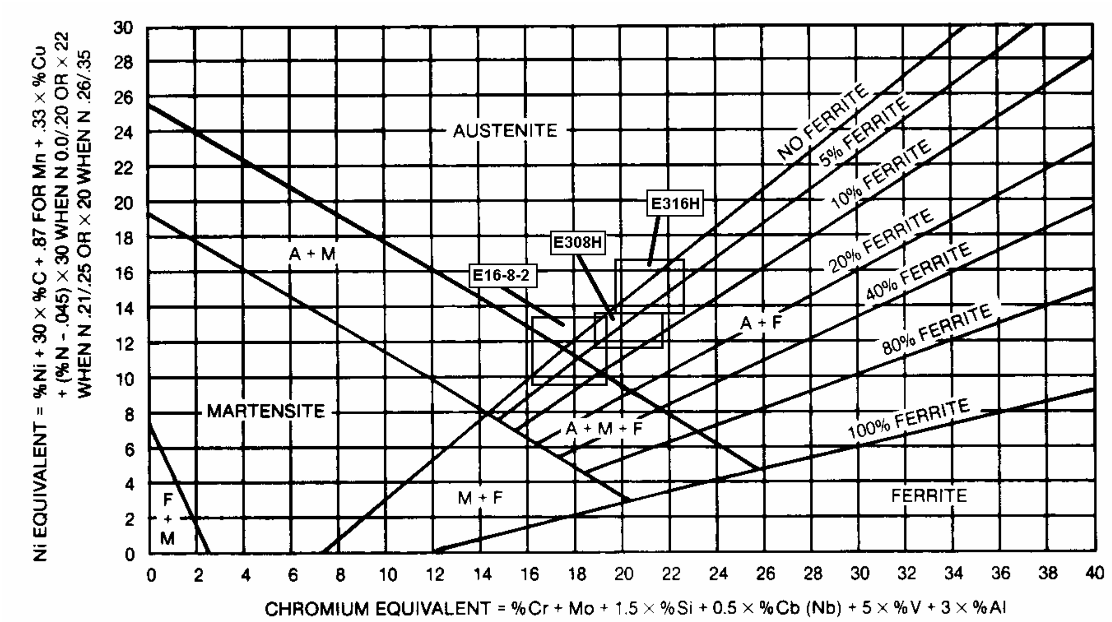

Figure 1: Espy diagram showing location of AWS E16.8.2 with partially constrained composition limits (see text) and similarly constrained E308H and E316H

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

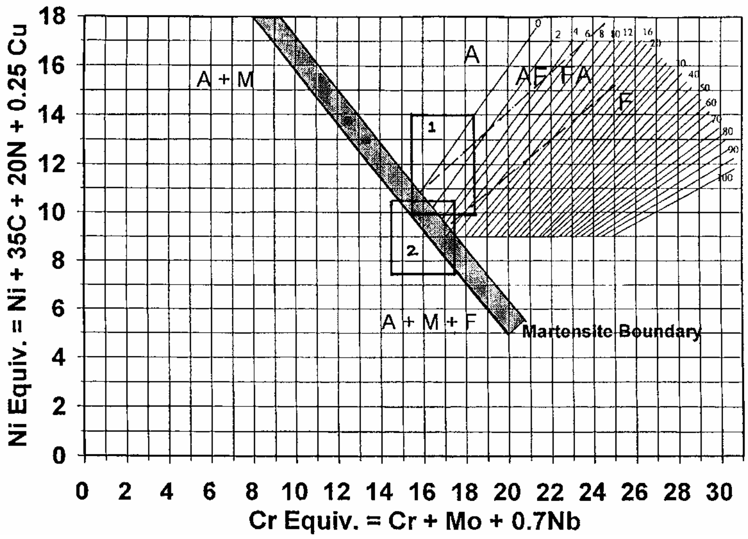

Figure 2: Modified WRC diagram showing location of 16.8.2 weld metal (box 1) and the same with carbon and chromium removed from the matrix as $M_{23}C_6$ (box 2)

In Figure 2, box 1 now locates the composition of E16.8.2 on the modified WRC-92 diagram with Kotecki's martensite boundary zone for welds with around 1%Mn (the boundary moves towards the left with higher %Mn). The lower boundary to this zone corresponds closely to the appearance of as-deposited martensite, and just touches the leanest corner of the 16.8.2 composition box. Below this zone, all 2T bend tests fail, owing to the presence of as-deposited martensite. Within the zone, bend test failures are possible because of excessive strain-induced martensite. The ‘constrained’ 16.8.2 composition box confirms practical experience that this weld metal has high ductility, but it is also clear that a deliberate level of C (and possibly N) is important in 16.8.2 for controlling the WRC Ni_{eq} and the proximity of compositions to the martensite boundary.

Note that very few weld metals of 16.8.2 type were included in the original WRC ferrite database and consequently the current WRC-92 diagram cuts off at $17Cr_{eq}$, although Figure 2 shows that the 16.8.2 specification range extends down to $15.5Cr_{eq}$. 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[6] for service at elevated temperature [7,8] or after stress relief PWHT. In a recent case, ferrite stability was assessed for GTAW ER16.8.2, ER316H and SMAW E17.8.2 weld metal deposits by exposure at 750°C for up to 5h. Under these conditions, the initial ferrite is expected to decrease as it transforms to austenite plus chromium carbides ($M_{23}C_6$). Depending on composition, this may be followed by (non-magnetic) intermetallics such as sigma or chi-phase.[1,7]

Figure 3 shows the results of these tests in terms of magnetic response FN (by Magne-Gage) and the 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.

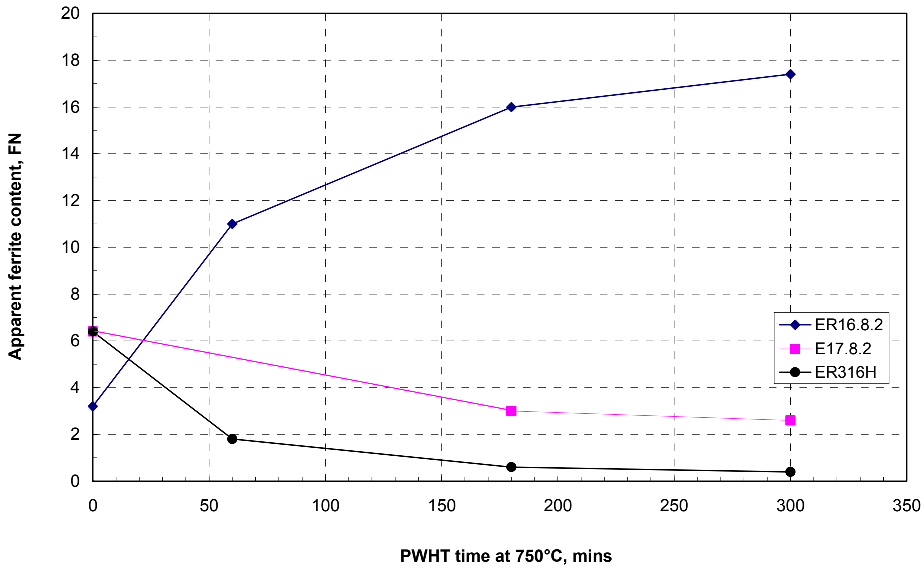

Figure 3: Effect of PWHT at 750°C on weld metal ferrite (magnetic response) in GTAW ER16-8-2 compared with ER316H and SMAW 17.8.2

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

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.

The explanation for this unexpected behaviour is that the chromium 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 the WRC diagram Figure 2, where the box marked 2 shows the effect of PWHT on box 1, which is shifted to the left and down towards the martensitic zone as a result of $Cr_{23}C_6$ removing carbon and chromium from the austenitic matrix.

A few subsequent experiments have shown that this behaviour is quite sensitive to relatively minor differences in composition, and that some 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 Ni_{eq} and a particularly low level of nitrogen. In this respect, alloy C is probably unusual. However, the SAW composition E has intermediate Ni_{eq} 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 of service-induced martensite have been found, or any unusual service behaviour which might be explained by the presence of martensite in 16.8.2 weldments. The high alloy martensite will have a low Ac1, so that reversion to austenite will occur in high service temperature applications, which are typically above 540°C.

In a detailed structural study, a GTAW ER16-8-2 weldment [9] was solution annealed at 1060°C/30min and then cold-straightened. Although strain-induced martensite might then be expected, no martensite was reported, but nor was it sought. Ferrite level was remarkably stable, since WRC 2FN can be calculated from the given analysis, and 2% ferrite was found by quantitative metallography before and after two annealing cycles at 1060°C (which would eliminate any prior martensite). Another study [10] 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. Again, 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 etchants,[4] ferrofluid techniques, [11] or comparative magnetic response studies are required.

2.2 Ferrite and hot cracking

The presence of some ferrite, determined at room temperature, is conventionally considered to be desirable or necessary for satisfactory resistance to hot cracking in nominally austenitic weld metals of commercial purity. Type 16.8.2 is unusual because neither solidification cracking nor microfissuring is reported in typical compositions, even though these often contain little or no measured or calculated ferrite. The fissure bend test [12] provides a useful quantitative measure of susceptibility to microfissuring.

Using the fissure bend test, Lundin et al [12,13] found trivial microfissuring (4 microfissures in total) in two of twelve tests on two commercial batches of E16-8-2-16 with 0.7FN and 1.2FN, and, unlike the other standard austenitic types investigated, and the extent of hot cracking could not be plotted against FN, see Figure 4. The test involves depositing a overlay of parallel overlapping beads under high restraint, followed by bending through 120°, and noticeably more strain-induced martensite was found by magnetic response in the E16-8-2 welds than the others.

Again, the WRC diagram provides a realistic explanation for the remarkable hot cracking resistance of 16.8.2. Unlike previous constitution diagrams for stainless steel weld metals (Schaeffler, Espy, DeLong), the WRC diagram marks the approximate location of solidification mode boundaries (Figure 2). This shows that the most desirable FA primary ferritic solidification mode is compatible with very low FN levels in the leanest compositions such as 16.8.2.

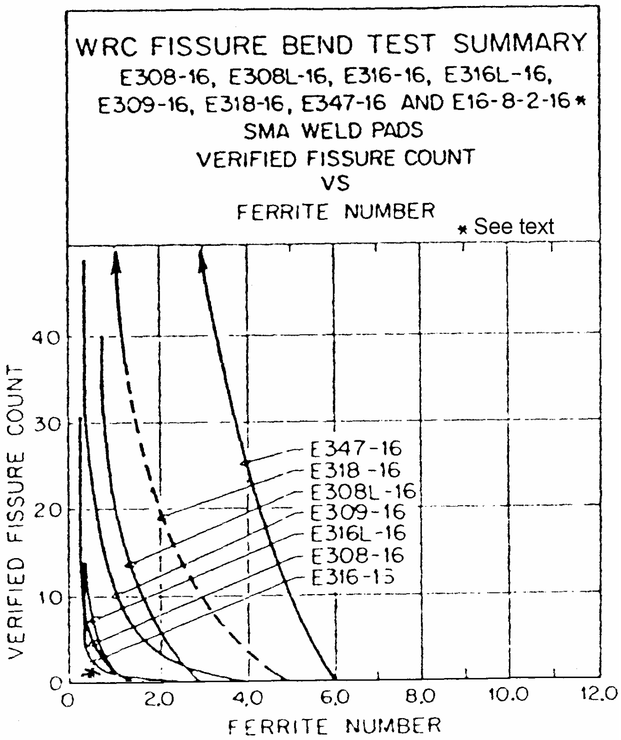

*Figure 4: Comparison of the fissuring relationship for eight different austenitic stainless steel weld metals[12,13] Note: E16-8-2-16 showed trivial fissuring and is marked **

The Suutala diagram,[14] Figure 5, provides another perspective, showing the dramatic reduction of solidification cracking (in relation to impurities S and P) at the transition to primary ferritic solidification, when the Cr_{eq}:Ni_{eq} is above about 1.5. Although this diagram was originally based on Schaeffler coefficients, the critical Cr_{eq}:Ni_{eq} ratio of 1.5 is found to be equally applicable when substituting the coefficients derived by Hammer and Svensson. The Hammer and Svensson[15] coefficients are considered to relate composition more precisely to solidification behaviour, as shown with the critical ratio of 1.5 in Figure 6.[16] A more conservative ratio of 1.55 has also been established to reflect the small influence of cooling rate on solidification.[17]

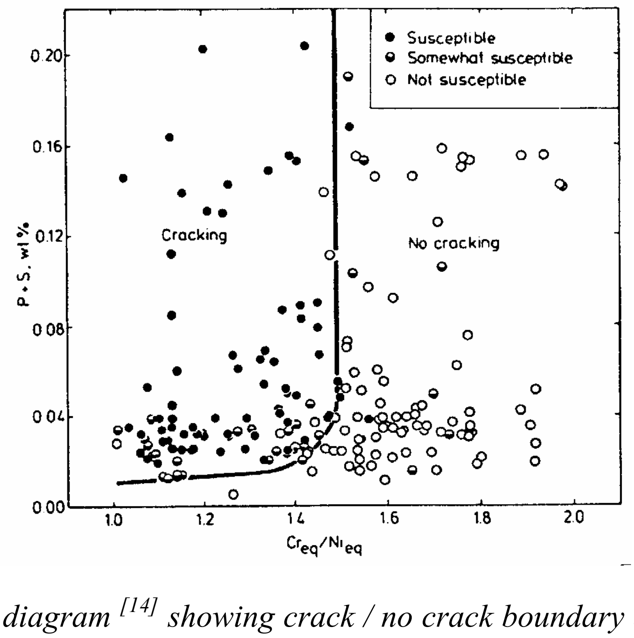

Figure 5: Suutala diagram [14] showing crack / no crack boundary at Cr_{eq}:Ni_{eq} ratio of about 1.5

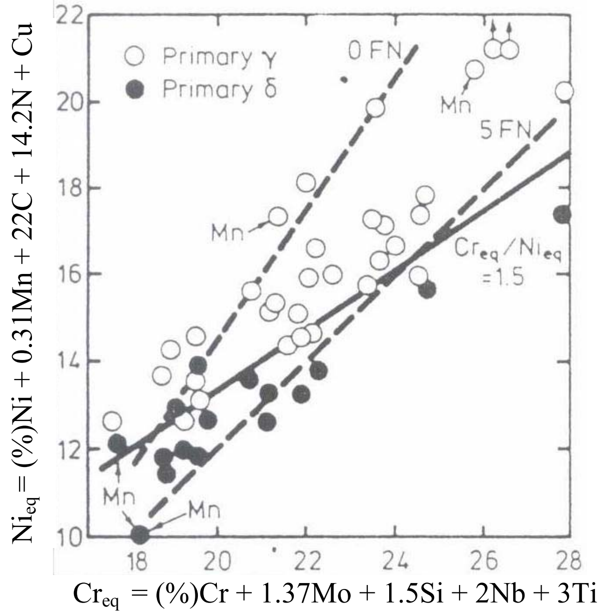

Figure 6: Solidification mode in relation to Hammer and Svensson Cr and Ni equivalents showing boundary for primary ferritic solidification at Cr_{eq}:Ni_{eq} = 1.5

On either assessment, the 16.8.2 compositions evaluated by Lundin et al have Cr_{eq}:Ni_{eq} ratios between 1.62 and 1.70 (assuming 0.06%N), which places them well into the 'safe' region. The WRC diagram places them close to the austenite boundary and correctly predicts <1FN at room temperature, whereas Figure 6 suggests that the leanest compositions may have primary ferritic solidification yet be fully austenitic at room temperature. Clearly, further work to explore these compositions would be fruitful.

The absence of any reported experience of hot cracking in 16.8.2 weld metal during the long history of its use is not always recognised in contract specifications. These may demand compositional restrictions to ensure that welds will contain a significant ferrite level, presumably to guarantee freedom from hot cracking. Of course, it is possible that some ferrite may be thought desirable for other reasons (perhaps in relation to stress corrosion cracking or creep ductility), and therefore it is preferable for specifiers to state the purpose of ferrite control.

However, the robust character of 16.8.2 weld metal is accepted by the ASME Code Section III [2] (nuclear Class 1 components). Ferrite determination and control is not required for type 16-8-2 welding materials, whereas for all 308/316 types >5FN is required for applications up to 427°C design temperature, and 3-10FN above 427°C.

3. Application properties

Before outlining the usual application of 16.8.2 consumables for elevated temperatures, some surprising virtues which commend them for cryogenic service will be illustrated in the context of the familiar alternatives.

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 about 20 years ago.[18] These tests were interesting in that E16-8-2 types were included, and the performance of the 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 the fracture properties of these welds.

The distinctive impact properties at –196°C of submerged arc (SAW) ER16.8.2 weld metal using a Cr-compensating flux (Table 2, composition E) are shown in Figure 7. By comparison, the various batches of SAW ER308L and ER316L show considerable scatter (using neutral, basic fluxes). The scatter is partly caused by differences of ferrite. The WRC-predicted ferrite based on weld analysis of the ER16.8.2 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 0.52mm lateral expansion at –101°C, which confirms a high resistance to thermal embrittlement, despite some martensite formation coupled with carbide precipitation as described earlier.

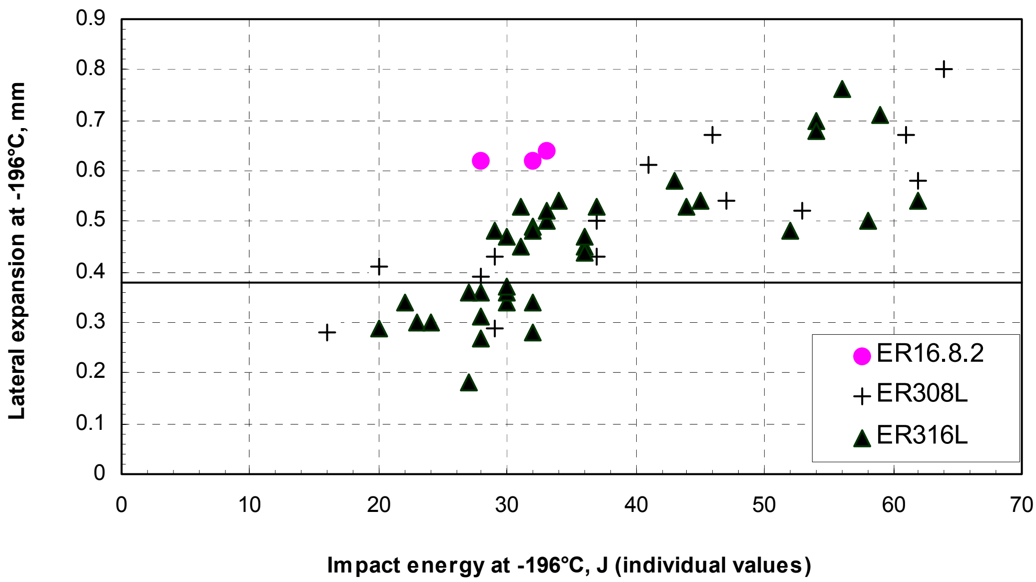

Figure 7: Relationship between Charpy impact energy and lateral expansion of ER316L, ER308L and ER16.8.2 SAW weld metals at –196°C

The gas-shielded FCAW process provides another example. All the data shown in Figure 8 are for normal batches not optimised for cryogenic applications, but the intrinsically superior toughness of 16.8.2 (similar to composition F, Table 2) is obvious. Comparable properties were obtained in FCAW 316L only in fully austenitic compositions specially modified to suppress hot cracking, identified as E316LMnT.

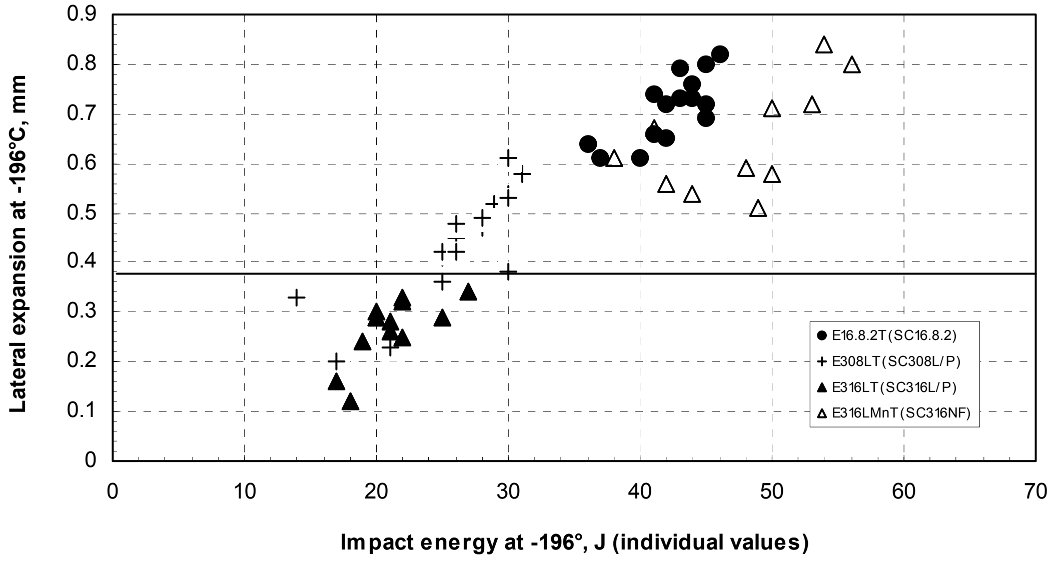

Figure 8: Relationship between Charpy impact energy and lateral expansion of E16-8-2T, E308LT and E316LT FCAW weld metals at –196°C

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 [19] 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 temperatures

The customary applications of 16.8.2 are for elevated temperature service. The weld metal was originally[3] developed for 316H to avoid sigma phase formation, and especially for thick section 347H where the use of matching 347 weld metal has been associated with low stress-rupture ductility, hot cracking, and in-service HAZ relaxation cracking.[3, 20, 21] Today it is also sometimes specified for welding 321H (in preference to 347 weld metal), and particularly for 304H, in preference to 308H weld metal.[22]

The presence of Mo is beneficial to creep rupture ductility [20] and the low Cr+Mo restricts formation of intermetallic phases.[1,7] Figure 9 presents trends in rupture ductility for some common austenitic weld metals including 16.8.2 and 17.8.2, and the advantage of Mo and disadvantage of Nb are evident. The data were collected from in-house and various published sources.

The ASME Code Section III [2] 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 matching weld metals. A thorough assessment of SMAW E16-8-2-15 welds compared with E316H for welding 316H steels has been presented [22] and this supports the ASME tables.

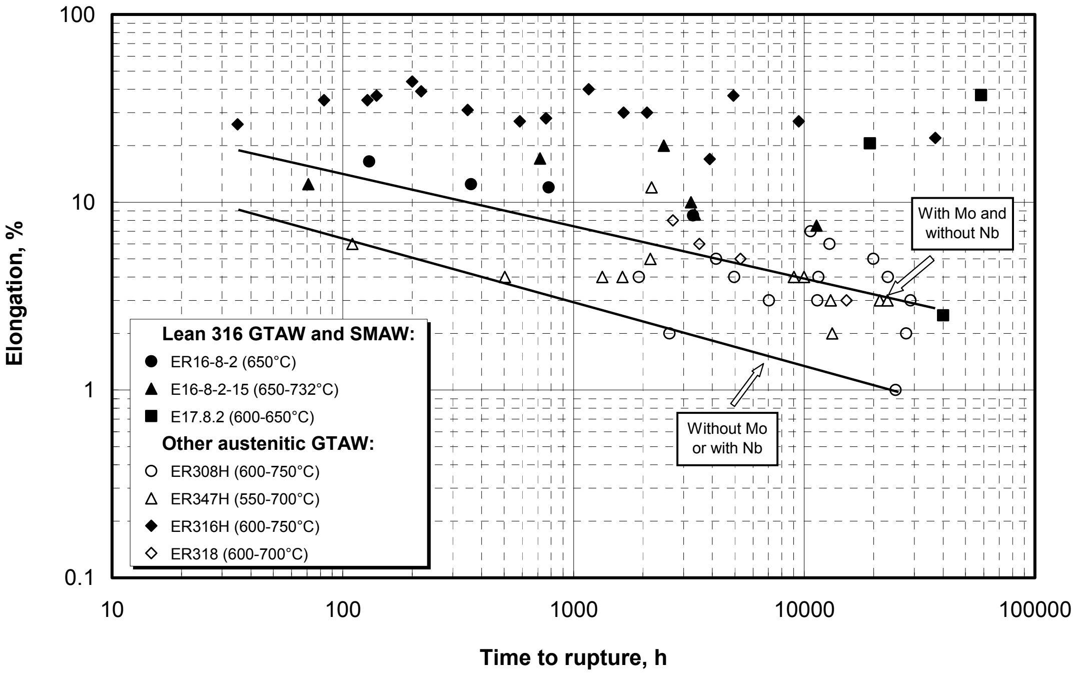

Figure 9: Rupture ductility of austenitic weld metals showing lower ductility for weld metals without Mo or with Nb (E17.8.2 = Metrode 17.8.2.RCF). Data from in-house and other sources.

All-weld metal stress-rupture properties for FCAW 16-8-2 (as composition F, Table 2) have also been presented recently.[23] The latter paper also emphasises the importance of forbidding any addition of bismuth compounds to FCAW formulations designed for high temperature service. Traces of bismuth may improve the cosmetic appearance of FCAW welds, but the influence on rupture ductility is catastrophic, with the possible consequence of premature failure in service. Figure 10 is an amended Larson-Miller plot for the previously published results, with FCAW 308H included for comparison, showing that minimum base material requirements were exceeded. The test temperatures were from 650°C up to 871°C. This gives confidence in extending applications well beyond 650°C which is important for welds in 304H used in the petrochemical processing industry.

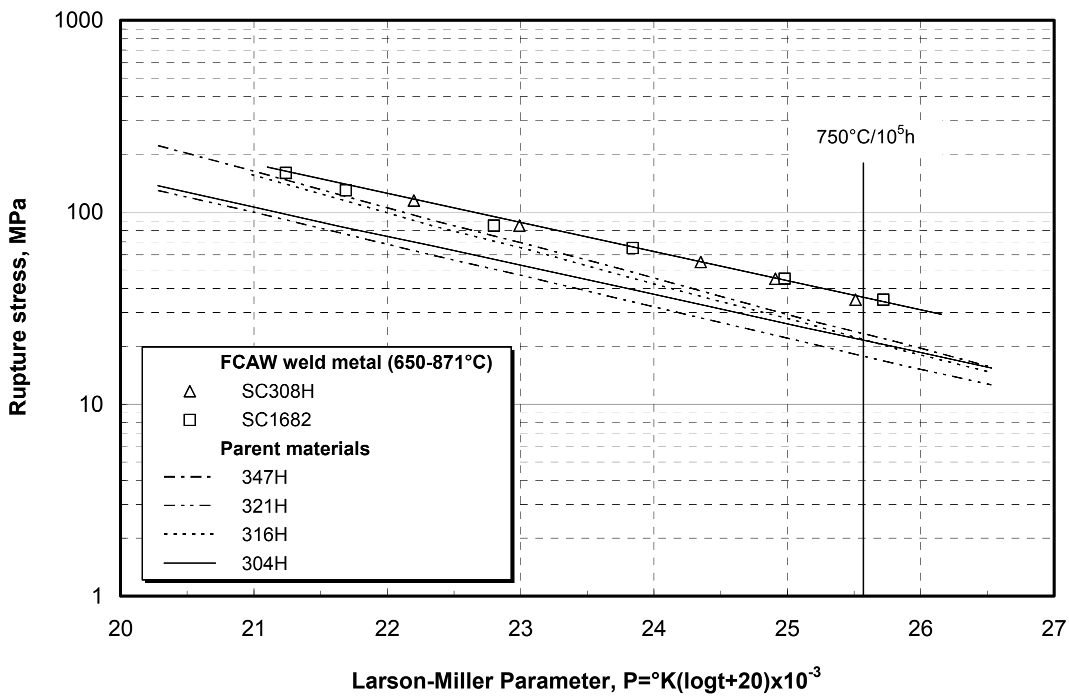

Figure 10: Larson-Miller plot of stress-rupture data for FCAW weld metals E16-8-2T (Supercore 16.8.2) and E308HT (Supercore 308H), compared with 3XXH parent material derived from ASTM DS 5S2.

3.3 Dissimilar weld metals

Strictly, the previous examples are dissimilar metal welds (equivalent base material, ASTM A376 grade 16-8-2H, exists but does not seem to be encountered). However, a more radical use of 16.8.2 for welding dissimilar materials has been presented.[24] Type 16.8.2 was chosen on the basis of intermediate expansion coefficient and successfully evaluated for welding 304 to an alloy 800 transition piece between stainless type 304 and P22 (2Cr-1Mo), see Figure 11. Despite dilution effects from alloy 800 with over 30%Ni, the microfissuring resistance of 16.8.2 in Y-groove tests was found to be slightly superior to type 182 nickel base weld metal traditionally used, although both were satisfactory.

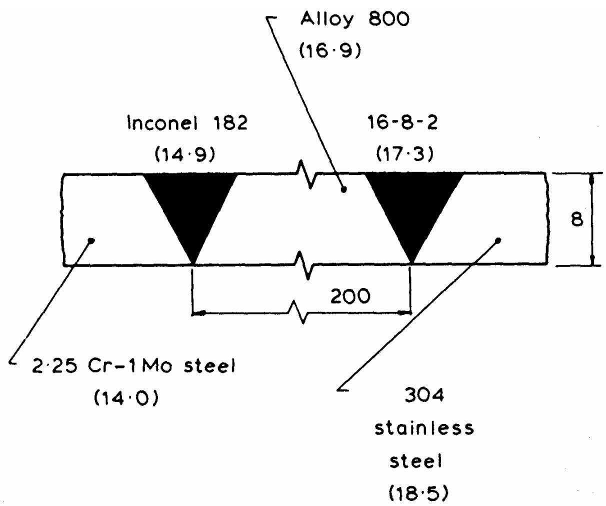

Figure 11: Use of 16.8.2 weld metal for transition joint in prototype fast breeder reactor. Thermal expansion coefficients are shown in brackets. [24]

4. Summary

The 'lean 316' or 16-8-2 family of weld metals has 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.

Weld metal microstructure consists of austenite with a small proportion of ferrite. There is no evidence of martensite in as-deposited weld metals but typical 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. Good 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. Type 16.8.2 is often used for welding 304H and is probably the first choice for welding 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 AWS 16-8-2 (including flux cored wire) for welding 304 and 316 materials is now recognised by the ASME Code Section III, which presents higher stress-rupture factors than for "matching" weld metals.

5. Acknowledgement

Thanks are due to Mitsui Babcock Energy Services for providing data for the effect of PWHT on austenitic weld metals shown in Figure 3.

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