Matching consumables for type 800 alloys

Development history, metallurgy and performance

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1.0   Introduction

Type 800 Nb welding consumables are designed for welding wrought and cast heat resistant alloys with a matrix composition based on Fe-21Cr-32Ni. Wrought alloys of this type belong to the Incoloy® 800 series (alloys 800, 800H and alloy 800HT). These are progressively strengthened with controlled and increasing levels of C (to 0.10% max.), Al and Ti (0.15 – 0.60% each). In equivalent cast alloys, Al + Ti are replaced with around 1%Nb, with slightly more carbon than the wrought alloys. Weld metal composition is closely related to the cast alloy, and is referred to as 'matching' as distinct from the dissimilar nickel-base consumables which are alternatively used. Typical compositions from shielded metal arc electrodes and solid wires are given in Table 1.

Table 1: Typical Compositions

Process	C	Mn	Si	Cr	Ni	Mo	Nb
SMAW electrode	0.1	2.5	0.3	21	32	<0.5	1.3
Filler wire	0.15	1.7	0.2	21	33	<0.1	1.5

Notes: Average carbon level of filler wire is typically higher than SMAW deposits to allow for transfer losses. Variants with 4.5%Mn are also produced.

2.0   Development History

Development of consumables based on 20Cr-32Ni plus controlled carbon and niobium additions is directly related to the emergence in the UK of two almost identical alloys intended as cast alternatives to alloy 800H. When these were patented in 1966, Metrode was commissioned to collaborate with the foundries of Lloyds (Burton) Ltd and APV-Paramount to develop a SMAW electrode (then 20.32.Nb – now THERMET 800Nb) to match these proprietary alloys, respectively Thermalloy T52 and Paralloy CR32W. Some concurrent work was also carried out with the Inco European R & D Centre, then at Birmingham, with the prospect of applications for the wrought alloys 800 and 800H.

Prior to that time, the nearest weld metal compositions were AWS types E330 and the higher carbon E330H. It was known to manufacturers of these 15Cr-35Ni electrodes that the lower carbon E330 was particularly sensitive to microfissuring in multipass deposits, reduced only when the proportions of C, Mn and Si were carefully balanced. Similarly, since its introduction in 1949, the

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observed unreliable autogenous weldability of wrought alloy 800 must have distracted attention from the possibility of obtaining useful properties with matching weld metal and, in any case, dissimilar nickel-base weld metal was available and accepted.

The hot cracking problems associated with E330 weld metal are effectively eliminated by raising carbon to 0.4% as in E330H. The same effect is found in E310H when compared with E310, owing to the formation of primary eutectic chromium carbide during solidification (an alternative strategy is to raise manganese above the AWS 2.5% limit). Unfortunately, high carbon alloys have low ductility, reduced further by voluminous secondary carbide precipitation during service, and are no match to the ductile lower carbon wrought or cast alloys.

By 1972 the compositional design factors required for technically sound welds had been established and Metrode 20.32.Nb became commercially available. This is believed to have been the first such electrode of its type, and on the basis of soundness, stress-rupture and ageing tests, was endorsed by Inco in 1973 as suitable for alloy 800, having previously been accepted for castings by the foundries.

The cast alloys T52 and CR32W continue to be produced, in addition to equivalent types which followed in continental Europe, and the alloy is now designated grade CT15C in ASTM A351. Since its introduction, many tonnes of matching weld metal have entered service for these and the wrought alloys, and no instance has been reported of a weldment failure attributable to weld metal service performance.

3.0   Metallurgical background

A direct relationship between the composition of cast Fe-20Cr-32Ni-Nb alloy and the optimum weld metal composition developed to match this alloy has already been noted. Since both castings and welds are the products of solidification processes, it is not surprising that the designed properties of the cast alloy and critical behaviour such as defect-free autogenous weldability, provide a robust basis for matching weld metal development.

3.1   Solidification behaviour and hot cracking

The microstructures of as-deposited weld metal and castings are very similar, consisting of primary cells ("grains") within which there is a continuous cellular network of niobium carbide eutectic in an austenitic matrix, as shown in Figure 1.

The formation of this eutectic network during solidification provides a back-filling mechanism which suppresses incipient solidification cracks and enhances resistance to microfissuring in the reheated beads of multipass welds. The stability of this network at high service temperatures also gives the alloy its excellent creep performance.

As is well known, single-phase austenitic alloys (without the benefit of delta ferrite in duplex solidification) are susceptible to the formation of hot cracks, usually owing to the segregation of non-metallic impurities to primary cell boundaries during solidification. A plain Fe-20Cr-32Ni base casting of commercial purity is highly sensitive to HAZ and solidification cracking during autogenous fusion. (Alloy 800 is normally resistant to HAZ cracking, but similarly prone to solidification cracking.) For castings and weld metal the addition of sufficient niobium to give a primary eutectic solidification has an effect comparable to primary ferrite solidification in the leaner 300 series austenitic stainless steels. It seems likely that the intracellular eutectic entrains a proportion of the undesirable impurities, thus reducing their activity at primary cell boundaries and suppressing microfissuring.

Satisfactory resistance to hot cracking requires a minimum of about 0.6%Nb in castings, and in weld metal this is coupled with a higher typical manganese and lower silicon than the cast alloy. It is not generally necessary or desirable to raise Mn beyond about 4-5%, because this element increases thermal expansion coefficient and excessive levels could have an adverse influence on microstructural stability and oxidation resistance. However, when used for welding the Nb-free wrought 800 alloys, the filler metal (or all-weld metal) niobium level should be sufficiently high to allow for the effect of dilution at the fusion boundary region.

Investigation of weldments in wrought 800 alloys has revealed a very low incidence of microfissures. The example shown in Figure 2, which occurred at the fusion boundary dilution zone in a 19mm wall 800H pipe weld is only 0.15mm in length.

Most authorities recognise that in practice undetected microfissures will be present in a large number of fully austenitic and nickel-base weldments prior to service. Research and expert bodies such as TWI and IIW have for some time noted the lack of any actual evidence for the deleterious influence of these microfissures on weldment service performance, for example in thermal fatigue.

4.0   Wrought 800 alloys and nickel-base filler metals

Whilst matching filler metal is conventional for the cast alloys, the wrought 800 series alloys have historically been welded with nickel-base fillers. This procedure was established long before the development of satisfactory matching filler metal, and continues today either as an option or as the accepted norm.

Three nickel-base filler wire specifications (and/or equivalent electrodes) are commonly applied to the 800 series alloys:

1) AWS ERNiCr-3 (FM82) was the only established choice until the 1970's, although its stress-rupture properties were considered to undermatch the higher strength 800H (and later

800HT) alloys above about 760°C-800°C. The equivalent SMAW electrode is AWS ENiCrFe-2..

2) AWS ERNiCrMo-3 (FM 625) became available in the 1970's and, with its superior stress-rupture properties, extended good joint efficiencies to the useful upper working range of 800HT at around 760-950°C.

3) AWS ERNiCrCoMo-1 (FM 617) arrived during the 1980's and offered further enhancement above the properties of FM625, particularly for alloy 800HT at the highest service temperatures. The aged ductility of FM617 weld metal is also recognised to be higher than FM625, because it does not precipitate the more deleterious Ni_3Nb. However, it seems paradoxical that such exotic filler metals, both derived from a high performance parent materials, should be required for optimum joint efficiency in the relatively lean and simple modified ternary alloy system of 800HT.

It is now recognised that alloys 800H and 800HT are susceptible to HAZ relaxation cracking (stress-relief or reheat cracking) in the range 500-760°C. Since this problem is related to residual stresses coupled with precipitation in the high temperature HAZ, susceptibility increases with higher C+Ti+Al (carbides and $Ni_3(AlTi)$ strengthening) as found in alloy 800HT. One remedy to avoid the problem is to apply high temperature post-weld stress relief at or above 900°C when service is at 500-750°C, and it is understood that this may be a forthcoming requirement of ASME IX.

Without PWHT, the relative strength of weld metal is influential. Consequently, many authorities specify FM82 and avoid higher strength FM625 or 617 for service below 760-800°C.

5.0   Performance of matching weld metal

The designed alloy performance criteria for weld metal are essentially the same as for equivalent cast and wrought base materials and include:

1) Good hot strength and stress-rupture performance over the service range up to about 950°C.

2) Stable austenitic structure without liability for forming embrittling intermetallic phases such as sigma.

3) Satisfactory retained ductility following exposure to service temperatures.

4) Scaling resistance at service temperatures (20Cr-32Ni base).

5) Satisfactory resistance to wet corrosion (niobium stabilised).

5.1 Strength and stress-rupture performance

Ambient strength of weld metal matches base material quite closely, as shown by the hardness survey in Figure 3 for an alloy 800H weldment. A lower hardness will be noted for the capping beads compared with the reheated lower region, where cumulative strain-hardening by successive weld beads and a degree of secondary carbide precipitation raises hardness. However, hardness is considerably lower than the values of typically >240HV found in weldments using nickel-base fillers FM625 and FM617, and is similar to FM82.

Hot tensile strength for 800Nb filler metal at 700^OC and 900^OC is given in Table 2, and shows good agreement with base material requirements. As expected, elongation values are good, but somewhat lower than typical for base materials. It is noteworthy that (unlike alloy 800HT) the test at 700^OC shows little evidence of a ductility dip when compared with the reported ambient tensile elongation.

Table 2: Tensile Properties of 21.33.Nb GTAW weld metal

Temperature C^O	0.2% Proof Stress, MPa	Tensile Strength, MPa	Elongation, %		Reduction of area, %
			4d	5d	
+20	472	630	28.5	26.0	50
+700	286	392	25.7	24.0	33
+900	170	216	42.9	40.0	62

Stress-rupture performance of 800Nb in casting weldments, as seen in Figure 4, shows excellent match to the parent alloy. Figure 5 shows a Larson-Miller plot of all-weld and transverse weldment tests in comparison with alloy 800 type base materials. Some of these data are plotted separately for alloy 800H on a stress-to-rupture basis at 700^OC and 900^OC in Figure 6. Figures 7 and 8 show representative microstructural features found during examination of the test specimens. No anomalous features or phases were reported. In similar but shorter-term transverse tests, rupture in all cases occurred in base metal. Like the cast alloy, the creep rate for this weld metal is typically lower than alloy 800H. Rupture elongations typically exceed 2%, with some evidence of recovery to >10% at the longest durations. Possibly owing to its smaller grain size, weld metal also shows a lower tendency for oxide penetration and the propagation of surface cracks than the base material when tested in air.

5.2 Retained ductility and microstructural stability

There is no obvious mechanism for drastic loss of ductility in correctly balanced 800Nb alloys because the modest carbon content of around 0.1% is mostly bound up as eutectic niobium carbide

during solidification, leaving little carbon free either to precipitate (as NbC or $Cr_{23}C_6$) at primary cell boundaries or within the ductile austenitic matrix. There have been no reports of Fe_2Nb Laves phase formation, and sigma phase has been found only in deviant weld metal variants with additional and excessive Mo or W. Retained ductility is therefore likely to depend on the eutectic carbide stability.

Aged ductility is usually judged by either ambient tensile elongation or toughness after exposure within the service temperature range known to correspond with metallurgical instability or ductility trough. This is associated with carbide precipitation kinetics peaking in the range 650-760°C, and is more pronounced in the strongest wrought grade 800HT, which in addition to forming TiC and $Cr_{23}C_6$, is also strengthened by more gamma-prime $Ni_3(TiAl)$.

The as-deposited toughness of 800Nb-type deposits is very satisfactory (Table 3). As noted earlier, some carbide precipitation will already be present to a varying degree depending on the actual weld chemistry and extent of multipass thermal cycling.

The limited available ageing test data show the following average values:

Table 3 Ageing Test Data

Weld metal	As-welded	After ageing at temp/time	
800Nb	112J	54J	750°C/1000h
800Nb	66J	55J	700°C/168h

The values above suggest superior behaviour in comparison with type 617 SMAW deposits, reported to decline from 52-66J as-welded to 22-26J after 769°C/500h. After initial precipitation of carbides, and in the absence of other phase transformations, the aged ductility or toughness should be expected to remain relatively stable. This situation is probably typical for both FM617 and 800Nb weld metals.

In contrast, alloy 625 is known to form the phase Ni_3Nb, and other more complex intermetallics are likely in FM625 weld deposits owing to the instability of microsegregation products arising partly from its excessive Nb, particularly at weldment fusion boundaries.

6.0   Contractor requirements for welding wrought 800 alloys

There is no global consensus as yet regarding the relative merits of applying matching or nickel-base consumables to welding the wrought 800 type alloys. Unless the work currently in progress at European research centres finds radical advantages in favour of using matching weld metal, it is likely that the current situation will continue. However, although nickel-base fillers have a longer

continuous tradition, the use of FM625 and FM617 is more recent and overlaps the introduction of matching filler. An increasing number of contractors have now accepted, or may even prefer, the use of matching filler metal.

7.   Advantages of matching over dissimilar weld metal

Given the availability of matching consumables for 800 alloys, capable of meeting the usual requirements for joint integrity in fabrication procedure qualifications, and with satisfactory service performance, it seems that more widespread use is justified.

With reference to alloys 800 and 800H for corrosive service, ASME Code Case 1325-7 (special ruling, 5 Nov. 1973) recommends "filler metal that will deposit weld metal with practically the same composition as the material joined". Matching 800Nb weld metal is effectively niobium stabilised like the cast parent alloy, which shows the expected and dramatic reduction in sensitisation as niobium increases towards the optimum Nb:C ratio of about 10:1. In contrast, wrought 800H is reported to be easily sensitised to dew-point SCC by polythionic acid. For most applications of type 800 alloys, hot corrosion resistance is paramount. Under sulphidising conditions, the use of dissimilar nickel-base weld metals can lead to preferential attack of the weld area. Matching weld metal has been selected as a satisfactory solution to this potential problem. More speculatively, its use is also being evaluated for dissimilar metal joints between alloy 800H and ASTM P22, for the same reason.

Finally, it is understood that there are some applications where the dissimilar thermal expansion coefficient of nickel-base weld metal is undesirable, for which the closely matching type is a logical choice. For the reasons given here and elsewhere in this article, matching weld metal is therefore considered suitable as an alternative to nickel-base consumables.

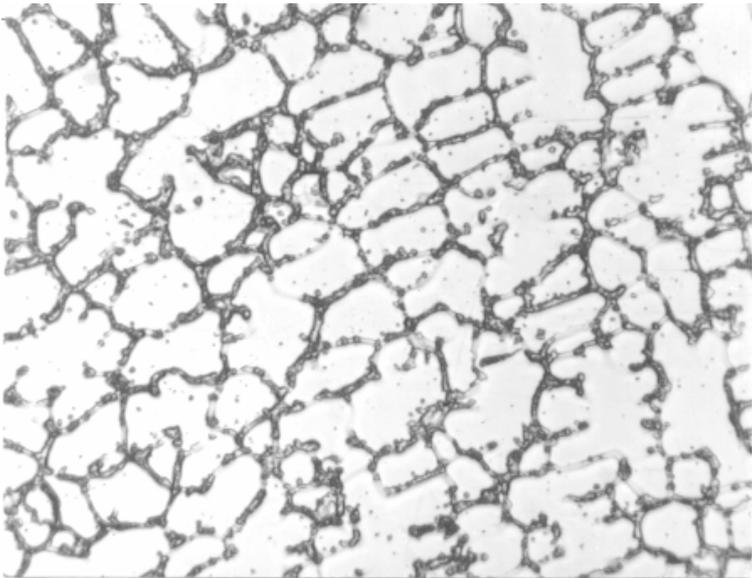Figure 1: 800Nb weld metal microstructure (x500)

Figure 2: Microfissure at fusion boundary between 800Nb weld and alloy 800H (x 500)
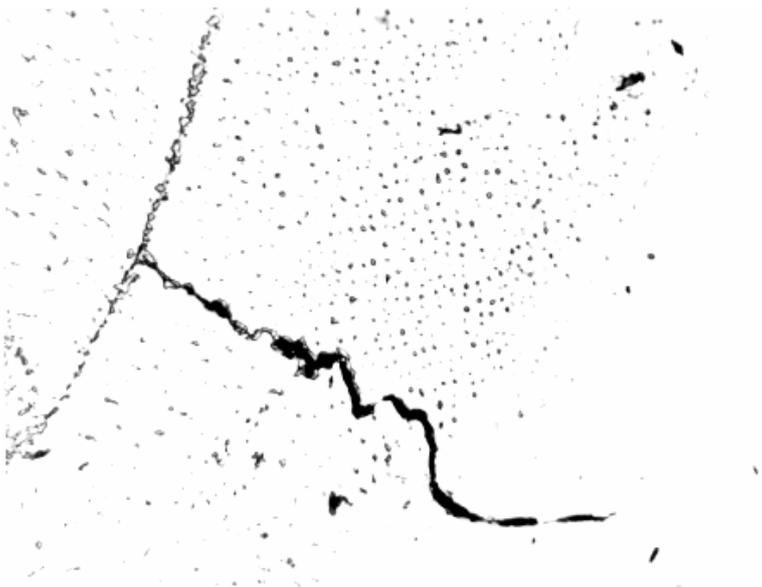
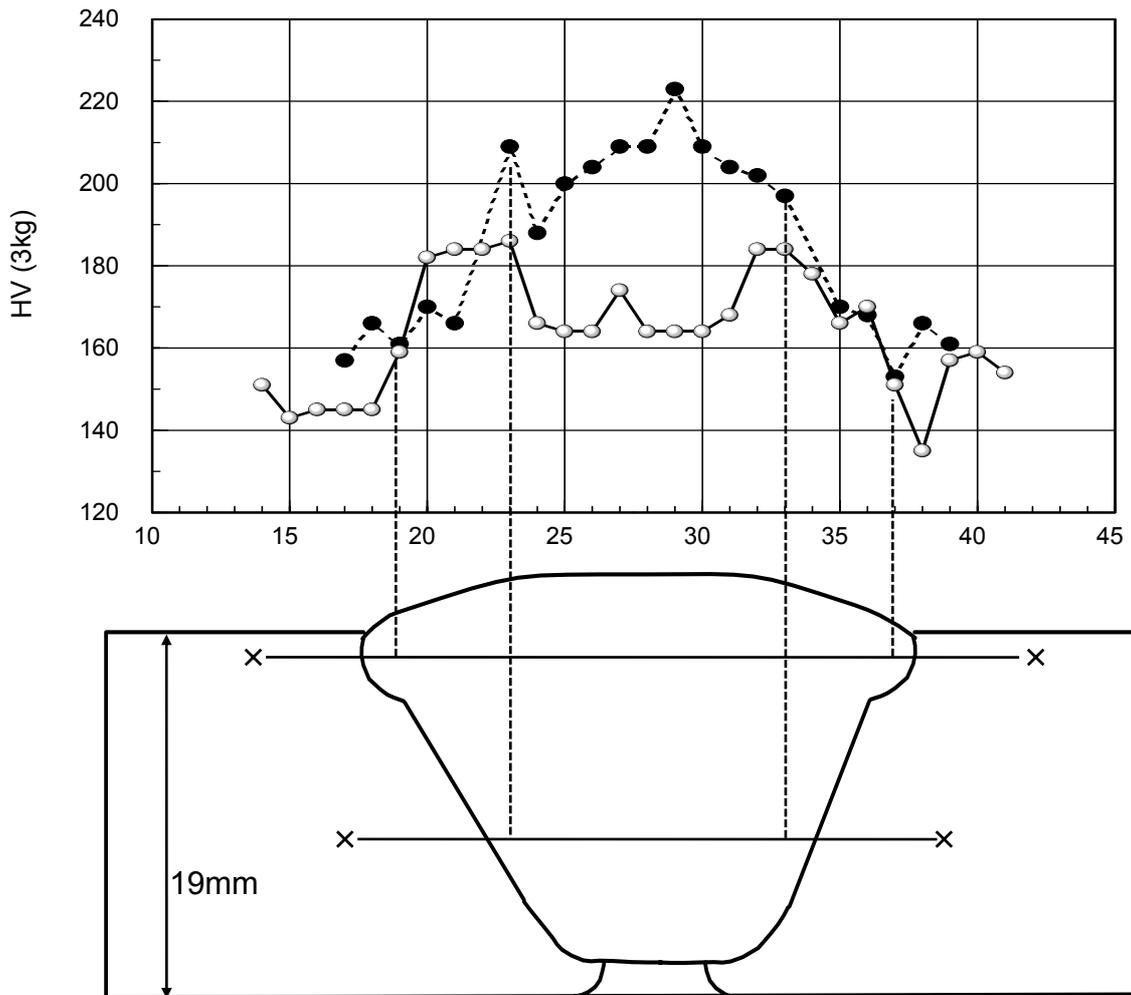Figure 3: Hardness survey of SMAW 800Nb weldment in 19mm thick alloy 800H

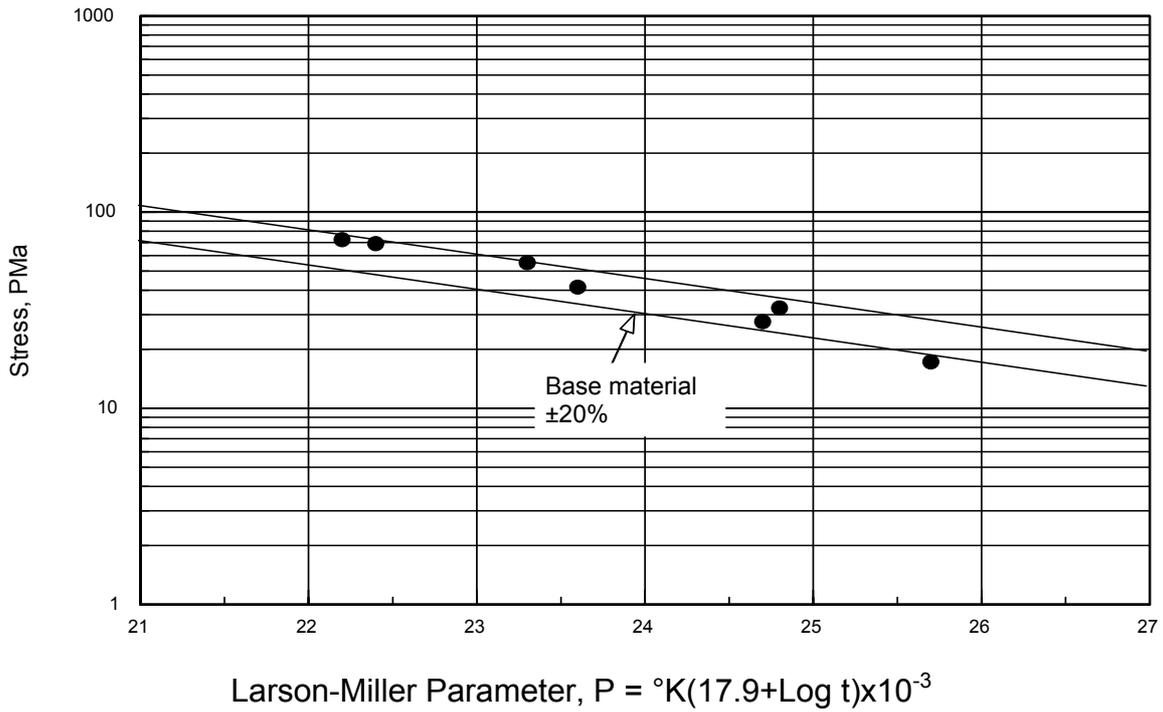Figure 4: Stress-rupture properties of 800Nb SMAW weldments in cast alloy CT15C.

Figure 5: Stress-rupture properties of 800Nb SMAW welds and weldments compared with some other weld metals and wrought 800 type alloys
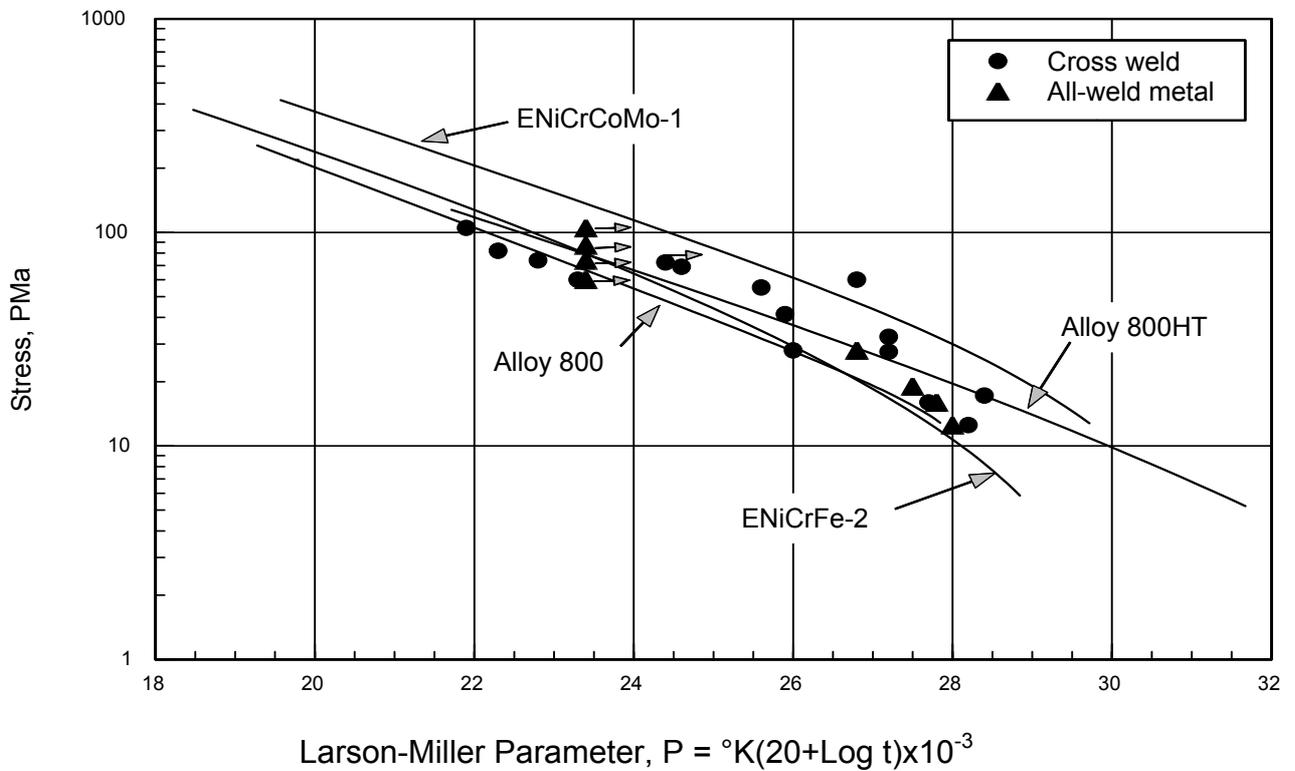
Figure 6: Stress-rupture properties of 800Nb SMAW weld metal and weldments in alloy 800H at 700°C and 900°C.
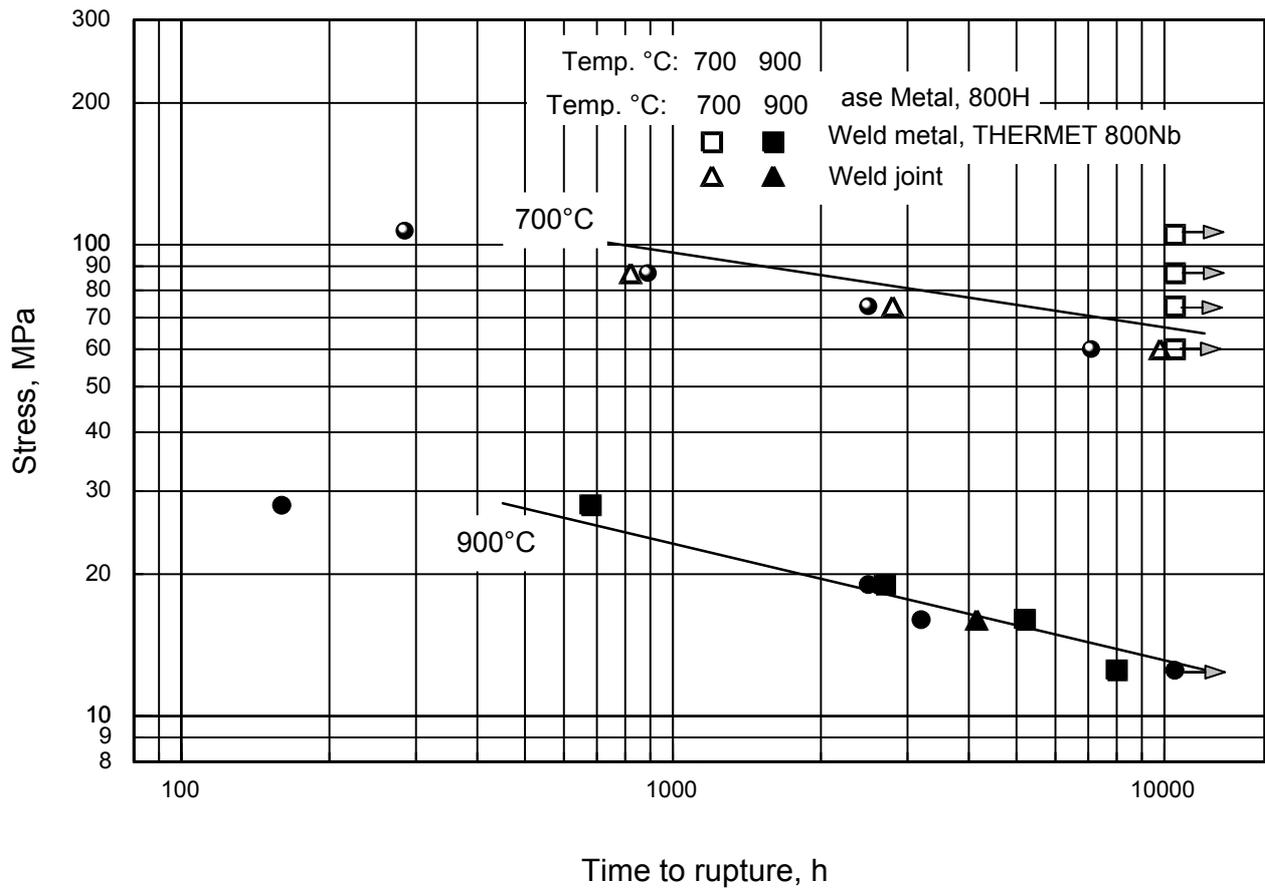

Time to rupture, h

Figure 7: Fusion boundary of SMAW 800Nb to 800H weldment after testing 2856h at 700°C (x 160)
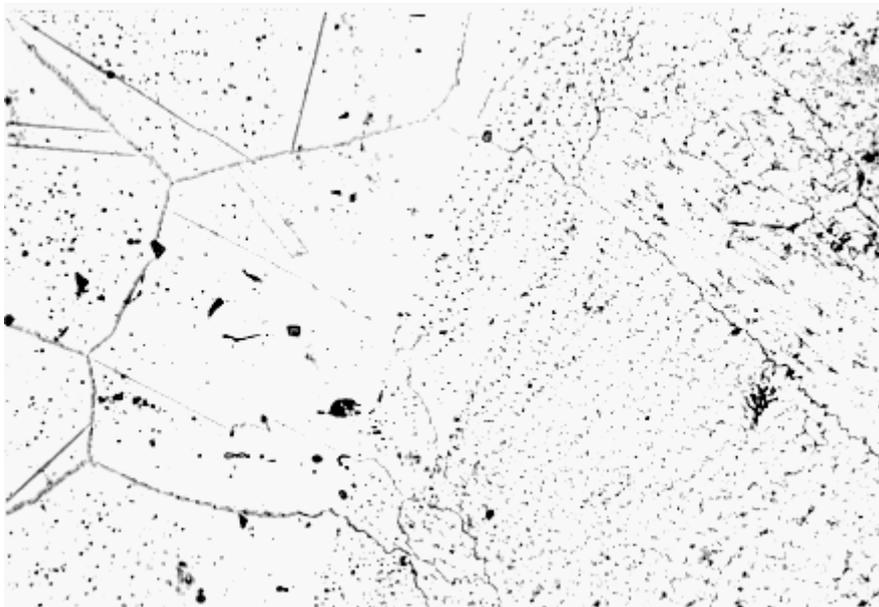
Figure 8: Fusion boundary of SMAW 800Nb to 800H weldment after testing 4153h at 9800°C (x 160)