Available online at www.sciencedirect.com

ScienceDirect

Journal of Nuclear Materials 367–370 (2007) 1316–1324

journal of nuclear materials

www.elsevier.com/locate/jnucmat

Extending ITER materials design to welded joints

A.-A.F. Tavassoli *

DMN/Dir, CEA/Saclay, Commissariat à l'Energie Atomique, 91191 Gif sur Yvette cedex, France

Abstract

This paper extends the ITER materials properties documentation to weld metals and incorporates the needs of Test Blanket Modules for higher temperature materials properties. Since the main structural material selected for ITER is type 316L(N)-IG, the paper is focused on weld metals and joining techniques for this steel. Materials properties data are analysed according to the French design and construction rules for nuclear components (RCC-MR) and design allowables are equally derived using the same rules. Particular attention is paid to the type of weld metal, to the type and position of welding and their influence on the materials properties data and design allowables. The primary goal of this work, starting with 19-12-2 weld metal, is to produce comprehensive materials properties documentations that when combined with codification and inspection documents would satisfy ITER licensing needs. As a result, structural stability and capability of welded joints during manufacturing of ITER components and their subsequent service, including the effects of irradiation and eventual incidental or accidental situations, are also covered.

1. Introduction

In December 1993, the ITER Joint Central Team (JCT) authorized the creation of a Material Properties Handbook (MPH). This handbook was a cooperative activity among the ITER Parties (Japan, the European Union, the Russian Federation and the US). The goal of this document was to provide the ITER designers with a single reference source of material data. The last version of the ITER MPH-IV (ITER Document No. G 74 MA 9 01-07-11 W 0.2) was issued as a part of ITER Final Design Report in July 2001. In addition to MPH, ITER JCT authorized creation of an ITER Interim Structural Design Criteria with its associated code qualified materials data in the form of an Appendix A. The last major package of this document was issued in 1997.

Since then, MPH and Appendix A documents have been updated with new data generated by ITER partners. With the approach of construction phase, a greater emphasis has been placed on traceability of materials data and databases, as well as increased harmonization between MPH and Appendix A reports. Lately, the organization of MPH files has been made component specific. This work started in 2004 with the vacuum vessel and its main structural material, Type 316L(N). This will be extended to internals and other materials at a later stage. This paper presents work done to date on the weld metals of 316L(N) steel in the frame of the vacuum vessel document.

* Tel.: +33 1 6908 6021; fax: +33 1 6908 8070.
E-mail address: tavassoli@cea.fr

0022-3115/$ - see front matter © 2007 Elsevier B.V. All rights reserved.
doi:10.1016/j.jnucmat.2007.03.260

2. Materials

Section IV – Welding of the RCC-MR and its Appendices ([1]) provide guidelines for selection and utilization of filler metals for welding of austenitic stainless steels, including the Z2 CND 17-12 grade with controlled nitrogen addition, the steel equivalent to the ITER 316L(N).

ASME code sections on welds ([2]) also provide guidelines for selection of weld metals and welding the austenitic steels that can be used for ITER vessel and in-vessel design. However, since Type 316L(N) is a grade qualified only in the RCC-MR, here, preference will be given to the latter. The differences between the two codes, with regard to the austenitic stainless steels are minimal and can in most cases be ignored.

RCC-MR allows use of the low carbon grades, 316L (19-12-2L) for applications at temperatures not exceeding 375 °C, where high temperature strength is not required, or the degradation of properties due to long time aging is negligible. Specifications for these metals are given in the Section IV/RS2900 and are summarized below.

– RS 2915: wire for TIG welding, ER 316L(Z2 CND 19-13).[1]
– RS 2925: covered electrode for manual arc welding, E 316L(Z 19-12-3 L).[2]
– RS 2945: Flux wire couple for automatic welding, 316L (SA 19-12-2 L).[2]

At temperatures greater than 375 °C, RCC-MR specifies the higher strength grades of weld metal: 19-12-2 (OKR3U) and 16-8-2. These grades also have a low delta ferrite content and are resistant to degradation of properties due to long-term aging or radiation embrittlement.

The data sheets for 19-12-2 and 16-8-2 grades are given in Section IV/RS 9000 of RCC-MR:

– RS 9513.1: 19-12-2 covered electrode for manual metal arc welding.
– RS 9513.2: 16-8-2 covered electrode for manual arc welding.
– RS 9523.1: 19-12-2 wire for TIG welding.
– RS 9523.2: 16-8-2 wire for TIG welding.
– RS 9543.1: 19-12-2 wire associated with a flux for submerged arc welding.
– RS 9543.2: 16-8-2 wire associated with a flux for submerged arc welding.

Compositions of the reference weld metals are given in Table 1 and their acceptance test results in Tables 2 and 3. Notice that the 316L(N)-IG, is an ITER grade of the 316L(N), where the specifications for high activation residual elements are more stringent.

3. Code procedures

RCC-MR ([1]), ASME [2] and ISDC [3] organize welds into different 'Weld Categories' (A, B, C, D, and E) based on their intended use. The joints are organized into different 'Weld Types' (I, II, III, IV, V, VI, VII) based on the configuration of the weld.

ISDC ([3]),which is compatible with all ITER partner codes, specifies that all welded joints for assemblies directly related to the mechanical function of the structure should be categorized as A or B and should be butt welded joints obtained by full penetration welding, with or without back welding, and without the use of permanent backing plates. Assemblies connecting flanges, internal support shells, tube plates, etc.to the main shell should be categorized as C, and assemblies connecting nozzles to the main shell should be categorized as D. Categories C and D welds may be full penetration fillet or T joints without permanent backing plate (type III.1). However, the backside being inaccessible for type III.2 joint, category C is not permitted but category D welded joints can be used.

For code-stamped pressure vessels, there are specific additional requirements concerning which weld types can be used to make welds in the different use categories.

The procedure for calculating the strength or the fatigue life of weld joints of different weld types is based on 'knock down' factors applied to the base material properties. The allowable stresses for a weld (the knock down factors) are intimately related both to the qualification of the process and the inspection of the weld after fabrication.

4. MPH procedures

ITER MPH recommends the code data, whenever available, for ITER Structural Design Criteria.

[1] To be used as Strength and buttering, TIG root support and seal, and Cladding.
[2] To be used as Strength and buttering, and Cladding.

Table 1
Weld metal compositions used for welding Type 316L(N) steel (FWC = flux wire couple, CE = coated electrode, MA = manual arc, AC = automatic covered)

RCC-MR weld metal	Filler metal	Range	C	Mn	Si	P	S	Cr	Ni	Mo	Nb	Cu	B (ppm)	Co	N_2	Ferrite calculated
RS 2915	Wire for TIG	Min		1.00				18.00	12.00	2.00						5
ER 316L (Z2 CND 19-13)	In weld deposit	Max	0.030	2.50	0.60	0.30	⩽0.020	20.00	14.00	3.00						15[a]
RS 2925	CE															
E 316L (Z 19-12-3 L)	In weld deposit	Min						18.00	12.00	2.00						5
		Max	0.035	2.50	0.90	0.025	0.025	20.00	14.00	3.00						15[a]
RS 2945	Flux wire couple	Min		1.00				18.00	10.00	2.00						5
316L (SA 19-12-2L)		Max	0.025	2.50	0.60	0.020	0.020	20.00	13.00	3.00						15[a]
	In deposit	Min		1.00				17.00	10.00	2.00						5
		Max	0.030	2.50	1.00	0.030	0.030	20.00	13.00	3.00						15
RS 9513.1	CE for MA	Min	0.045	1.20	0.40	–	–	18.0	11.0	1.90	–	–	–	–	–	3
19-12-2		Max	0.055	1.80	0.70	0.025	0.020	19.0	12.0	2.2						7
RS 9513.2	CE for MA	Min	0.045	1.80				15.5	7.5	1.8	–		–	–	–	3
16-8-2		Max	0.055	2.5	0.5	0.025	0.020	16.5	9.0	2.5		0.30		0.25		7
RS 9523.1	Wire for TIG	Min														3
19-12-2		Max														7
RS 9523.2	Wire for TIG	Min	0.030	1.8				16.0	8.0	1.8	–		–	–	–	3
16-8-2		Max	0.045	2.5	0.5	0.025	0.020	17.0	9.0	2.2		0.1				7
RS 9543.1	FWC for AC	Min	0.030	1.20		–	–	18.0	11.0	2.0	–		–		–	3
19-12-2		Max	0.055	2.0	0.70	0.025	0.020	19.0	12.0	2.20		0.10-		0.25-		7
RS 9543.2	Submerged arc	Min	0.030	1.8	–	–	–	16.0	8.0	1.80	–	–	–	–	–	3
16-8-2		Max	0.045	2.5	0.5	0.025	0.020	17.0	9.0	2.50		0.10		0.25		7

[a] Preferred max12% evaluated using Delong diagram (RCC-MR RS-2000, Fig. 2).

Table 2
Specified tensile and impact values for 316L weld metals according to RS 2915, RS 2925, RS 2945

Tensile (orientation parallel to weld line)	20 °C	360 °C
Yield stress S_y ($R_{p_{0.2}}$)	⩾210 MPa	⩾130 MPa
Ultimate tensile strength, S_u (R_m)	520–670 MPa	
Total elongation over 5d	⩾30%	
U-Notch impact property (RT)		⩾30 J

All results are for deposited welds and in the as-welded condition.

Table 3
Specified tensile, impact and creep values for 19-12-2 welds made in the flat position according to RS 9513.1

Tensile (orientation parallel to weld line)	20 °C	550 °C
Yield stress S_y ($R_{p_{0.2}}$)	⩾350 MPa	
Ultimate tensile strength, S_u (R_m)	⩾550[a] MPa	⩾380 MPa
Total elongation over 5d	⩾35%	⩾20%
CU initial	CU (19-12-2)	
⩾35 J		⩾15 J (100 h/750 °C)
Test temperature, °C	Creep stress, MPa	Minimum life, h
550	260	700
550	230	2000

[a] Impact U-notch test results are obtained from tests on standard size specimens:$10 \times 10 \times 55$ (in mm). To convert these values to J/cm^2, divide J values by 0.5 cm^2.

In fact, in each materials properties file, a clear distinction is made between code recommendations and additional recommendations made as a result of the present work.

The number and type of property sheets used in MPH files varies according to the type of material examined. In general, they cover all specifications for products, compositions, mechanical properties and physical properties.

In each property file, available code recommendations are presented first. Then the available materials properties are collected and analysed, including the effects of exposures to high temperatures and neutron irradiation. Finally the results obtained are compared with code recommendations to see if the safety margins recommended in the code are maintained under ITER service conditions. For welded joints, special attention is also paid to welding conditions, welding positions, weld sections, etc.

An example of MPH file code for 19-12-2 weld metal is given below. Several figures and tables have been removed to reduce the length of the paper.

5. File code: ITER-AA08-2101 tensile strength

5.1. Code recommendations

The 316L and 19-12-2 weld metals given in File Code ITER-AA08-1100 are RCC-MR Code qualified materials [1]. The low temperature grades (316L) are also RCC-M [4] and ASME code qualified materials [3].

For the low temperature grades (316L), the specified S_u at room temperature (RS 2915, RS 2925, RS 2945) is in the range of 520–670 MPa. For the high temperature grades (19-12-2), the specified values according to RS 9513.1 (covered electrodes for manual welding) are:

S_u (RT) ⩾ 550 MPa
S_u (550 °C) ⩾ 380 MPa

The section on RS 9523.1 (wire for TIG welding) is not yet available in RCC-MR.

For flux covered automatic welding (RS 9543.1) these values are slightly lower:

S_u (RT) ⩾ 540 MPa
S_u (450 °C) ⩾ 400 MPa
S_u (550 °C) ⩾ 380 MPa

Data sheet 9513.1 also gives a series of S_u (R_m) specified values for qualification test coupons.

Position 1G (flat):
S_u (RT) ⩾ 550 MPa in *L* direction
S_u (RT) ⩾ 525 MPa in as welded and *T* direction
S_u (550 °C) ⩾ 380 MPa in as welded and *T* direction

Data sheet 9543.1 values for qualification test coupons are given below:

Position 1G (flat):
S_u (RT) ⩾ 540 MPa in *L* direction
S_u (RT) ⩾ 525 MPa as welded in *T* direction
S_u (450 °C) ⩾ 400 as welded in *T* direction

6. Additional analyses

6.1. General

Codebooks such as RCC-MR do not give materials properties data that are the origin of their recommendations. These are usually available in the supporting documents, such as the Appendix A (see e.g., Appendix A for 316L(N)-IG, Ref. [5]).

In the additional analysis that follows, we will compare the materials properties data available for 19-12-2 (OKR3U) weld metal with the tabulated values given in RCC-MR. The main purpose of this comparison is to verify that the safety margins incorporated in the code recommendations are still valid when these materials are used under ITER and its anticipated future conditions.

Recommendations for low temperature weld metals are relatively simple and do not require additional analyses. The additional analyses are, therefore, performed only on high temperature grade: the 19-12-2 grade known as OKR3U. Experimental data used in this file are taken mainly from the CEC Study contracts such as CT-92-0211-F [6] and selected ITER partner reports [5,7–15].

6.2. Mechanical properties

Experimental data reported for tensile strength of 19.12.2 (OKR3U) weld metal are shown in Fig. 1.

Equation fitted to the data in the temperature range of 20–700 °C is:

$$S_u(\text{ave}) = 606.83 - 0.993190\theta + 0.0029250\theta^2 - 3.1479 \times 10^{-6}\theta^3, \quad (1)$$

where θ = temperature (°C) and S_u = tensile strength (MPa).

The usual code practice is to multiply the average values at temperature by the ratio of specified minimum value at RT over the average value at RT to obtain the minimum values at temperature. Here, the minimum curve is obtained by simply shifting the average curve by the difference between the average and minimum values at room temperature (38 MPa). This is a more conservative approach and has also been used for 19.12.2 weld metal in the code.

Fig. 1 shows that the minimum curve obtained in this way is also above the specified values at 450 and 550 °C. The few data at RT that fall below the minimum curve are from the T direction that correspond to RCC-MR specified min value of 525 MPa.

Nevertheless, the simple shift approach is not suitable for extrapolation to temperatures higher than 700 °C. S_u average in the temperature range of 700–900 °C is tentatively represented by:

$$S_u(\text{ave}) = 10047 - 34.277\theta + 0.040204\theta^2 - 1.6 \times 10^{-5}\theta^3. \quad (2)$$

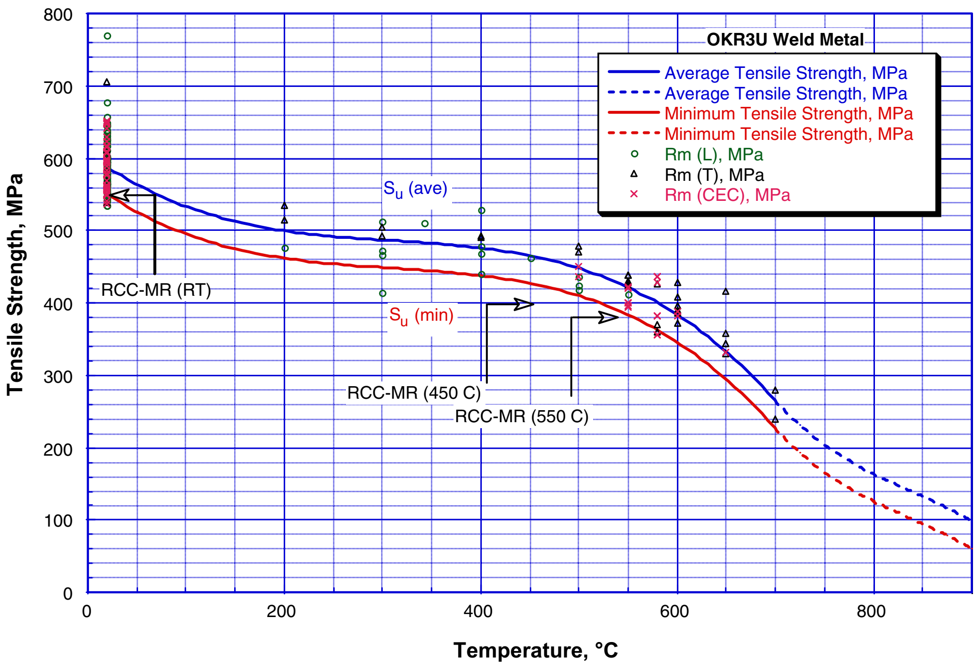

Fig. 1. Dependence of S_u average and minimum on temperature for 19-12-2 weld metal. (experimental data: triangles = L and circles = T orientations).

6.3. Effect of weld thickness and welding position

Codes such as RCC-MR ([1]) contain comprehensive guidelines and recommendations for different types of welds, sizes, forms, etc. Here, two aspects that may not appear clearly in codes are analysed: namely weld thickness and welding position.

Most of the weld data shown in Fig. 1 come from tests performed on specimens taken from small and large weld deposits (molds). Such data are useful for characterization of bulk weld metal but may not fully reflect variations of the properties in the welded assemblies. Fig. 2 shows the results obtained from tests performed on welded joints with joint thickness of 15–126 mm. It can be seen that despite the large variations in size, the joint strength in all three welding positions has limited scatter.

Fig. 3 extends the above observation to higher temperatures for the tensile strength versus the test temperature for different welding positions. Here, the results from the flat welds are situated in the lower part of the dispersion band, but again the scatter is small.

6.4. Structural stability tests

Two types of tests are performed for verification of structural stability of the weld materials. One is part of the acceptance tests and consists of U-notch Charpy impact tests in T direction after short time exposure of weld metal to a high temperature. The other is the long time aging of weld metals at various temperatures. The latter is part of high temperature service qualification and is not needed for service at low temperatures. A third type of tests may be needed for fusion components that have to be subjected to HIPing after welding.

(a) Initially for the high temperature welds, the accelerated aging tests were: 15 h of exposure

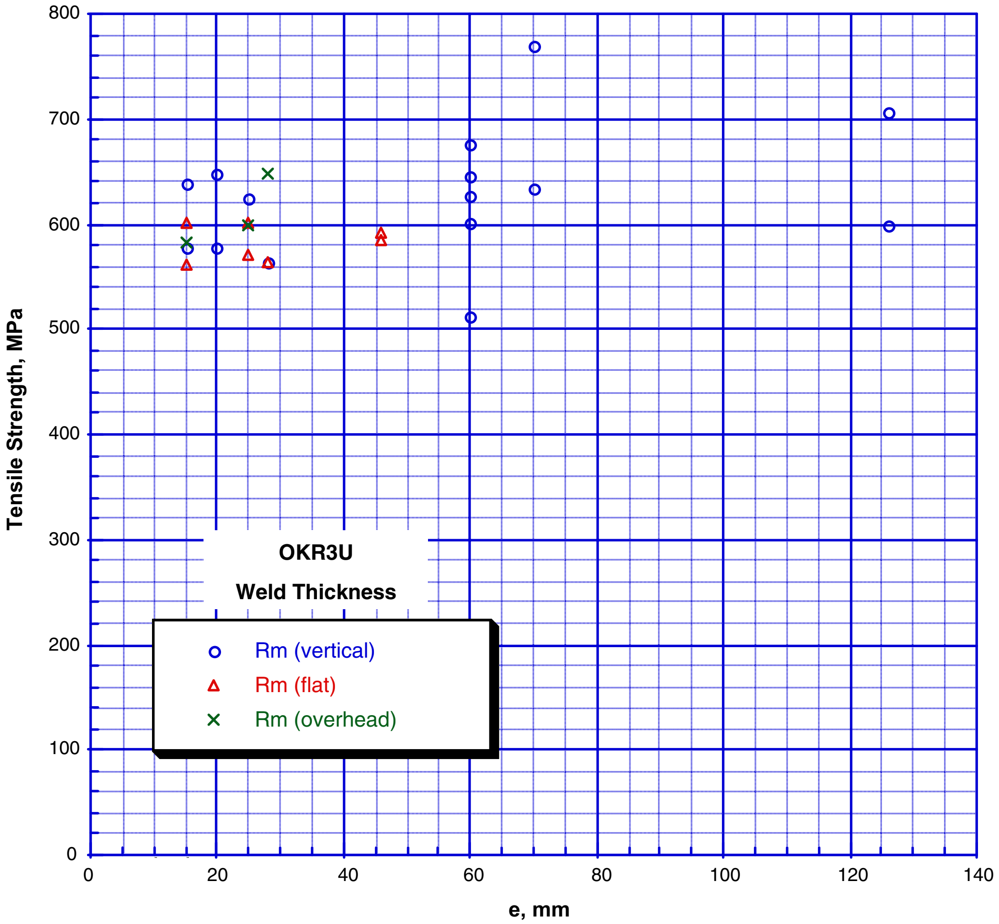

Fig. 2. Effect of joint thickness on room temperature tensile strength of OKR3U welds in three different orientations.

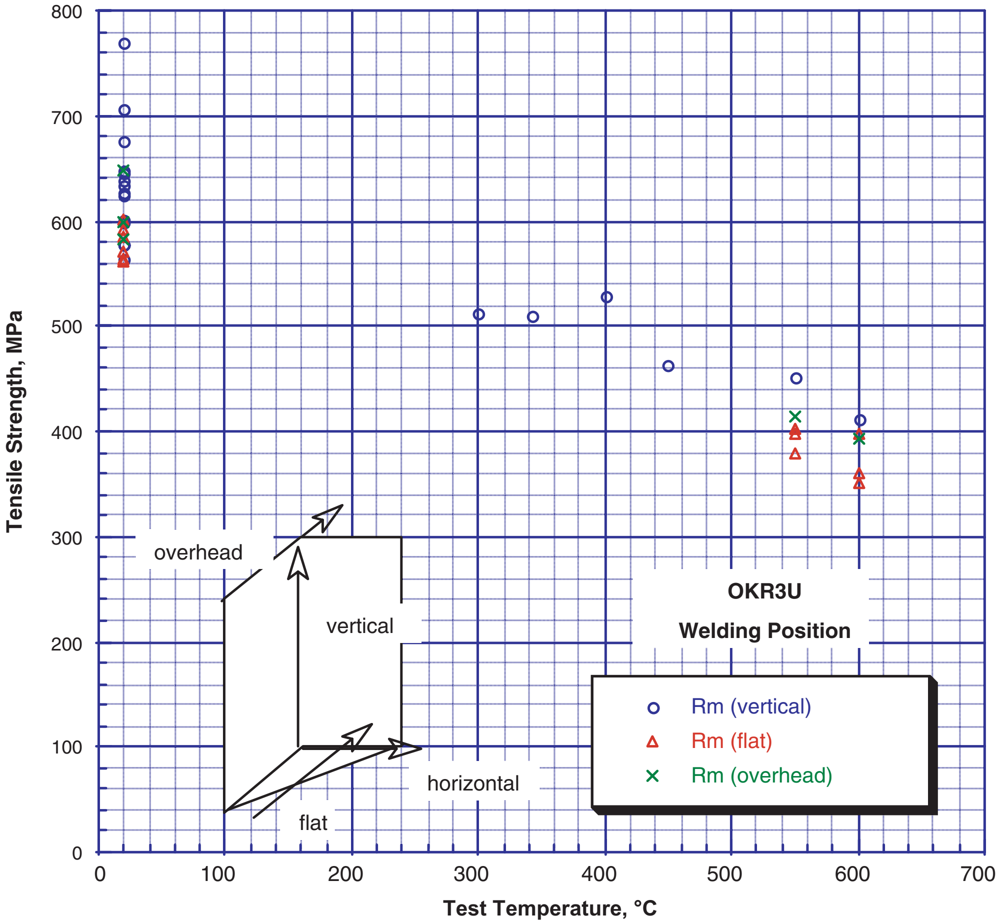

Fig. 3. OKR3U tensile strength versus temperature in three different welding positions.

at 850 °C. Later, however, this temperature was considered excessive and the tests were done for 100 h at 750 °C. The results of tension tests performed on OKR3U weldments after 100 h exposures at 750 °C are all situated above the minimum curve shown earlier in Fig. 1.

(b) Fig. 4 shows the effect of aging at different temperatures on the tensile strength of OKR3U. The tensile strength of the weld metal remains stable at ageing temperatures up to 750 °C and only at higher temperatures is there a significant drop in strength. This does not mean that some microstructural transformations do not occur in the weld metal at lower temperatures. It simply means that the effects of such transformations on S_u are negligible.

(c) Some ITER welded joints may go through the HIPing treatments along with the parts that are HIPed. Tension test results obtained after exposure of OKR3U weld metal to 1050 °C followed by cooling at a rate of 100 °C/h show that the strength of the weld is reduced to about that of the base metal.

6.5. Effect of irradiation

During the initial phase of ITER operation the effect of irradiation on vessel and in-vessel components is kept low: dose levels <3 dpa guard against irradiation embrittlement and the amount of helium generated <1 appm allow for reweldability. However, even at such dose levels there are changes in the mechanical properties. In any case, for future phases of ITER operation the effects of higher doses need to be investigated.

As shown in Fig. 5 the effect of irradiation on tensile properties of the weld metal is similar to effects in the base metal, although the variations are less pronounced (weld metal has a higher strength and a lower ductility to start with). At

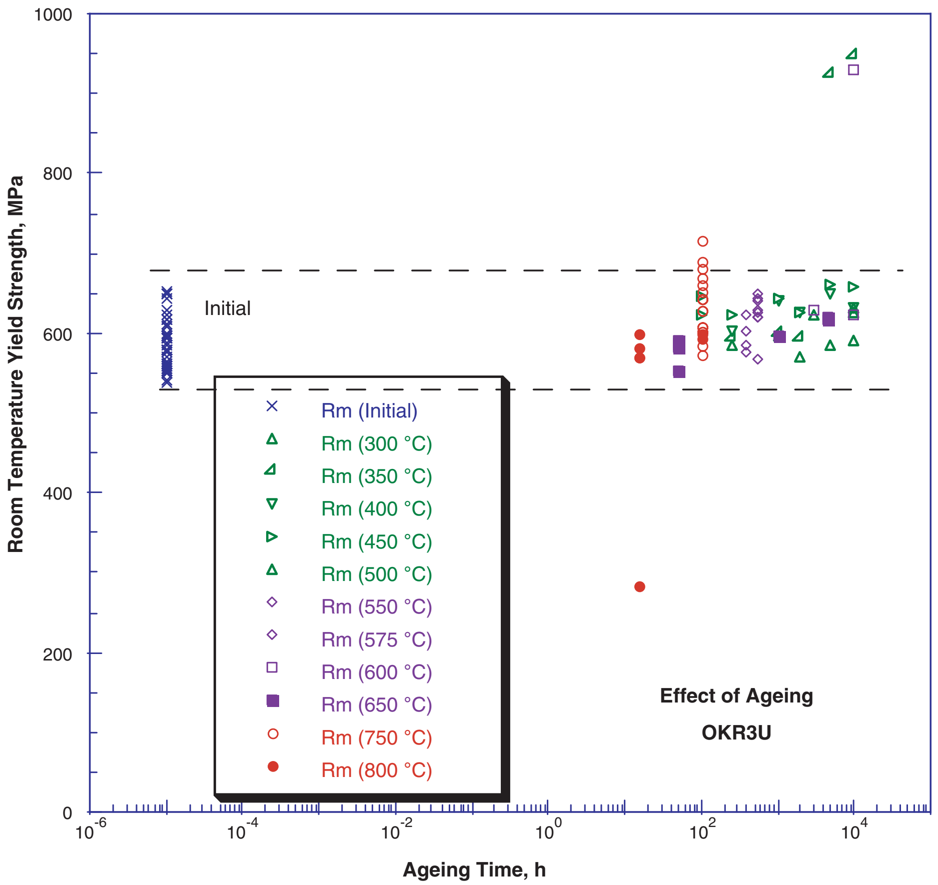

Fig. 4. Effects of ageing on tensile strength of OKR3U weld metal.

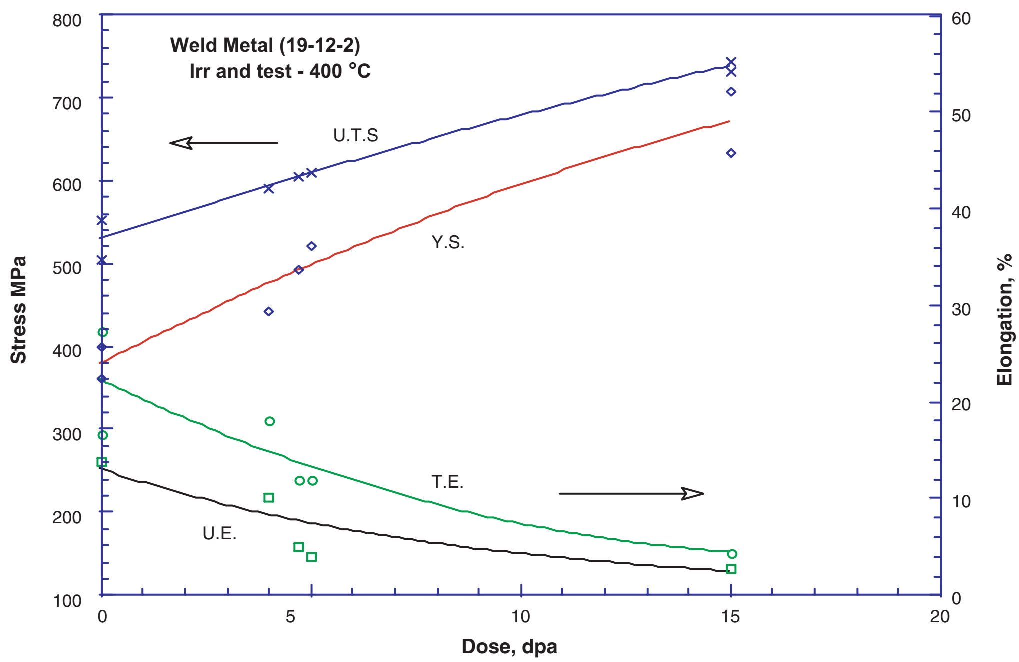

Fig. 5. Effect of irradiation at about 400 °C on tensile properties of OKR3U weld metal.

irradiation temperatures below about 400 °C, there is a hardening effect, i.e., an increase in tensile strength associated with a decrease in ductility. Saturation in hardening and reduction in ductility is observed with increasing dose level. When the test temperature is increased to above about 500 °C, the hardening effect observed in materials irradiated at low temperatures is reduced and eventually becomes negligible at higher test temperatures. The reduction in ductility, however, persists at higher test temperatures due to the presence of helium at grain boundaries, as reported for the base metal ([5]).

6.6. Design allowables

Comparison of S_m values derived from the base metal properties data with those derived from weld metal data show that the latter are bound by the former.

7. Conclusions

The above analyses show that both the low temperature and high temperature grades of 316/19-12-2 weld metal satisfy the existing code requirements. The evolution of tensile strength of weld metal under ITER initial conditions is moderate and covered by the safety margins already included in the code.

Acknowledgements

This work is supported by EFDA and is performed in the frame of the European contribution to ITER.

References

[1] Design and Construction Rules for Power Generating Stations, Design and Construction Rules for Mechanical Components of the FBR Nuclear Islands, RCC-MR, Section IV Welding, AFCEN, Edition 2002.

[2] ASME, Boiler and Pressure Vessel Code, Code Cases, Nuclear Components N-47-24, Class 1 Components in Elevated Temperature Service, Section III Div. 1, 1986.

[3] ITER Interim Structural Design Criteria (ISDC), S 74 RE 2 97-02-30 W 1.2, IRB/Welds/Revision 3.

[4] Design and Construction Rules for Mechanical Components of the LWR Nuclear Islands, RCC-M, AFCEN, Edition 2002.

[5] A.A. Tavassoli, Fusion Eng. Des. 29 (1995) 371, See also Appendix A of ISDC for 316L(N)-IG.

[6] T. Forgeron, A.A. Tavassoli, J. Wareing, D. Lehmann, C. Escaravage, B. Breitling, C. Picker, Effect Of Thermal Ageing on Mechanical Properties of Type 316L(N) Base and Weld Metals, CEC Study Contract CT-92-0211-F, CEA Report 94.

[7] J.L. Puzzolante, M. Scibetta, R. Chaouadi, W. Vandermeulen, Tensile and Low Cycle Fatigue Properties of Solution annealed Type 316L SS Plate and TIG Weld Exposed to 5 dpa at Low Temperature (42 °C), BLG-821, SCK·CEN, September 1999, ITER Library Number – SS39, SS50.

[8] J.W. Rensman, J. Boskeljon, M.G. Horsten, M.I. De Vries, Irradiation Testing of Stainless Steel Plate Material and Weldments, Tensile Properties After 0.5 and 5 dpa at 350 K and 500 K, Report ECN-C-97-088, October 1997, ITER Library Number – SS17.

[9] G.L. Tjoa, J. Boskeljon, D.S. D'Hulst, M.I. de Vries, Results of Tensile tests on Type 304 and 316 Stainless Steel Plate and Welded Joints, Report ECN-I-94-007, February 1994, ITER Library Number – SS100.

[10] H. Yamada, H. Kawamura, Qualification of structural materials and joints, Final report on ITER task T427 JA, Task No G 16 TT fr 97 FJ, May 2001, ITER Library Number – SSCuJ19.

[11] W. Vandermeulen, W. Hendrix, V. Massaut, J. Van de Velde, Ch. Raedt, FAFUMA 1 test results, FT/MOL/90-01, WV/MJW-V, Mol, February 1990, ITER Library Number – SS87, SS1.

[12] R. Källstrom, B. Josefsson, Y. Haag, Results from Tensile Testing of 316L Plate and Weld Material, Studsvik Nuclear – Report No. Studsvik/M-93/45, April 1993, ITER Library Number – SS7.

[13] M.G. Horsten, J. Van Hoepen, M.I. de Vries, Tensile Tests on Plate and Electron-Beam Welded Type 316L(N) Material, ECN, Petten, NL – Report No. ECN-CX-93-112, November 1993, ITER Library Number – SS9.

[14] A. Rowcliffe, Irradiation Testing of Stainless Steel and Inconel Including Welding and Rewelding of Irradiated Materials, Final report on ITER task T214 US Task No G 16 TT fr 75 95-07-04 FU, March 1998, ITER Library Number – SS29.

[15] H. Sagawa, Irradiation Testing of Stainless Steel and Inconel Including Welding and Rewelding of Irradiated Materials, Final report on ITER task T214 JA, Task No G 16 TT fr 73 95-07-04 FJ, June 1998, ITER Library Number – SS30.