REVIEW OF WELDMENT CREEP AND FATIGUE STRENGTH REDUCTION FACTOR FOR DESIGN OF ELEVATED TEMPERATURE COMPONENTS

Chetal S.C. and Chellapandi P.
Nuclear Systems Division
Indira Gandhi Centre for Atomic Research
Kalpakkam 603 102 INDIA

ABSTRACT

Weldments can be the life limiting feature of high temperature components and premature failures of weldments have become a matter of concern in the recent times. In order to allow for the weakening effect of the welds in the design, factors are applied to the parent material properties. The two factors which are of current interest are the fatigue strength reduction factor, and the creep strength reduction factor, although the creep-fatigue strength reduction factor also needs consideration. This paper provides some of the background for these factors and their use in the nuclear as well as non-nuclear pressure vessel design codes. The results of recent works carried out for ferritic steels, austenitic steels and dissimilar metal welds are also brought out.

INTRODUCTION

In high temperature plants, life is usually limited by the welds rather than by the parent material. In many of the instances which were reported, failures occurred before the end of the design life. The premature failure of welds can be attributed to a number of causes like plant operated under different conditions, extension of defects and cracks in welds during service, poor welding procedures and incorrect post weld treatment, inferior mechanical properties of welds, overheating and over stressing. All design codes specify a series of weld procedure tests. For components which operate in the non-creep temperature regime, failure associated with the weld due to mechanical properties is not expected to occur. In the case of plants which operate at high temperature the weld procedure tests and the tests on production welds at room temperature cannot give such an assurance. Long term performance can be ensured only by defining proper allowable stress levels for weldments so that full design life will be achieved.

There is also additional issue of fatigue damage on startup and shutdown thermal cycling and creep fatigue interaction effects. This is particularly important in the case of transition joints and thick components. Thermal fatigue has led to weldment cracking in a number of liquid metal reactor components.

So far, only minimal design guidance for weldments has been included in the nuclear design codes. Notable examples are the creep and fatigue strength reduction factors introduced in the ASME code case N-47-29[1] and RCC-MR [2]. These factors significantly improve the overall elevated temperature design methodology for welded components.

This paper provides some of the background of the creep-rupture and fatigue strength-reduction factors that are used on the allowable stresses of the current nuclear design codes.

Issues related to the adoption of these weld strength reduction factors that are used in the design of nuclear power plant components, for the non-nuclear components are also addressed. In this, the results of recent works carried out for ferritic steels, austenitic steels and dissimilar metal welds are also brought out.

FAILURE EXPERIENCES AND DEGRADATION OF WELDS AT HIGH TEMPERATURE

Failure Experience of Weldments in Fossil Plants

Recently, elevated temperature features have begun to occur in some fossil plant welded pipes. In June 1985, a failure (a fish mouth shaped axial rupture in one side of the weld fusion line) on a hot reheater pipe (0.76m diameter 11/2Cr-1/2Mo steel) is reported [3]. This failure occurred after 10.5y in the pipe that should have lasted ~ 30y. Another failure of reheater pipe (a line crack ~ 5.5m along the weld fusion line) is reported in the same ref [3] after 12 y of operation. The failure of these two welds are clearly due to the fact that local stresses exceeded the allowable limit after particular years of operation due to mismatch of creep properties of the welds and the parent metal.

A failure of 1/2Cr-1/2Mo-1/4V pipe is reported in ref [4]. This is a Type IV cracking caused by the development of a very thin, weak zone in the intercritically annealed parent material adjacent to the convectional heat affected zone. The development of this zone means that, in the long term, the complete weldment becomes significantly weaker in the transverse direction than in the direction parallel to the weld. At 100 000 h there is around a 50% loss of strength, which was not taken into account when the plant was designed. The operating temperature of all the above 3 components is about 565 deg C.

More recently, Type IV cracking associated with a weak band in the parent material adjacent to the heat affected zone has started to show up, in some instances as early as 50,000h[5]. The material of construction is 1/2Cr-1/2Mo-1/4V at 560 deg C. This form of failure is not associated with the fabrication process. It represents the end of the useful working life of the weld in plant which was designed for a nominal 10^5h service. Because of the large number of nuclear plants in France, the EdF fossil fuelled plant has been opeated in two-shift or peak load regimes. This has led to a preponderance of fatigue or creep-fatigue failures in welds, in distinction to the creep failures observed in power stations in the UK which have opeated under relatively steady base-load conditions.

Failure experience of Weldments in Nuclear Plants

Generally thermal fatigue has led to weldment cracking in a number of liquid metal reactor components. For example, the French Phenix liquid-metal fast breeder reactor, although extremely successful overall, was initially plagued with several problems of weldment cracking [6,7]. More recently failures were reported in the weldments during a phenomenon called thermal striping [8]. To quote some more examples, in British Dowireay Fast Reactor (DFR) and Prototype Fast Reactor (PFR) thermal fatigue cracks were developed in the primary and secondary pipe welds[9]. Fast reactors in the Soviet Union have also reportedly experienced weldment failures [10].

Lesson Learnt from Weld Failures at High Temperature

The number of weld failures, expressed as a percentage of the total number of welds in the plant has been relatively small so far. However, there is a marked increase as the plant gets older. One aspect which is of particular concern is that a significant proportion of the weld failures have occurred long before the design life of the plant has been reached. The reason for this lies in the design procedures which are currently used for boilers, pipe work and other high temperature components. Many of the failures occurred because the plant had not been designed to accommodate cyclic loading. In the case of weld failures in fast reactors, the cause was identified as fatigue or creep fatigue resulting from repeated thermal transient loading. Although lessons regarding such aspects as weld placement, composition, and procedures were learned from these incidents, the need for explicit, experimentally based design rules is clear.

The adoption of weld design procedures that are used in the current design of nuclear power plant components, for the non-nuclear components, would do much to eliminate failures in future design.

WELDMENT STRENGTH REDUCTION FACTORS IN DESIGN CODES

An important responsibility of a designer is to select a proper allowable working stress or safety factor for welds used in the design. It is generally believed that adequate weldment life can be best ensured through the basic margins on allowable stress. One advantageous way to achieve this is to express the strength of the weld metal in terms of the strength of the parent metal modified by an efficiency factor, say R, < 1 to compensate for possible variations in the weld quality and approximations in the stress computations.

Elevated temperature design rules are included in both nuclear and non-nuclear codes. There is no doubt that codes constitute a significant asset to regulatory agencies, manufacturers, users, engineering community and to the public. However, one should recognise that codes are not perfect and in certain cases represent a liability. Present rules for qualification of weld procedures, welders qualification, weld inspection and weld efficiency factor do not necessarily provide safeguard for elevated temperature welded structures. Treatment to weld design, based on parent material property for creep and fatigue is oversimplified and may be non-conservative in certain cases. There are enough reasons to conclude that non-nuclear design codes for elevated temprature design .of welded structures represent liability. Part of this difficult situation is the inability of the various segments of our profession (for example, metallurgists and stress analysts) to work together.

Weld Strength Reduction Factors in Non-nuclear Presssure Vessel Codes

High temperature pressured components in fossil power stations, as well as in chemical and petrochemical industries, are usually designed by simple rules based on base material propeties and by introducing weld joint efficiency factor which is a function of weld geometry and inspection.

For example, the design methods developed to permit calculation of an appropriate component wall thickness (t), are based on the internal design pressure (P), and the outside diameter (D), using the expression :

$$t = PD/(2SE + P)$$

where E is an efficiency factor and S the allowable component stress. E which is a function of weld geometry and inspection represents the weld strength reduction factor. This design does not address the issue that properties of weldments could be inferior to base material at elevated temperature. To illustrate this, the following Table 1 is shown wherein the strength reduction factors JRT are shown for certain welds [11]. The

TABLE 1 : TRANSVERSE STRENGTH REDUCTION FACTOR

Base metal	Weld Metal	Welding process	Temp. deg C	Time h	JRT
1/2 CrMoV	2 Cr	MMA	565	50000	0.60
P91		MMA	570	10000	0.65
X20			600	60000	0.50
			575	60000	0.80
316L	19-12-2L	TIG	550	60000	0.95
			550	10000	0.85
316Ti	19-12-3Nb	'EG	600	20000	0.80

strength reduction factor JRT is defined as the stress applied to the weld in the transverse direction to cause failure in the stated time, divided by the stress which would have to be applied to the parent material to cause failure in the same time.

Even under relatively steady creep conditions, some caution is needed in the application of the strength reduction factors presented in the Table 1. The reason for this is that the parent material, weld metal, HAZ and other narrow bands of materials will have different specific creep deformation rates. As a result, the material which creeps the fastest will shed stress to regions which creep relatively slowly. Fig.1 shows a typical result for a butt weld in a tube under internal pressure after steady state conditions have been achieved. The HAZ creeps more slowly than the other portions and is subjected to a stress significantly higher than that would be presented from simple calculations. In this particular instance, the observed failure time was predicted with reasonable accuracy by reading from the rupture curve for the HAZ at this higher stress level.

Weld Strength Reduction Factors in German Codes

In AD-Merkblatter S2 (1977) [12], for fully stressed welded joints in pressure parts which are operated in the creep range the calculation should be based on a strength value

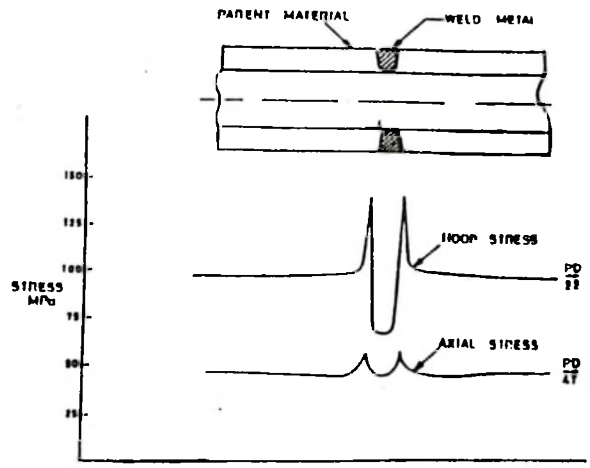


Fig.1: Stresses in weld in pipe under internal pressure. Weld metal softer than parent material, hard HAZ

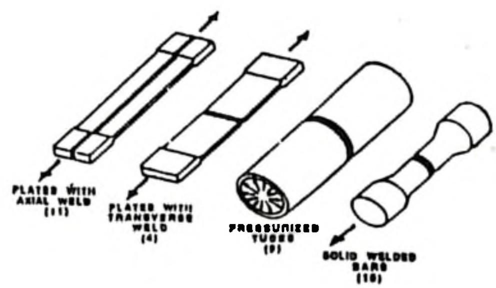


Fig.2: Test specimens and loadings for confirmatory tests for creep strength reduction factors.

which is 20% lower than that of the base material as long as no creep data of the weld deposit are available.

Weld Strength Reduction Factors in British Design Codes

In the UK, the design rules are based on ASME Code Case N47 high temperature and the LTK master pressure vessel code BS 5500 for low temperature applications. The BS 5500 uses a single fatigue design curve derived from tests on flush ground weldments. For full penetration butt weldments, the fatigue curve lies beneath the RCC-MR design curve and supports the use of an empirically derived fatigue strength reductin factor (FSRF) greater than unity. The thermal peak strains are considered local and do not enhance the stress concentration effect of the weld.

For flush ground full penetration butt and dressed tee butt weldments subjected to full inspection, the geometrical stress concentration is determined by the designer. A FSRF-1.5 is applied to the local strains for estimating fatigue damage. For calculating creep damage, the FSRF is put equal to unit and the effective stress is calculated from the detailed analysis of the welded profile. For as-welded full penetration tee butt weldments, a FSRF of 2.5 is applied to the strain range computed from mechanical loading and 1.5 is applied to the thermal strains. For partial penetration weldments the FSRF are 3.2 and 1.5 respectively. The creep damage is calculated using the effective creep stress obtained from the factored total strain ranges for each weldment type.

Also in the UK a new life assessment method is under development [13]. The procedure is reported in R5. Recent issue of R5 contains 7 Volumes. Volumes 6 and 7 are completely devoted to weldments. Volume 6 uses a simplified reference stress method to assess the behaviour of dissimilar metal weldments. An appropriate multiaxial definition of the reference stress in the region of the transition joint is evaluated and used in conjunction with laboratory data on cross-weld specimens to estimate the creep damage fractions in the transition joint. This is then added to fatigue damage fractions, allowing for strains induced during temperature changes as a result of the different thermal expansion coefficients of the material in the joint to give the total damage fraction. The approach has been validated by comparison with model tube tests and some full scale pressure vessel tests for a limited range of material combinations and temperatures. Volume 7 addresses the behaviour of similar welds and Issue I gives guidance for steady state creep loadings of CrMoV pipe work. In particular, factors are given to allow for the stress redistributions which occur in weldments as a result of off-loading of stress from the weaker constituent materials to the stronger ones. For as-welded weldments, the additional concentration effect of the reentrant corners is also covered by the FSRF. For as-welded full penetration butt weldments, FSRF of 1.5 is applied to strain ranges whether derived from mechanical or thermal loads.

Weld Strength Reduction Factors in Nuclear Pressure Vessel Codes

Nuclear structures are subjected to rigorous design analysis. The stress and strain analysis is carried out as if the structures were made of homogenous material and factors are then applied to the parent material failure properties to allow for any weakening effect of the welds. The two which are of current interest are the fatigue strength factor, and the creep strength reduction factor, although the creep-fatigue reduction factor also needs consideration. In the following sections weld strength factors introduced in various design codes used for fast reactor design are illustrated with their background.

Weld Strength Reduction Factors in ASME Code Case N 47

The ASME Code Case N47 took into account the welding effect for the first time in 1987.

Creep Strength Reduction Factor

In the code the primary time and temperature dependent stress limit St is defined to be less than or equal to 2/3 Sr, where Sr is the expected minimum creep-rupture strength of the base metal. At weldments, the allowable stress limit St is specified to be the lower at the tabulated values for the base metal or 0.8 Sr x R where R is the appropriate ratio of the uniaxial weld metal creep-rupture strength. Average creep rupture curves obtained from all weld specimens were compared to average base metal curves to develop the R factors [14]. The appropriate R values for various allowable weld filler metal/base metal combinations are listed in the tables in Code case N47. These factors are given for 2.25Cr-1Mo,SS 304, SS 316 and Alloy 800 welded with traditional welding process and consumable. As an example, the R factor table for 316 stainless steel welded with 316 filler metal is reproduced in Table II.

TABLE II : R FACTORS FOR SS 316 WELDED WITH 316 FILLER METAL

Temp (F)	Rupture time (h)									
	10	30	100	300	1000	3000	1×10^4	3×10^4	1×10^5	3×10^5
850	1.00	0.98	0.95	0.95	0.95	0.94	0.92	0.92	0.92	0.92
900	1.00	0.94	0.88	0.88	0.88	0.87	0.84	0.84	0.82	0.82
950	1.00	0.90	0.81	0.81	0.81	0.80	0.77	0.76	0.73	0.72
1000	1.00	0.87	0.75	0.75	0.74	0.73	0.70	0.68	0.64	0.62
1050	1.00	0.89	0.78	0.78	0.77	0.76	0.74	0.72	0.67	0.60
1100	1.00	0.90	0.81	0.81	0.79	0.79	0.76	0.71	0.69	0.63
1150	0.90	0.88	0.86	0.82	0.79	0.77	0.74	0.70	0.64	0.57
1200	0.81	0.80	0.79	0.79	0.76	0.75	0.70	0.64	0.57	0.49

For this example, the reduction factors drop below 0.7 at higher temperature and higher life. The quantity Sr x R used in determining the allowable stress limit at weldments is essentially the minimum expected creep rupture strength of the weld metal. Thus, the intent of the code is to simply substitute weld metal creep-rupture strength for base metal strength in determining St at a weld. Then why the factor 0.8 rather than 2/3? The factor 2/3 already includes some allowance for reduced weld strength. Use of the 0.8 factor for weld metal produces a further reduction in St only if the weld metal strength reduction is fairly pronounced. Substantiation of the overall adequacy of the Codes primary stress limits for weldments was done based on 40 pertinent structural weldment creep rupture test results. The various specimen types employed are depicted in Fig 2.

Fatigue Strength Reduction Factor

Elevated temperature fatigue data for both austenitic stainless steel (Type 304 and 316) and ferritic steels (2.25Cr-lMo and modified 9Cr-lMo) weldments generated both under the DOE reactor programs and under similar programmes in the UK, France, Germany, the Netherlands and Japan are systematically analysed. Weldment fatigue data are usually generated by using 3 different types of uniaxial solid-bar specimens as shown in Fig 3a. The general trend of the data studied from these three specimen types is depicted in Fig ib. In terms of strain range, the reduction factor varies generally between 1.5 and 1.8, although, depending on weld process, the factor can be somewhat larger for 2.25Cr-1Mo steel weldments. At very high and very low strain ranges, there is often little difference between weldment and base metal. The premise is that these observed differences are largely due to the metallurgical notch effect resulting from widely varying yield strengths in weld and base metal. At low strain ranges (high cycle fatigue), little yielding is believed to occur, thus, the metallurgical notch effect is minimal. At large strain ranges, which are outside the normal design region, any hardening and softening occur quickly. For the intermediate strain ranges, there is a difference in yield strength across a weldment specimen, the fatigue life will be reduced.

Based on the available data and also the possible structural ramifications, a reduced elevated temperature of only 1.2 on strain ranges was judged to be adequate for elevated temperature design. In the midcycle range of the code case N47 design curves, this corresponds, approximately to a reduction factor of two on cycle life. Thus the actual rule reads : In the vicinity of a weld (defined by ± 3 times the thickness to either side of the weld central line), the fatigue evaluation shall utilise reduced values of the allowable number of design cycles, Nd. The Nd values shall be one-half the value permitted for the parent material.

Confirmatory tests have been done on tubular and torsional specimens. Fig 4 shows the specimen details. Fig 5 shows the comparison of tubular weldment fatigue data with the tubular base metal axial fatigue data curve. If the safety factor of 20 on cycles to failures were applied to the circumferential weldment data, the "design points" would fall slightly below the proposed weldment design curve for fatigue. However, welds do not normally compose almost one-half of a region experiencing a fixed cycle deformation as the case of test specimens. Thus it is believed that the tubular weld data support the suitability of the code factor for the fatigue of welded joints at elevated temperature.

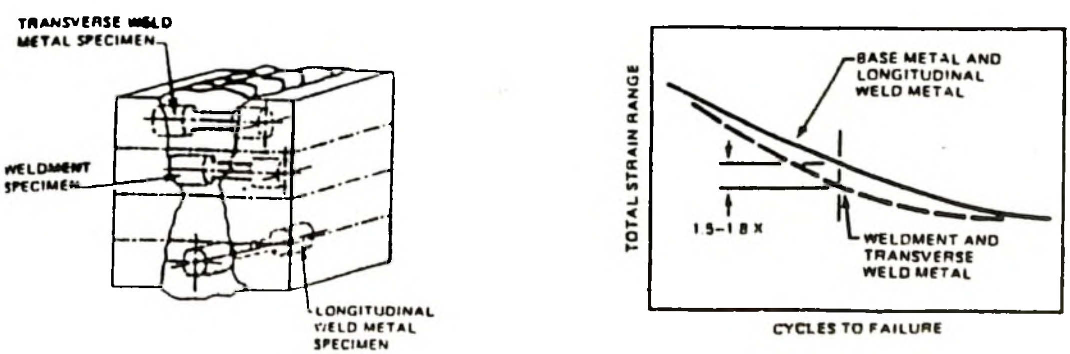
TABLE III : FATIGUE STRENGTH REDUCTION FACTOR IN RCC-MR

	Parent material	Weldmetal and welding procedure	Type of weld and inspection
Time independent stress limit	Sm	Jmsm	nJmSm
Time dependent stress limit	St	itst	nJtSt
Creep damage	Sr	JrSr	nJrSr
Fatigue damage	Fatigue curve $\Delta\varepsilon$ >N	Fatigue curve 1 JL$\Delta\varepsilon$ >N	Fatigue curve f$\Delta\varepsilon$.Jf >N

J, n & f factors are presented in RCC-MR A3 Appendix Z (1993) for some limited materials.

Weld Strength Reduction Factors in RCC-NM Code

The RCC-MR rules are mainly based on the experience gained in France in the construction of Superphenix 1 and also the experience gained by the other European countries. Accordingly a common approach to the design of weldments are presented [15]. For the design calculations the data of the parent material of the component should be used and the metallurgical features of the joint are not required to be specifically modelled. To take into account the effect of weldments several reducing factors should be used which are applied to the parent material allowable limit. Basically 3 reduction factors are introduced. They are "J" factors to account for the material differences with respect to parent material behaviour, "n" factors to cover the possibility of defects being present in the weldments and it is related to the type of inspection formed and "f" factors to be used as a fatigue strength reduction factor and is dependent on the type of welds. These factors are operated on parent material property data as seen in Table III.



(a) Specimen orientation (b) Schematic of test results

Fig.3: Trends of available weldment fatigue data.

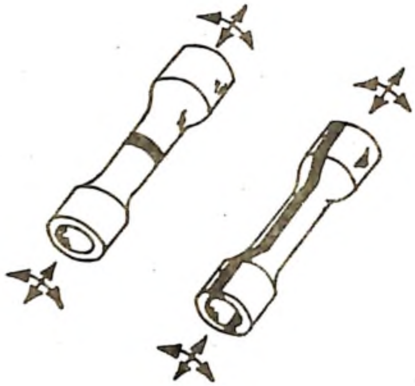


Fig.4: Tubular fatigue specimens for confirmatory tests on fatigue strength reduction factors

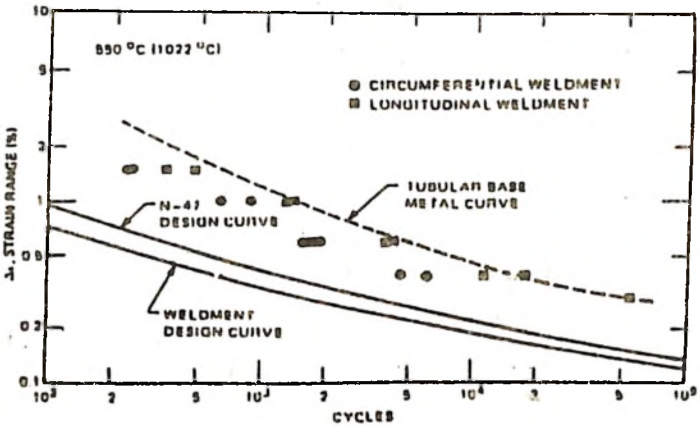


Fig.5: Comparison of tubular weldment fatigue data with tubular base-metal axial fatigue curve.

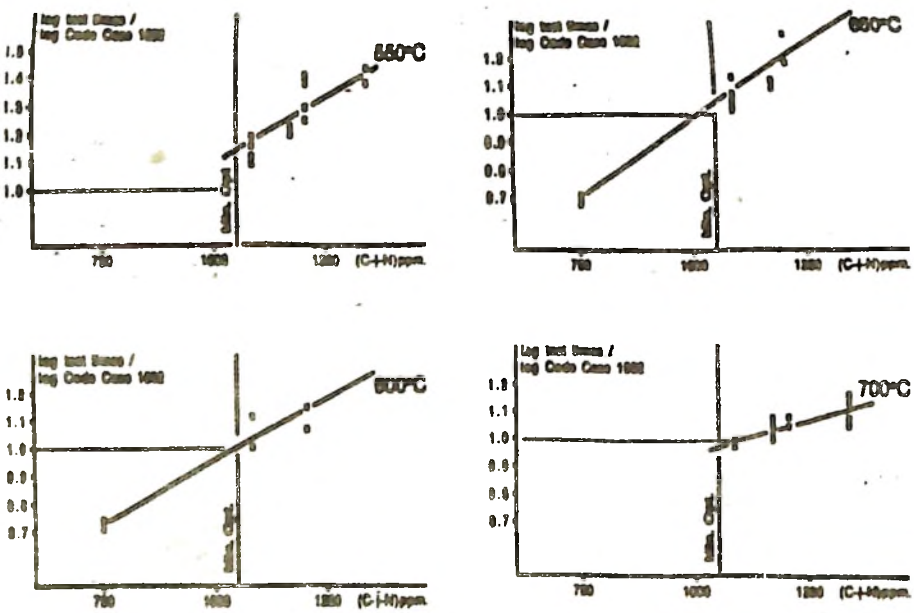


Fig.7: Optimisation of filler wire composition to arrive at lower reduction in the weld strength.

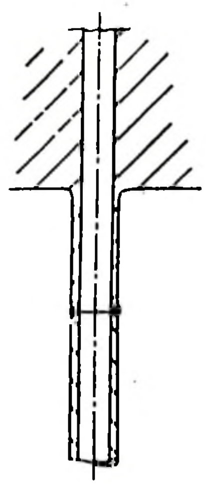


Fig.6: Tube-pintle weld for SG

Reduction Factors for SS316LN

Jm, Jt, Jr, Jf and f factors are given in RCC-MR Vol.Z. Jt and Jr are given in the tabular form as a function of time and temperature. The following are the essential features of these factors :

Jm	=	1
Jr	=	08 - 1
Jt	=	0.82 - 1
Jf	=	1 - 1.25

For full penetration weldments with full volumetric inspection, n=1, f—1 and Jf-1.25. For welding with partial penetration with reduced inspection carried out n=0.5 and f=4. These values are chosen to penalise such weldments so that they are avoided in critical parts.

Reduction Factors for Modified 9Cr-IMo

Upto now valves are not given in RCC-MR(93). Some limited data are available for this material [16]. A Jm value of unity was derived from the results of tests on LTK 9Cr-IMo weldments. The values of Jt and Jr were studied on the basis of the rupture strength of transverse butt weldments at temperature of 520-677 deg C. There is a significant reduction in weldment strength at high temperature, i.e. when approaching about 600 deg C, attributed to the so called Type IV cracking. This phenomenon is explained in detail in the reference [16]. Upto 525 deg C, a value of Jr and Jt of 0.9 is recommended for European Fast Breeder Reactor (EFR). Regarding Jf value, tests indicated that the HAZ is the weaker region. As an interim position, the value of Jf-1.25 is recommended for EFR for MMA or TIG full penetration welds (butt weldments and tee weldments) subjected to full inspection. However, it is stated that certain welds such as steam generator internal bore welding (See Fig 6) may require, in the future, specific tests to establish values of weld factors. The summary of the interim recommendations are as follows :

Jm = 1

Jr = Jt = 0.9 for temperatures between 425 - 525 deg C

Jf = 1.25 for full penetration welds subject to full inspection.

It is expected in future that RCC-MR will provide a complete set of weld strength reduction factors.

In a specific paper [17], revised fatigue strength reduction factors are recommended for RCC-NM. Essentially these are :

Type 1 weldments (butt welds) Jf = 1.5

Type 2 weldments (full penetration groove welds) = 2.5

Type 3 weldments (partial penetration welds) = 3.2

For thermal shock peak stresses a fatigue strength reduction factor of 1.5 is advocated for all types of weld.

ON-GOING R & D

Current design rules for welds are usually based upon uniaxial creep rupture strength data. The effects of stress multiaxiality and corresponding stress distribution process of welded components are relatively ignored. Experimental and theoretical investigations are under development to evaluate the weld strength reduction factors after taking into account the effects of multiaxiality [18].

To minimise the effect of weldment strength reduction at high temperature, proper choice of welding consumables is also important. Towards development of Super Phenix fast reactor, improved welding consumables are used for MMA welding for AISI 316 high temperature welding [19]. The composition is optimised for freedom from cracking, adequate input strength, absence of intergranular corrosion and creep resistance meeting ASME CC 1592 criteria for SS 316. The typical chemical composition of weld metal deposit by newly developed electrode is : C 0.05, Mn 1.1, Si 0.3, Cr 18.3, Ni 11.4, Mo 2.25, N 0.07 and Ferrite 4. It is to be noted that Nitrogen is specified. Combined effect of (C + N) on creep behaviour is well known (Fig 7).

CONCLUSIONS

Creep and fatigue weld strength reduction factors defined in the various nuclear and non-nuclear codes are discussed with sufficient background. For future high temperature fossil plants and petrochemical units, the use of weld strength reduction factors and utilisation of improved welding consumables must be made as is the case with nuclear power plants to achieve their design life with enhanced confidence.

REFERENCE

1. ASNM Code Case N-47 Class 1 Components in Elevated Temperature Service, Section III, Div 1 Cases of ASME Boiler and Pressure Vessel Code.
2. RCC-MR Design and Construction Rules for Mechanical Components of FBR Nuclear Islands, Association Francaise pour les regles de conception et de construction des materials deschaudieres electro-nucleairs, June 1985 Edition.
3. Stevick G.R, Failure of welds in elevated temperature, WRC Bulletin No 390, April 1994.
4. Coleman, M.C., Parker, J.D., and Walters, D.J., The behaviour of ferritic weldments in thick section 1/2Cr-1/2Mo-1/4V pipe at elevated temperature, Int. J. Pressure Vessels Piping, 18, 1985, 277-310
5. Thoraval, G, The behaviour of welds in EdF fossil fuel power plants, a paper in "life of welds at high temperature", High temperature structural design, ESIS12 (Edited by L.H. Larsson) 1992, Mechanical Engineering Publication, London, pp. 401-412.
6. The Phenix Nuclear Plant after three Years of operation, Central Phenix, Bagnols sur Ceze, France, July 14, 1977.
7. Conte, F., Sauvage, M., and Roumailhac, J.F., The intermediate heat exchanger leak on Phenix plant and their report, Optimisation of sodium cooled fast reactors, Proceedings of the International Conference, London, November 28-Dec 1, 1977, British Nuclear Energy Society, London, 1978, pp. 291-196
8. Ann Mc Cladhan, Small sodium leaks to delay restart of Phenix breeder, Nucleonics Week, June 24, 1993.
9. Gregory, G.V., Operating experience with the Pototype Fast Reactor at Dounreay, Proc. International Conference of Fast Reactor and Related Fuel Cycle (FR 9 1), Kyto, Japan, Paper No-5.3, 1991.
10. Saraev, O.M, Oshkanov, N. N and Vylomov, V.V., 14 year operating experience from BN600 power unit, Proc. Conference on Sodium Cooled Fast Reactor Safety, Obninsk, 1994.
11. Walters, D.J. (1976) The stress analysis of cylindrical butt welds under creep conditions, CEGB Report RD/B/N3716.
12. Design of pressure vessels, AD-Merkblatt, Edition Feb 1977.
13. R5-an assessment procedure for the high temperature response of structures (1990) Nuclear electric plc, Berkeley Nuclear laboratories, Berkeley, Gloucestershire.
14. Corum, J.M., Evaluation of weldment creep and fatigue strength reduction factors for elevated temperature design, ASNE Trans Journal of Pressure Vessel Technology, Vol.112, Nov. 1990, 133-139.
15. Acker, D., Dabaene, J.P., Lane, H., and Rose R.T., On-going developments in design methods and criteria for the LMFBR, High Temperature Structural Design, ESIS12 (Edited by L.H. Larsson), 1992, Mechanical Engineering Publications, London, pp.61-84.
16. Lane, H. et al., Design and construction rules committee for the EFR -Current status and developments - Trans SMIRT 11, Vol E Tokyo, Aug 91, Jan E02/6.
17. Escaravage, M., Bauermeister, M. and Bestwick, R.D.W., Weldment design rules for European fast reactor, 'Life of welds at high temperature', Structural Design, ESIS 12 (Edited by L.H. Larsson), 1992, Mechanical Engineering Publications, London, pp.401-412.
18. Sanstrom R.T. and TuS., The effect of multiaxiality on the evaluation of weldment strength reduction factors in high temperature creep, ASME Journal Pressure Vessel Technology, Vol 116, Feb 1994, pp.76-80.
19. Lefebvre, J., Daemen, R., and Niset, N., Welding consumable for AISI 316 high temperature weldments, Proceedings of Conference on Stainless steel-84, Sept 1984, Goteborg. pp.332-335. ☒