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CREEP OF 316L(N) STAINLESS STEEL- MECHANISTIC AND ENGINEERING ASPECTS

[1]C. Girish Shastry, [1]M.D. Mathew, [1]K. Bhanu Sankara Rao, [1]S.L.Mannan and [2]S. D. Pathak

[1]Metallurgy and Materials Group, Indira Gandhi Centre for Atomic Research, Kalpakkam, 603 102

[2]Dept. of Metallurgical & Materials Engineering, Indian Institute of Technology, Madras

ABSTRACT

Nitrogen-alloyed, low carbon grade of type 316 stainless steel has been developed indigenously in collaboration with Alloy Steel Plant (ASP), Durgapur for the nuclear steam supply system components of Prototype Fast Breeder Reactor. Creep properties of this material have been determined at 823, 873 and 923 K at various stress levels and compared with the creep properties of imported steel of similar chemical composition. Material developed at ASP was found to be comparable to the imported steel with respect to its creep properties at 823, 873 and 923 K.

Keywords: creep, design**,** activation energy

1.0 INTRODUCTION

Low carbon grade type 316 austenitic stainless steel (SS), alloyed with nitrogen, designated as 316L(N) SS, has been chosen for the various high temperature nuclear steam supply system components of the Prototype Fast Breeder Reactor (PFBR) at Kalpakkam. 316L(N) SS is selected based on considerations of its good high temperature mechanical properties, compatibility with liquid sodium coolant, weldability, availability of design data, and above all the fairly vast and satisfactory international experience in the use of austenitic stainless steels in sodium cooled fast reactors. A low carbon grade SS (0.024 to 0.03 wt%.) has been chosen to ensure freedom from sensitisation during welding and thus avoid any stress corrosion cracking that may occur during storage of the components, before installation and commissioning, due to the chloride environment in the coastal construction site[1]. Nitrogen is specified as an alloying element (0.06 to 0.08 wt%.) to increase the mechanical properties of low carbon grade 316 SS to those of 316 SS containing normal amount of carbon[2]. The PFBR specifications are more stringent than the ASTM specifications. The chemical composition has been narrowed down to reduce the scatter in mechanical properties so that accurate inelastic analyses can be carried out on the components; inelastic analyses use the non-linear stress-strain curve for modelling the material behavior under various loading conditions. The composition limits have been revised to meet specific property requirements. Lower limits for carbon and nitrogen have been specified to ensure that the mechanical properties match those of 304 and 316 SS grades for which design curves are available in the nuclear codes. Minimum limit has been specified on boron to increase creep strength and ductility. The upper limit of nitrogen is set on considerations of minimising scatter in mechanical properties and improving weldability. Phosphorus, sulphur and silicon are treated as impurities, having adverse effects on weldability. Therefore, acceptable maximum limits are lowered to the minimum values that can be achieved in steel making practice.

316L(N) SS plates have been developed indigenously in collaboration with Alloy Steel Plant (ASP), Durgapur. The mechanical properties of the indigenously developed steel are compared with the data obtained on the imported material. This paper presents the results obtained on creep properties of indigenously developed 316L(N) SS at 823, 873 and 923 K.

2.0 EXPERIMENTAL

All the creep tests were carried out in air. Creep testing of imported material, obtained from Thyssen, Germany, in the form of 20 mm thick plates, was carried out using round specimens of 10 mm gauge diameter and 50 mm gauge length. ASP steel was tested using round specimens of 50 mm gauge length and 5 mm gauge diameter; thickness of the ASP plates (12 mm) was not sufficient to machine 10 mm gauge diameter samples. The specimen blanks were given a solution treatment at 1373 K for 1 hour followed by water quenching before machining the specimens. Creep rupture tests have been conducted as per ASTM standard E139-85[3]. The creep test matrix is given in Table 1.

3.0 RESULTS AND DISCUSSION

Table 2 shows that the chemical composition and grain size of indigenously developed and imported materials. Chemical compositions of both the materials conform to PFBR specifications. The grain size of ASP material was finer than that of the imported material (60-70 μm vs 85-90 μm), but was well within the specifications (< 160 μm).

The variation of steady state creep rate with applied stress (on a log-log basis) at 823, 873 and 923 K is shown in Figs. 1a-c. At 823 K, the steady state creep data for the imported SS is not available. The steady state creep rate values of ASP material at 873 K are approximately 2 times higher than those of imported material. The data at 923 K shows that the steady state creep rate values for ASP material are higher by a factor of 5 as compared to the imported material. A power-law relationship is found to be obeyed between steady state creep rate and stress indicating that creep deformation is controlled by dislocation creep mechanism. At 823 K, the stress exponent (n) was 14.0 for the ASP material. Values of n were 15.0 and 15.6 at 873 K and 11 and 13 at 923 K for the ASP and imported grades respectively. The activation energy for creep deformation was determined for the ASP material by carrying out temperature change test at a nominal stress level of 150 MPa at different temperatures between 923 and 1023 K. Once the test reached steady state region, the temperature was increased by 25 K till a new steady state region was reached. The test was continued thus till the sample reached failure which occurred at a temperature of 1023 K. Figure 2 shows the Arrhenius plot for the variation of ln(steady state creep rate) with reciprocal of absolute temperature. The activation energy value was estimated to be 550 kJ/mol. Value of Q for the imported material in the temperature range of 873-973 K was estimated to be 585 kJ/mol[4]. Both stress exponent and activation energy are thus found to be comparable in ASP and imported materials.

A creep stress exponent in the range 4-7 and an activation energy for steady state creep deformation equal to the activation energy for self-diffusion are expected for pure metals and single phase alloys when dislocation creep is the rate controlling mechanism. From tracer diffusion experiments, Hirano and Ijima[5] have determined, the activation energy for self-diffusion of various elements in type 316 SS as 228 kJ/mol for iron, 243 kJ/mol for chromium, 143 kJ/mol for molybdenum and 260 kJ/mol for manganese. The activation energy values determined for 316L(N) SS are thus higher than the activation energy for self-diffusion mentioned above. However, the results in this investigation are in close agreement with the activation energy values for creep determined by Shinya *et al*[6] for type 304 SS and type 316 SS (410-560 kJ/mol), Morris and Harries for type 316 SS (480-500 kJ/mol)[7], and Park and Lee for type 316 SS (395 kJ/mol)[8]. The higher values of activation energy, as compared to the activation energy for self-diffusion, obtained in this study and the earlier studies reported in literature are attributed to microstructural and substructural differences (i.e. carbide and dislocation density) at the different temperatures used for activation energy determination. On the other hand, constant structure activation energy determinations carried out after initially creeping the specimens to stabilize the microstructure and dislocation structure yielded a value of 270 kJ/mol[8], suggesting that self-diffusion of various alloying constituents is the deformation controlling mechanism. Similarly, the activation energy determined after ageing to give a stabilised microstructure was found to be equal to that of the activation energy for self-diffusion in 20Cr-25Ni-Nb stabilised steel[9].

Figures 3a-c show rupture life against applied stress on a log-log plot at 823, 873 and 923 K for imported and ASP materials. The RCC-MR design curve for expected minimum stress to rupture is also superimposed in Figs. 3a-c. RCC-MR minimum curve is used in the creep design of high temperature structural components. Rupture life curve for ASP material lies well above the RCC-MR minimum curve at the three temperatures.

It is found that ASP material is slightly weaker than the imported 316L(N) SS. The creep strength of ASP material lies within 10% scatter band on rupture strength of imported material at the three temperatures. The lower rupture life of indigenously produced steel is mainly attributed to its lower nitrogen content (0.06%) in comparison to that of imported material (0.086%). Nitrogen is known to be a strong solid solution strengthening element in austenitic stainless steels. The major creep strengthening mechanism of nitrogen is by way of decreased stacking fault energy and thereby increasing slip planarity[10]. Nitrogen interacts with solutes to form complexes[11] and short range ordered precipitates[12], which contribute to strengthening. At high temperatures, nitrogen helps to refine the carbide precipitates on grain boundaries thereby retarding grain boundary embrittlement and formation of creep damage[4]. Nitrogen also lowers diffusivity of chromium and carbon in the austenite matrix thereby delaying coalescence of the carbide precipitates[13].

Indigenous material has a slightly finer grain size (60-70 μm) as compared to the imported material (85-90 μm). A finer grain size is generally known to result in longer rupture life in 316 SS in the temperature range of 873-973 K[14]. Creep tests on ASP and imported material were performed on 5 and 10 mm diameter samples respectively. Increase in section stress consequent to oxidation will be greater for the smaller diameter sample. Using Kachanov's continuum damage mechanics formulation, Pandey *et al*[15] have modeled the mechanics of oxidation damage. They have found the rate of evolution of damage to be inversely proportional to square of current sample radius. This could be another factor for the lower rupture life of ASP material.

Figures 4a-c show the variation of rupture elongation with rupture life at 823, 873 and 923 K. At 823 K, the rupture elongation of both ASP material and indigenous material decreased with increase in rupture life. At 873 K, the rupture elongation of ASP material was constant for rupture lives ranging from 7 to 2465 h. Imported material at 873 K showed a minimum in ductility at intermediate rupture lives. In the case of imported material at 923 K, rupture elongation was nearly constant initially while it decreases with increase in rupture life at long durations. At 923 K, rupture ductility of ASP material was higher than that of the imported material at long rupture lives while the reverse trend was observed at short rupture lives. The differences in rupture ductilities of ASP and imported materials were not high at 923 K. The high ductilities observed at all the test conditions indicate a predominantly transgranular mode of fracture. This is expected as the rupture times are not long enough for intergranular cavities to nucleate and grow. Figure 5 shows a typical scanning electron fractograph for the test at 923 K and 125 MPa showing transgranular fracture characterized by dimples.

4.0 CONCLUSIONS

Nuclear grade type 316L(N) SS has been developed indigenously in collaboration with Alloy Steel Plant, Durgapur. Creep strength of indigenously developed material was found to meet the design requirements. Comparison of the creep properties of the indigenously developed material with those of the imported material showed that the properties are comparable with that of the imported material. Creep strength of ASP material meets the RCC-MR minimum requirement for design of high temperature components.

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TABLE

Table 1

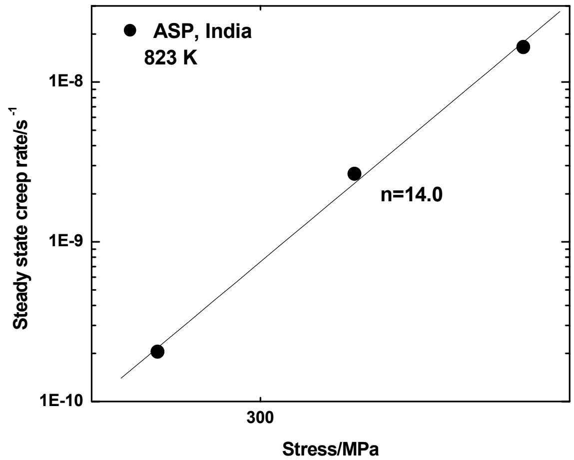
Creep test conditions

Temperature, K	Stress, MPa					
823	375		325		275	
873	325		275		225	
923	225	200	175	150	125	100

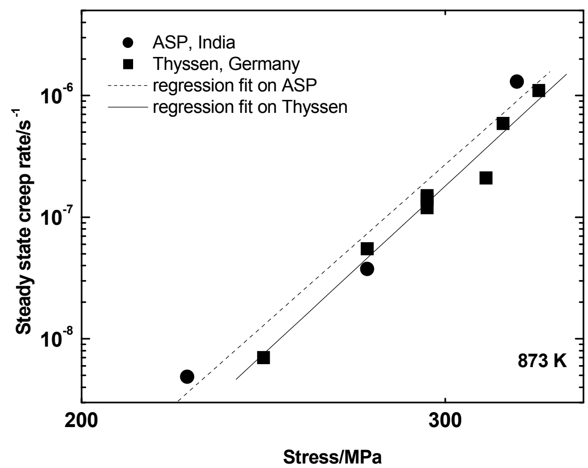
Table 2

Chemical Composition of 316L(N) SS (wt%)

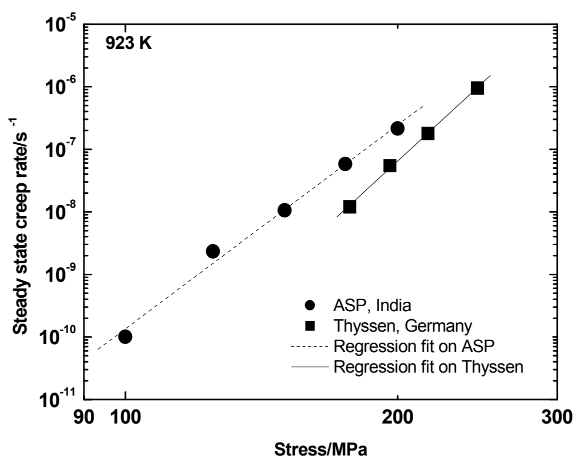
	C	Cr	Ni	Mo	Mn	Cu	Si	N	P	S	B (ppm)	Grain size (μm)
ASTM A-240 specification	0.03	16-18	10-14	2-3	2.0	-	1.0	0.10-0.16	.045	0.03	-	-
PFBR specification	0.02-0.03	17-18	12-12.5	2.3-2.7	1.6-2.0	1.0	0.5	0.06-0.08	0.03	0.01	20	<160
ASP material	0.02	17.93	12.09	2.43	1.76	0.44	0.3	0.06	0.03	0.01	20	60-70
Imported material	0.023	17.12	12.21	2.31	1.65	0.10	0.29	0.086	0.02	0.03	12	85-90



(a)



(b)



(c)

Fig. 1. Variation of steady state creep rate with applied stress at (a) 823 K (b) 873 K and (c) 923 K.

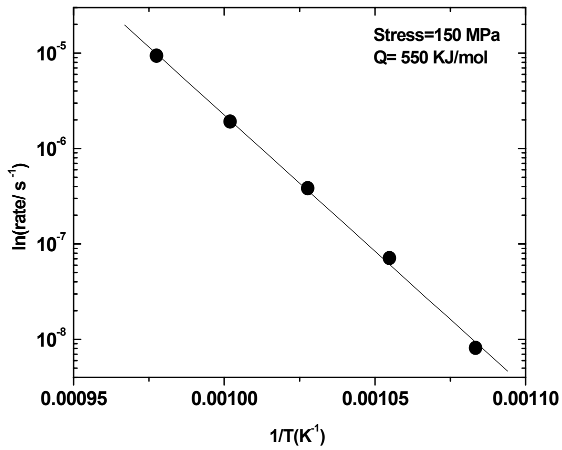
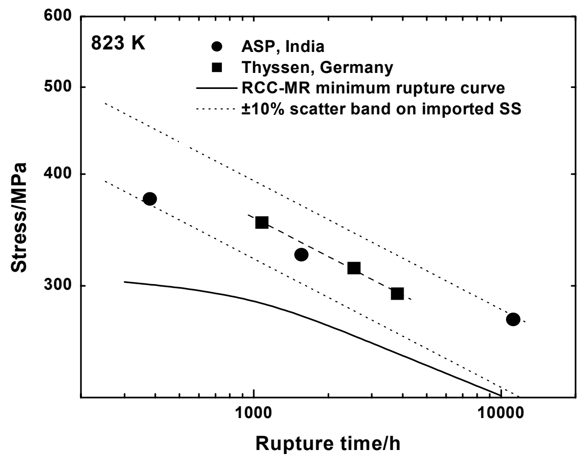
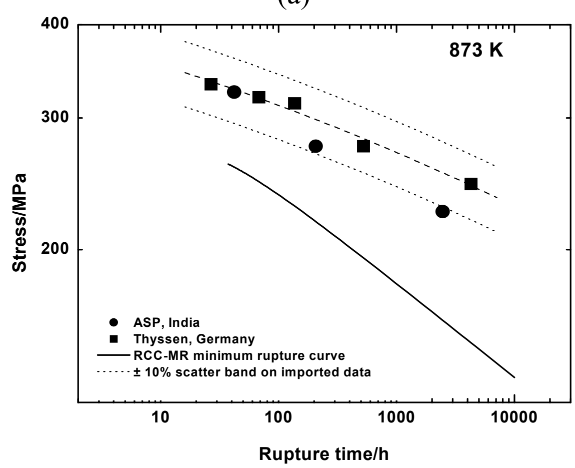


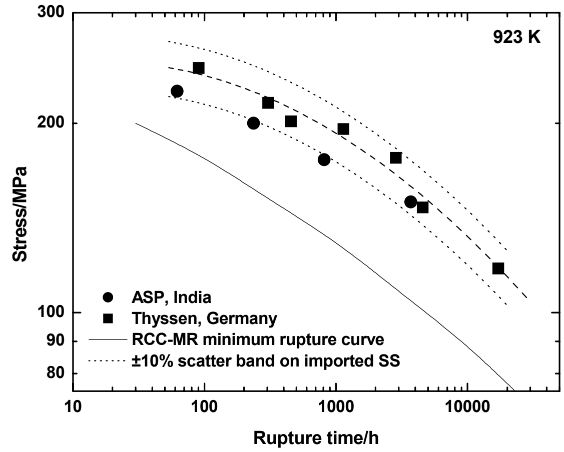
Fig. 2. Arrhenius plot showing the variation of steady state creep rate with reciprocal of absolute temperature



(a)

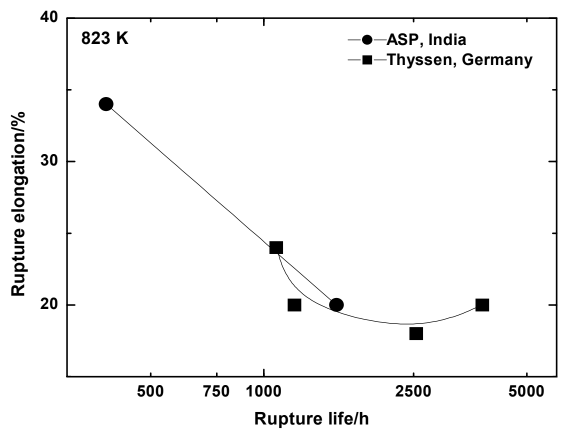


(b)

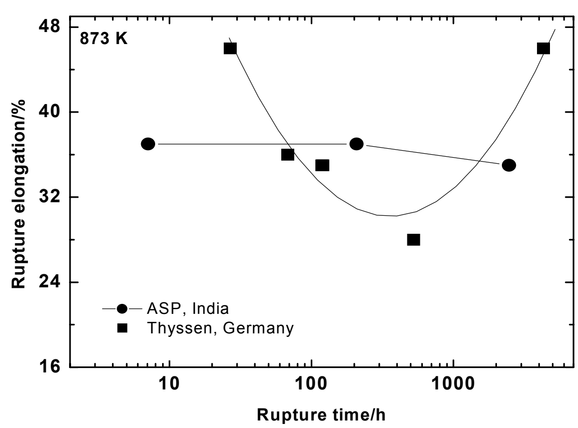


(c)

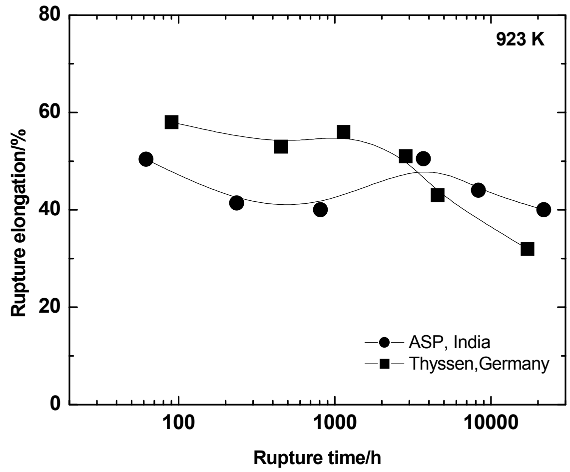
Figs. 3. Comparison of rupture life of indigenous and imported 316L(N) SS and RCC-MR design curve at (a) 823 K (b) 873 K and (c) 923 K.



(a)



(b)



(c)

Figs. 4. Comparison of rupture elongation of indigenously developed 316L(N) SS with imported material at (a) 823 K (b) 873 K and (c) 923 K.

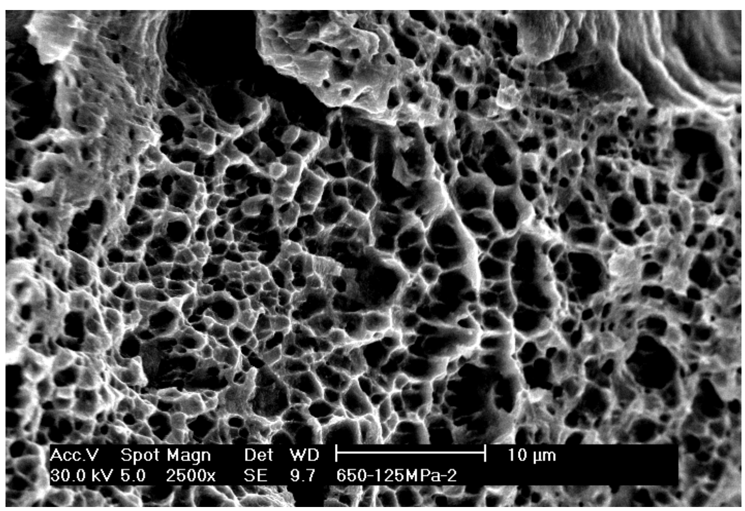


Fig. 5. Scanning electron micrograph showing typical creep fracture surface after testing at 923 K; stress = 125 MPa.