CREEP NOTCH SENSITIVITY OF 316LN SS AND THE EFFECT OF NITROGEN

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ABSTRACT

Nitrogen-alloyed 316LN stainless steel (SS) is used as a structural material for high temperature components of sodium cooled fast reactors which are designed for 40 years of service life. With a view to increase the design life to 60 years and beyond in the future reactors, studies are being carried out to develop 316LN grade austenitic stainless steels with superior high temperature mechanical properties. As a part of this development programme, four laboratory heats of 316LN SS containing 0.07, 0.11, 0.14 and 0.22 Wt. % nitrogen are being evaluated extensively. Creep tests have been carried out on smooth and notched sample geometries at a nominal stress level of 200 MPa and at a temperature of 923 K. The notched specimens contained a V-notch at an angle of 60^0 with root radius of 0.19 mm, which provide a theoretical stress concentration of 4.2. The gauge diameter of the notched specimen at the notch root was 6.4 mm and was 10 mm for the smooth specimen. It was found that the presence of notch increased the creep life for all the four heats. In the case of smooth specimens, rupture life increased with increase in nitrogen content. In the case of notched specimens, rupture life showed a peak value at 0.14 Wt. % nitrogen content. The ratio of rupture life of smooth to notched specimens decreased with increase in the nitrogen content from 18 for the material containing 0.07 Wt. % nitrogen to 3 for the material containing 0.22 Wt. % nitrogen thereby implying that the notch strengthening effect decreased significantly at high nitrogen levels. The notched specimens showed a lower value of ductility, measured in terms of reduction in area, as compared to the smooth specimens. Finite Element Method (FEM) was used to obtain the stress and strain distribution in the notch region as a function of nitrogen content. The stress concentration factor (K_t) evaluated through FEM analysis was also found to be 4.2 for the geometry used in this study. The creep analysis was run for a sufficiently long time to achieve the steady state creep condition. The influence of nitrogen content on the values of triaxial stresses under steady state conditions for the given notch geometry was evaluated.

INTRODUCTION

For high temperature structural components of sodium cooled fast reactors, 316L(N) stainless steel (SS) containing 0.02-0.03 Wt.% carbon and 0.06-0.08 Wt.% nitrogen has been selected. By keeping the carbon content low, the susceptibility to sensitization of the heat affected zone (HAZ) in welded components can be minimized and thus the potential for stress corrosion cracking of HAZ in a corrosive environment, can be alleviated [1]. Alloying with 0.06-0.08 Wt.% nitrogen helps to increase the high temperature strength of 316L SS to levels comparable to that of 316 SS. In order to increase the economic competitiveness of fast reactors, there is a strong desire to increase the design life time from the current level of 40 years to at least 60 years. As part of the effort to develop structural materials suitable for longer design life, the influence of nitrogen at concentrations higher than 0.08 Wt.% on the high temperature mechanical properties of type 316LN SS are being evaluated. Nitrogen has been shown to improve creep and fatigue strength at high temperatures and fracture toughness at cryogenic temperatures in ferritic steels, austenitic steels, martensitic steels and duplex steels [2, 3].

Four heats of 316LN SS, containing 0.07, 0.11, 0.14 and 0.22 Wt. % nitrogen were produced to study the effect of nitrogen on the tensile and creep properties of 316LN SS. The carbon content in these heats was maintained at ~ 0.03 Wt. % and the actual chemical composition of all other elements was similar (Table 1). The influence of nitrogen content on the mechanical behavior of austenitic stainless steels has been reported extensively [2-5]. Recent studies on the effect of nitrogen on the mechanical properties of 316LN SS have shown that the alloying element nitrogen increases the tensile, creep and low cycle fatigue properties of 316LN SS significantly [6-8]. However, all those results were derived from the tests conducted on smooth specimens. In view of the complex geometries and the potential for weld defects in fabricated components, notwithstanding the strict weld inspection practices, it is necessary to evaluate the material behavior in the presence of notches. In this investigation, the influence of nitrogen on the notch sensitivity of 316LN SS during creep deformation has been studied. The amount of nitrogen content in the four heats of 316LN SS was in the range of 0.07 to 0.22 Wt.%.

EXPERIMENTAL DETAILS

Four heats of 316LN SS were produced through double melting process. Primary melting of the steel was carried out by an air induction melting. The charge consisted of pure raw materials in order to achieve good control on the chemical composition of the steel. During primary melting, nitrided ferrochrome was used to achieve the required amounts of nitrogen in the different heats. Other major and minor elements were controlled to the same level in all the heats. Secondary melting was carried out by electro slag refining process in order to produce the steel with very low inclusion content. The ESR ingots were hot forged into slabs and subsequently hot rolled into plates of 22 mm thickness and finally given a solution annealing treatment between 1323 and 1423 K. Equiaxed grains free of carbide precipitates were observed in all the heats. The grain size of the four heats varied in a small range of 78 to 96 μm. The chemical composition of the four heats of 316LN SS and their grain sizes are given in Table 1. Creep tests have been carried out on smooth and notched sample geometries at a fixed stress level of 200 MPa and at a temperature of 923 K. Figures 1(a) and 1(b) show the geometry of smooth specimen and notched specimen respectively. The notched specimen contained a V-notch at an angle of 60^0 with root radius of 0.19 mm, which provides a theoretical stress concentration factor of 4.2. The gauge diameter of the notched specimen at the notch root was 6.4 mm and was 10 mm for the smooth specimen. All the creep tests were conducted in accordance with ASTM standard recommended practice E-139 and the test temperature was controlled within ± 2 K.

Table 1: Chemical Composition of 316LN SS [Wt.%].

Designation	**N**	C	Mn	Cr	Mo	Ni	Si	S	P	Fe
7N	**0.07**	0.027	1.7	17.53	2.49	12.2	0.22	0.0055	0.013	Bal.
11N	**0.11**	0.033	1.78	17.62	2.51	12.27	0.21	0.0055	0.015	Bal.
14N	**0.14**	0.025	1.74	17.57	2.53	12.15	0.20	0.0041	0.017	Bal.
22N	**0.22**	0.028	1.70	17.57	2.54	12.36	0.20	0.0055	0.018	Bal.

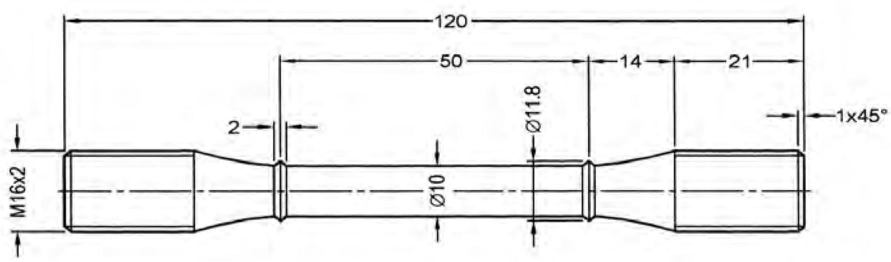

Fig. 1(a): Details of geometry of smooth specimen.

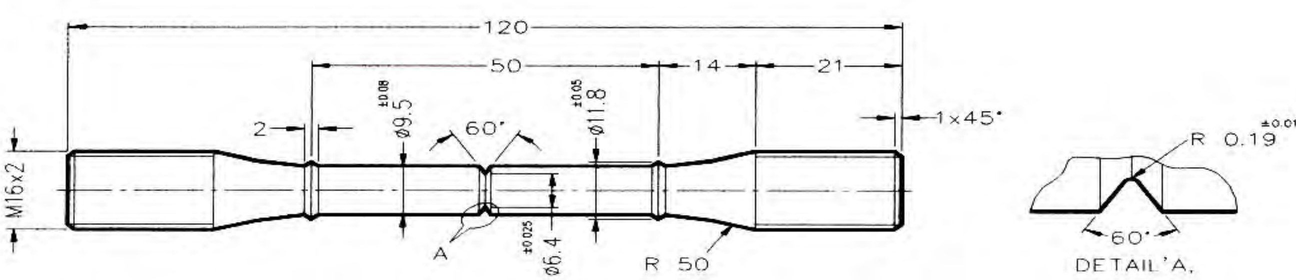

Fig. 1(b): Details of geometry of notched specimen.

RESULTS AND DISCUSSION

Test Results

Creep tests have been carried out on smooth and notched sample geometries at a nominal stress level of 200 MPa and at a temperature of 923 K. The creep curves of 316LN SS showed a small instantaneous strain on loading followed by typical primary, secondary and tertiary creep stages for all the nitrogen contents. Typical creep strain-time curves for smooth and notched specimens for 7N are shown in Fig. 2. Figure 3 shows the variation of rupture life with nitrogen content for smooth and notched specimens. It was found that the presence of notch increased the creep life for all the four heats. In the case of smooth specimens, rupture life increased continuously with increase in nitrogen content. In the case of notched specimens, rupture life showed a peak value at 0.14 Wt.% nitrogen. Figure 4 shows the variation of ratio of rupture life of smooth to notched specimens with nitrogen content. The ratio decreased with increase in the nitrogen content from 18 for the material containing 0.07 Wt. % nitrogen to 3 for the material containing 0.22 Wt.% nitrogen, thereby implying that the notch strengthening effect decreased significantly at high nitrogen levels. This trend is consistent with the value of rupture elongation with nitrogen content shown in Fig. 5 for the smooth specimens. The ductility falls from 42% to 7% on increasing the nitrogen content from 0.07 to 0.22 Wt.%. It is well known that materials with high ductility will show high notch strengthening and brittle materials will show notch weakening. This argument is further substantiated with the variation of reduction in area with nitrogen content for smooth and notched specimens as shown in Fig. 6. The notched specimens showed a lower value of ductility, measured in terms of reduction in area, as compared to the smooth specimens.

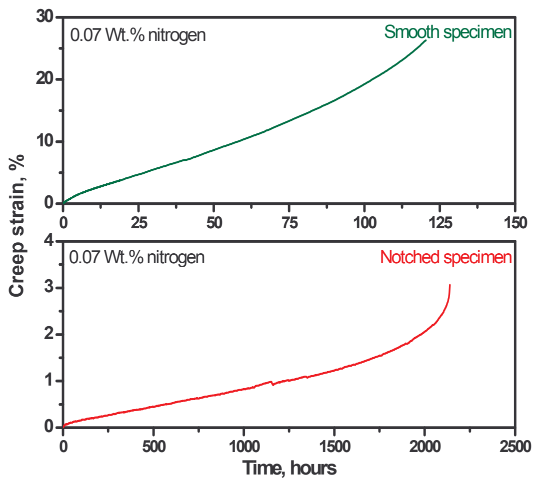

Fig. 2 : Typical creep curves for smooth and notched specimens, tested at 923K at a stress level

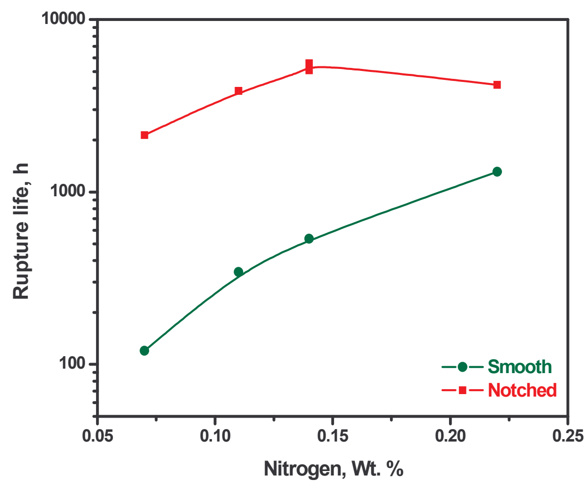

Fig. 3 : Variation of rupture life with nitrogen content for smooth and notched specimens tested at 923 K at a stress level of 200 MPa.

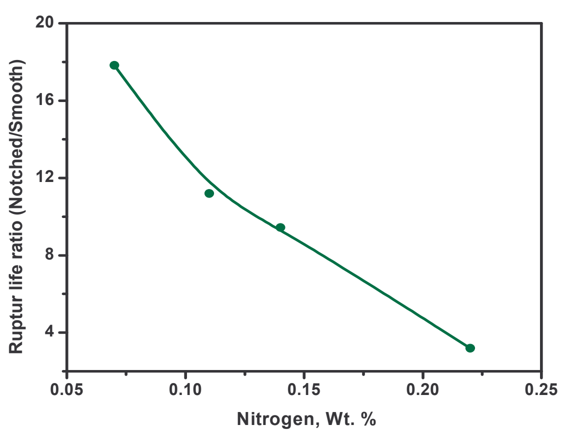

Fig. 4 : Variation of ratio of rupture life of notched/smooth specimens with nitrogen.

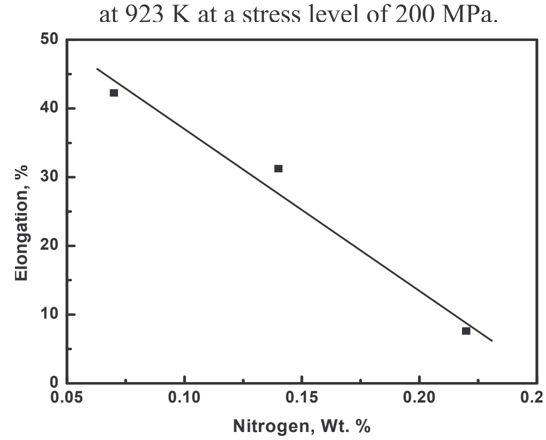

Fig. 5 : Elongation in smooth specimens at 923K at 200 MPa as a function of nitrogen content.

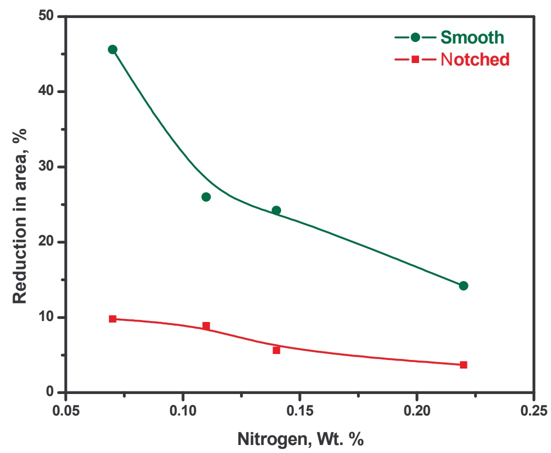

Fig. 6 : Variation of reduction in area with nitrogen content for smooth and notched specimens.

Finite element analysis

The steady state creep analyses were performed to evaluate the stress and strain values in the notch region as a function of nitrogen content, using the finite element code ABAQUS [9]. A quarter axisymmetric model of the notched creep test specimen was employed to carry out the analyses. The model was meshed using 8-noded biquadratic axisymmetric quadrilateral elements with reduced integration (CAX8R). Finer elements were used in the notch region to capture the stress gradients across the notch section. Elastic properties such as Young's modulus and Poisson's ratio were taken as 147000 MPa and 0.3 respectively and were assumed as the same for the four heats [10]. To define the plastic behavior of the material, true stress - plastic strain data obtained from standard tensile tests conducted on four different nitrogen content have been used. Bailey Norton equation, $\dot{\varepsilon}_s = C\sigma^n$, was used to define the creep behavior of the material. The material parameters C, n in Bailey-Norton equation were derived for 7N, 11N, 14N and 22N using the creep tests data, on the basis of RCC-MR code procedures [11]. The material parameters so obtained are tabulated in Table 2.

Table 2: Material parameters of the creep constitutive equation, $\dot{\varepsilon}_s = C\,\sigma^n$ for 316LN SS with various nitrogen content. Temperature=923 K.

Parameters	7 N	11 N	14 N	22 N
C	1.1330×10^{-20}	0.1207×10^{-20}	8.4569×10^{-20}	8.4087×10^{-17}
n	8.3076	8.7317	7.5734	5.9305

The analysis was carried out by applying loads in two steps. In the first step, nominal stress corresponding to 0.02% strain (i.e., 28MPa) was developed in the minimum section, in order to calculate the stress concentration factor for the given notch acuity. In the subsequent step, the balance load was applied to develop totally a nominal stress of 200MPa in the minimum section. The same boundary conditions and loads were applied for the models of all the four heats. Finally, a visco-analysis procedure was called for doing creep analysis. The creep analyses were run for sufficiently long period of 500 hours to achieve steady state values and the results were obtained.

The stress concentration factor obtained from the above analysis was 4.2, which was the same as the value calculated by Noda et al. [12] for the given notch acuity. The equivalent creep strain accumulated in the minimum section after 500 hours of creep is shown in Fig. 7 for the various nitrogen contents. The radial distance from the notch root is normalised with respect to radius of the minimum (notch) section in X-axis. Appreciable strain was accumulated at the notch root whereas less strain was found away from the notch section, irrespective of nitrogen content. The equivalent creep strain generally decreased with increase in nitrogen content. The maximum principal stress values observed in the minimum (notch) section were plotted for the four heats in Fig. 8. The peak value observed closer to the notch root increased with increase in nitrogen content. However the average value across the notch section was actually decreasing with increase in nitrogen content. The equivalent (Von Mises) stress given by $\sigma_{Eq} = [0.5^* \{ (\sigma_1-\sigma_2)^2 + (\sigma_2-\sigma_3)^2 + (\sigma_3-\sigma_1)^2 \}]^{1/2}$ is shown for the four heats in Fig. 9. The corresponding stress values in the same section for a plain specimen are shown as a straight line. The presence of notch brought down the effective stress across the section as can be clearly inferred from the figure.

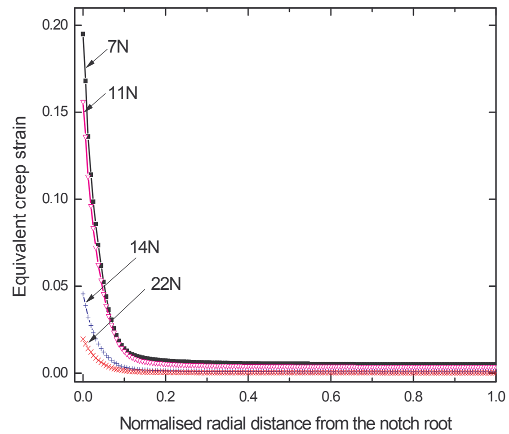

Fig. 7: Equivalent creep strain values in the notch section for the four heats after 500 hours of creep.

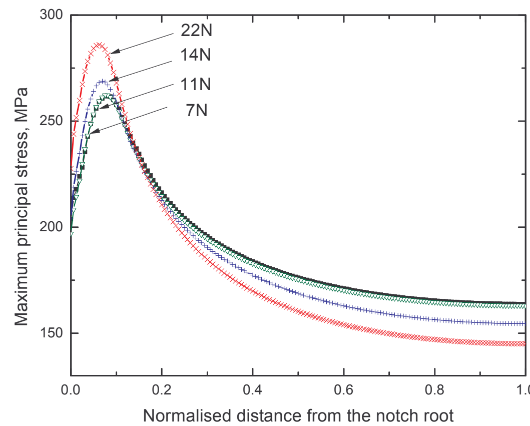

Fig. 8: Maximum principal stress in the notch section after 500 hours of creep.

The principal stress saturates at around 150 MPa and the peak value is more than 250 MPa as seen from Fig. 8. The equivalent stress saturates around 100 MPa and the peak value which occurs near the notch root is less than 175 MPa (Fig. 9). Figure 10 shows the rupture life curves determined for smooth specimens at different stress levels as a function of nitrogen content. The rupture life curve for the notched specimen is superimposed in Fig. 10. Comparison of Figs. 8 and 10 suggests that the notched specimen rupture curve is closer to the principal stress curve (saturated value of 150 MPa and the peak value of more than 200 MPa). Hence it is concluded that the notch lowers the maximum principal stress at the notch section and this leads to a higher rupture life.

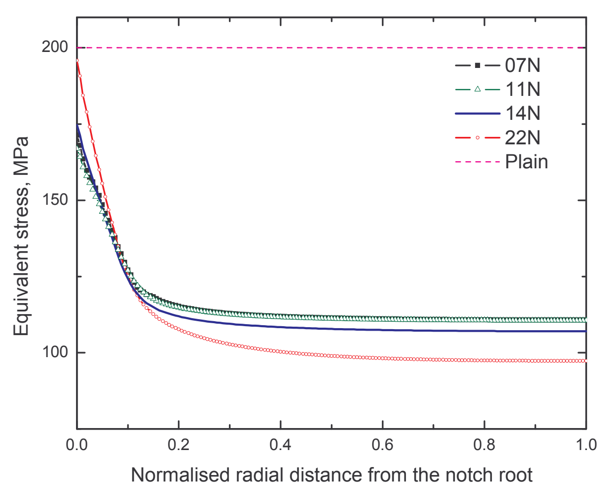

Fig. 9: Influence of nitrogen content on effective stress after 500 hours of creep.

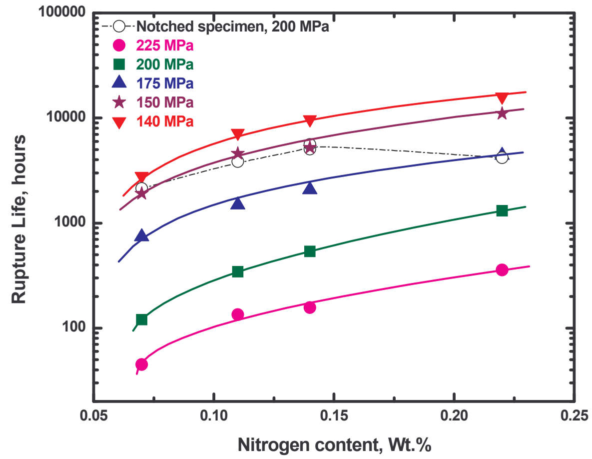

Fig. 10 : Rupture life curves at various stress levels as a function of nitrogen content at 923K.

The contours of hydrostatic stress for 22N steel after 500 hours of creep are shown in Fig. 11(a). Figure 11(b) shows the values of hydrostatic stress developed in the notch section as a function of the normalised distance from the notch root for the four heats. This plot reveals a trend similar to maximum principal stress and the peak value increased with increase in nitrogen content. The triaxiality factor is defined as the ratio of hydrostatic mean stress to the effective stress and is given as, $(\sigma_1 + \sigma_2 + \sigma_3) / 3\,\sigma_{Eq}$, where σ_1, σ_2 , σ_3 are the principal stresses. The triaxiality factor is 0.3 when the stress is acting only in one direction as in the case of the smooth specimen; in the case of the notched specimen, σ_2 and σ_3 components are generated although stress is applied only in the σ_1 direction. The contours of triaxiality factor around the notch for 14N steel resulting after 500 hours of creep is shown in Fig. 12(a). The values of triaxiality factors with radial distance from the notch root are shown for the four heats in Fig. 12(b). The triaxiality factor at the notch root is about 0.6 and the peak value is 1.5 for 22N steel. These values decreased with decrease in nitrogen content. The triaxiality factor and maximum principal stress values obtained for 14N steel are plotted against normalised radial distance from the notch root, as shown in Fig. 13. The positions of peak values of triaxiality factor and maximum principal stress occur closer at 0.09 mm distance apart from one another.

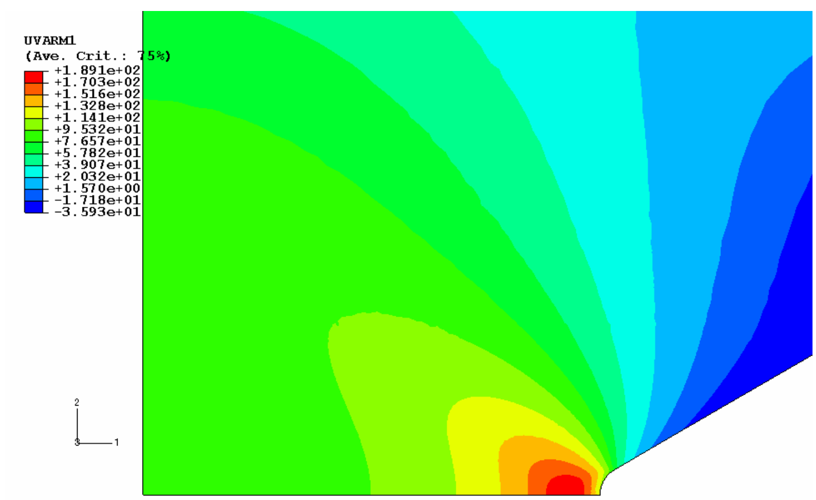

Fig. 11(a) : Hydrostatic stress distribution around the notch for 22N steel after 500 hours of creep.

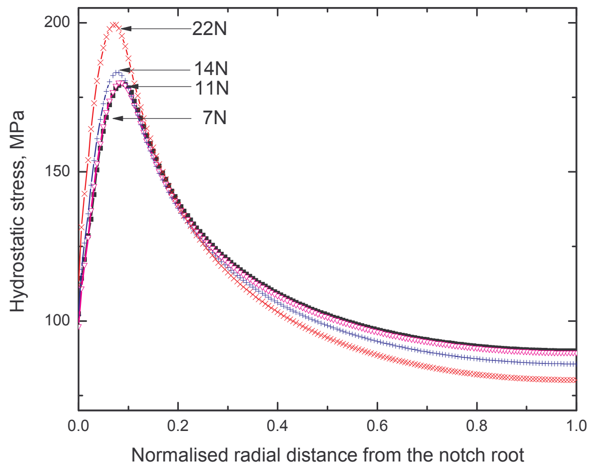

Fig. 11(b) : Hydrostatic stress variation in the notch section after 500 hours of creep.

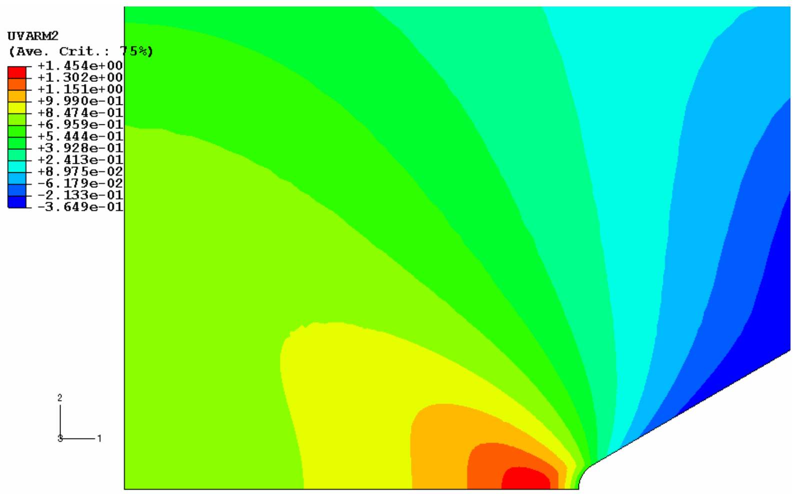

Fig. 12(a): Triaxiality factor in the notch region for 14N steel after 500 hours of creep.

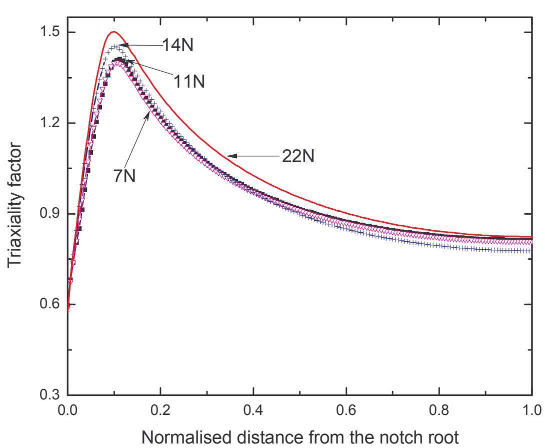

Fig. 12(b): Triaxiality factor across the notch section after 500 hours of creep.

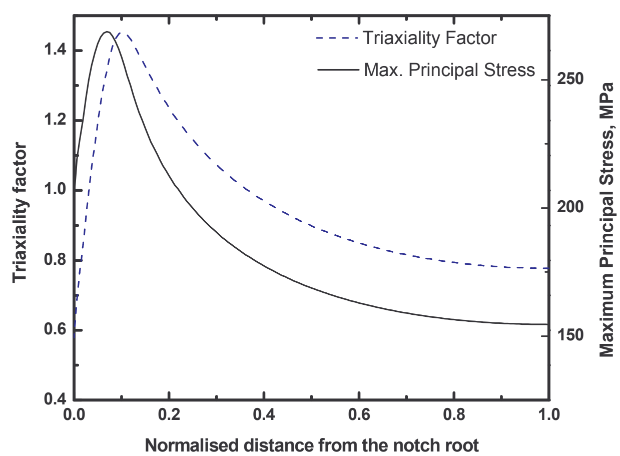

Fig. 13: Triaxiality factor and maximum principal stress values in the notch section for 14N steel after 500 hours of creep.

CONCLUSION

Creep tests have been carried out on both smooth and notched sample geometries at a temperature of 923 K at a nominal stress level of 200 MPa on 316LN SS. The test results showed that the presence of notch increased the creep life for all the four heats. The notched specimens showed a lower value of ductility, measured in terms of reduction in area, as compared to the smooth specimens. The ratio of rupture life of smooth to notched specimens decreased with increase in the nitrogen content. The stress and strain values in the notch region were obtained using finite element method and analysed as a function of nitrogen content. It was observed that the presence of notch lowers the maximum principal stress and this leads to higher rupture life in all the four heats.

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