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Effect of Notch on Creep Behavior of 316L(N) SS Weld Joint

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Abstract

Creep testing of notched cross-weld specimens was carried out at 873 K temperature and 300 MPa stress to study the effect of notch on creep properties of 316 L (N) SS weld joint. Various stress states were achieved by changing the notch profile. It was observed that, multiaxial state of stress developed during creep had a decisive role in creep life and the deformation mechanism. Thus, presence of notch and its consequences on creep life of the specimen prompted to offer exact solutions to explain the creep behavior. Notch strengthening effect is reported in the present investigation. Single mode of fracture was observed and fractures were located at the notch root. The transformation of δ-ferrite to sigma phase during creep exposure for about 2700 to 6200 h had resulted in ductile fracture in weld metal.

Keywords: 316L(N) SS; creep; notch; weld joint; multiaxiality, FEM analysis

1. Introduction

A major threat to structural integrity of high temperature components is posed by the thermal stresses developed in the components. The failure modes under this condition are the accumulation of inelastic strain and the associated creep or creep-fatigue damage. Shang-Tung Tu [1] has presented a damage mechanics approach applied for general understanding of damage developed in the welded structures. In such cases, life assessment requires long term tests on small specimens for at least one percent of the service life, to ensure the extrapolation accuracy. Researchers suggest laboratory tests on cross weld specimens to compare relative creep strength with single material specimens and then extrapolating the results with the help of constitutive laws by numerical simulations. In order to obtain necessary material data, conventional creep tests are to be performed separately on constituents of a weld joint i.e. base metal (BM), weld metal (WM), and in totality weld joint (WJ). Kouichi Maruyama [2] has shown the significance of multi region (weld joint) creep data analysis in evaluation of long term creep strength of 316 SS.

A multiaxial stress state is introduced in the component by any kind of material and geometrical non-uniformity. Such discontinuities act as local stress raisers and are called as metallurgical and mechanical notch,

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respectively. The information regarding the effects of stress concentrations of varying magnitude can be accomplished by conducting notch tests by varying notch acuity. The notch test can be used as a sensitive measure of the embrittlement which accompanies creep of certain high strength alloys [3]. A high heterogeneity is expected not only in dissimilar weld joints, but also in similar weld joints. This could be attributed to differences in the properties of various regions of weldment, due to the heterogeneity in microstructure. Therefore, it is necessary to perform creep testing of weld joints and to evaluate microstructural stability at different creep conditions. Especially, long-term creep testing is of great importance for life assessment of power plant equipment because some of microstructural changes occur only after several tens of thousands hours of creep exposure of the components [4].

The metallurgical zones of a weld joint cause anisotropic creep characteristics because they act as a metallurgical notch. The ductility of the material in the zones of weld joint decreases for lower strain rates or longer rupture lives, at high temperatures and at higher constraints. M.J. Manjoine [5] quantified the creep crack growth rate for a type 308 CRE SS weldment and showed that, it as a function of weld and base metal creep rates. According to Johnson (1962) and Henderson and Dyson (1981), two arrangements are popular and are successfully designed to study response of materials to multiaxial stresses at elevated temperature. One arrangement is designed to measure creep rate and second one focuses on the study of creep fracture process. Out of these two methods, selection depends on applicability for the situation. During loading in creep, each constituent of weld joint experiences the same stress but responds differently. This is mainly because of thermal gradients resulting into different composition and microstructure in various zones. Thus, there exists a gradient of creep strength [6].

In this context, 316L(N) SS weld joint with notch is creep tested at different multiaxial stress states. Present paper is an effort to study notch effect on creep properties of 316L(N) SS weld joint under various multiaxial stress state.

2. Material and sample preparation

2.1. Material

Nuclear grade 316 L (N) SS is chosen as the material for components of Prototype Fast Breeder Reactor (PFBR) according to RCC-MR (2000) design code. This material has high creep resistance, good weldability, high mechanical properties, and good corrosion resistance. It differs from the normal commercial variety of austenitic stainless steel in the fact that, it has closely controlled composition, lower residual element concentration, and lower inclusion content. 316 L (N) SS was supplied in the form of 2500 x 1500 x 30 mm plate in mill annealed condition with solutionizing treatment at 1373 K for one hour followed by water quenching in order to bring the nitrogen into solution.

In the as-weld condition, one of the constituents of weld joint i.e. weld metal has a duplex microstructure consisting of δ-ferrite distributed more or less uniformly in the γ-matrix. The presence of δ-ferrite in the welding consumable is, generally, in the range of 4 to 7 FN. In the present study, the weld metal used had δ-ferrite with 4.48 FN. There is a compositional change in 316 L (N) SS base metal and weld metal and its chemical composition is shown in Table 1.

Table 1. Chemical composition of 316 L (N) SS base metal and weld metal (wt.%).

| Sr. No. | Material        | C   | Mn    | Ni  | Cr   | Mo  | N   | S   | P  |
|---------|-----------------|-----|-------|-----|------|-----|-----|-----|----|
| 1       | Base metal      | 0.025 | 1.75  | 12.0 | 17.0 | 2.4 | 0.07 | 0.002 | 0.023 |
| 2       | Weld metal      | 0.052 | 1.355 | 11.5 | 18.78 | 2.014 | 0.077 | 0.004 | 0.019 |
2.2. Weld pad preparation for single V-joint

For obtaining cross weld joint creep specimen, two plates of 316 L(N) SS were joined along the longitudinal direction after edge preparation. The joining process used was shielded metal arc welding (SMAW). Single V-weld pad was prepared with root face of 2 mm and root gap of 3.15 mm. The electrodes used for welding were made up of core wire flux coated. The electrodes conform to AWS classification 316-15 of SFA 5.4 specifications. The electrodes were baked for 1 hour at 473 K before the commencement of welding. Welding details are given in Table 2. The weld pad was examined by radiography for its soundness. The location of cross weld specimens is shown in Fig.1. The geometrical details of weld joint creep specimen are shown in Fig.2 and Fig.3.

![Fig. 1. Weld pad geometry and location of cross WJ (weld joint) creep specimen in weld pad.](image)

2.3. Specimen preparation

From the weld pad, as shown in Fig. 1, over-sized rectangular strips were cut with the help of EDM wire cut machine and cross weld specimens of 50 mm gauge length and 9.5 mm gross diameter were prepared, (Fig.2). Circumferential 60° V-notch was prepared exactly in the center of gauge length of specimen. The notch geometry details are shown in Fig. 3.

| Process                          | Shielded metal arc welding |
|----------------------------------|----------------------------|
| Joint design                     | Single V- groove           |
| Number of passes                 | 34                         |
| Inter-pass temperature           | 433 K                      |
| Flux                             | Basic coated               |
| Current (DC electrode positive)  | 150 A                      |
| Voltage                          | 25 V                       |
| Travel speed                     | 3 mm/sec                   |
| Heat input rate                  | Average 0.875 kJ/mm        |
| Welding position                 | Flat                       |
### 3. Experimental

#### 3.1. Creep rupture test

Different multiaxial stress states were introduced by varying notch profiles. There were five multiaxial stress states for which specimens were creep tested for studying notch effect and are given in Table 3. The nomenclature followed here is in the ascending order of notch depth of specimens i.e. WJ1, WJ2, WJ3, WJ4, and WJ5. The creep test was carried out at constant load of 300 MPa and 873 K in air. The stress concentration factor, $K_t$, was calculated for each notch profile as per the literature [7,8].

#### 3.2. Post test investigations

Metallographic studies were carried out on fracture surfaces of specimens to explore the modes of fracture. The characterization of fractured surfaces of weld joint specimens was carried out by Scanning Electron Microscopy (SEM). It was also carried out at locations by tilting fracture surface to 45° angle to observe more features. The precipitates identified by Energy Dispersive Spectroscopy (EDS) were $M_23C_6$, which confirmed with the literature on 316 SS [9]. Optical microscopy was carried on longitudinal section of fractured specimens for studying changes in microstructure during creep.

| Specimen No. | Notch depth (t) mm | Net dia. (d) mm | Notch root radius (ρ) mm | $K_t$ |
|--------------|--------------------|----------------|--------------------------|-------|
| WJ1          | 0.60               | 8.3            | 0.141                    | 4.168 |
| WJ2          | 0.80               | 7.9            | 0.16                     | 4.17  |
| WJ3          | 1.282              | 6.936          | 0.3                      | 3.2   |
| WJ4          | 2.03               | 5.44           | 0.3                      | 3.15  |
| WJ5          | 2.303              | 4.894          | 0.16                     | 1.58  |
4. Results and discussion

4.1. Creep life

All specimens failed at notch i.e. in the weld metal. For studying the effect of notch geometry on the creep behavior, a comparison was made between creep rupture lives of notched specimens with five different notch geometries, as shown in Fig. 4. It was observed that, the creep life of notched specimens ranged between 2700-6200 hours and creep life increased with the notch depth. In other words, specimens exhibited notch strengthening effect. To explore the reason of notch strengthening effect, the information regarding percentage reduction in area, fracture modes, and grain boundary precipitation for the specimens after creep test was collected.

![Fig. 4. Creep life as a function of notch depth.](image)

4.2. Percentage reduction in area

Percentage reduction in area is a measure of creep ductility, since it is more sensitive measure of ductility than elongation at high temperatures. Table 4 shows the % reduction in area of different weld specimens and it is seen that, as the notch depth increases the percentage reduction in area increases. As the constraint is reduced, percentage reduction in area increased.

| Specimen | % Reduction in area |
|----------|---------------------|
| WJ1      | 6.01                |
| WJ2      | 7.99                |
| WJ3      | 8.6                 |
| WJ4      | 10.19               |
| WJ5      | 11.21               |

4.3. Creep fracture modes

SEM micrographs of creep fracture surfaces of two extreme cases WJ1 and WJ5 are presented in Fig.5 and Fig.6. The following observations can be made:

1. It is seen from general view Figs. 5 (a) and 6(a) that, the fracture surfaces were fibrous in nature, a characteristic of inter-dendritic failure.
2. The cracks were seen at notch root along the circumference of notch cross section.
3. Single mode of fracture i.e. brittle fracture was seen in WJ1-WJ5.
4. The fracture surface appeared ductile dimpled at notch center as seen in Figs. 5 (b) and 6(b) indicating transgranular ductile fracture.
5. SEM taken at tilt of 45 deg. as shown in Figs. 5 (c) and 6(c) indicated the region of shear leap. The region of shear leap seemed to be pulled in towards center of specimen as notch depth is increased.

![Fracture surface of the weld joint crept at 873 K/300MPa/2670 hrs, highly constraint specimen WJ1](image1)

![Fracture surface of the weld joint crept at 873 K/300MPa/6124 hrs, least constraint specimen WJ5](image2)

### 4.4. Microstructural changes

The damage morphology of the weld joint specimens tested under various multiaxial stress states was examined using optical metallography. No defects were detected near the fusion line or in the weld metal, which could cause a premature fracture. The microstructural details at the notch root of highly constraint specimen (WJ1) and least constraint specimen (WJ5) were as shown in Figs. 7 (a) and (b), respectively. It was observed that, numbers of micro cracks were more at the notch root of WJ1 than that in WJ5. The optical metallographs for WJ1 to WJ5 are as shown in Figs. 8 (a) to (e) and the results are discussed as below:
- After etching with modified Murakami’s etchant, the presence of carbide, intermetallic σ (sigma) phase, and untransformed ferrite was identified.
- In WJ1, WJ2, WJ3 the transformation of δ-ferrite seemed to be partial, as seen in Figs. 8 (a), (b) and (c).
• Whereas from Figs. 8 (d) and (e), it seems that, δ-ferrite network has been broken to a greater extent. It can be concluded that, nucleation, growth and linkage of cavities at second phase particles that form along the δ-γ interface, could lead to failure in weld metal.

• In least constraint case of WJ5, the sigma phase was seen to be uniformly distributed in the ferrite. The WJ5 specimen rupture life was 6124 h. The justification lies in the fact that, the driving force ahead of the crack tip must be utilized in overcoming the barriers imposed by evenly distributed sigma particles. Thus, the crack propagation would be retarded in highly constrained specimen WJ5 and creep life is maximum.

It can be concluded that, in highly constrained specimen, stresses higher than the yield stress are developed and as a result plastic flow begins at notch root. Due to high constraint, plastic flow cannot relieve the high elastic stress and it limits the peak stress to the yield stress resulting into number of cracks.

![Fig. 7. Optical microscopy of (i) WJ1 at 10X and (ii) WJ5 at notch root at 100X.](image)

![Fig. 8. SE micrographs showing δ-ferrite network in WJ1, WJ2, WJ3, WJ4 and WJ5 and presence of sigma phase.](image)

5. Conclusions

Notch strengthening phenomenon was exhibited by weld joint specimen. It can be concluded that, the notch strengthening is the effect of multiaxial stress state which is the function of notch geometry and material
property. The severity of notch strengthening, in turn creep life, increased with reduction in notch geometrical constraint. The structural analysis of multiaxiality revealed single mode of failure in the weld joint specimens. Thus, structural changes like precipitation, nucleation and growth of cavities and grain boundary sliding contribute to the deformation mechanism. Number of micro cracks at notch circumference was seen to be more in case of highly constraint specimen while, fewer microcracks were seen in case of least constraint specimen. The transformation of $\delta$-phase to sigma phase was found to be influenced by the presence of stress. It is, hence, concluded that, nucleation, growth and linkage of cavities at second phase particles that form along the $\sigma/\gamma$ interface causes failure in all the WJ specimens.

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