Effect of the Grain Boundary Reaction on the Notched Creep Rupture Strength of the Austenitic Heat Resisting Steel*

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Synopsis

An analysis of stress and strain during creep was made on notched bar specimens of austenitic 21-4N steel by finite element method.

A decrease in stress concentration at the notch root due to creep deformation occurred more rapidly in the notch-strengthened ductile steel with 36 % of the grain boundary reaction (GBR) than in the notch-weakened brittle one of greater hardness (4 % GBR). The equivalent strain at the notch root was smaller than that of a smooth specimen except in the early stage of creep in the ductile steel, but the former was always larger than the latter in the strongly notch-weakened one.

In the brittle steel, an increase in nominal stress enhanced creep deformation at notch root and consequently lowered the rupture time ratio of notched specimen to smooth one. Most of rupture life was spent in creep deformation before initiation of grain boundary cracks in notched specimen as well as in smooth specimen, independently of amount of GBR. Amount of plastic deformation necessary to initiate cracks was larger in the ductile steel than in the brittle one. This is considered to greatly affect the rupture strength of notched specimen.

1. Introduction

In commercial alloys including austenitic heat-resisting steels and nickel base superalloys, the notched creep rupture strength is especially one of the important problems. A complete explanation has not yet been given on the cause of notch-strengthening or notch-weakening, despite of a large number of studies made so far. Such difficulty is considered to arise from many interacting factors in mechanical engineering and materials science, including mechanical properties of materials, geometry of notched specimen and test conditions. From the viewpoint of mechanical engineering, an analysis has been made on the stress and strain in creep deformation by finite element method, and the effect of specimen geometry on the stress and strain distribution has been discussed.^{5,6)} It was empirically known from studies in materials science that notch-strengthening is apt to occur in the ductile materials in creep deformation, and that there is a close relationship between ductility of materials and the creep rupture strength of notched specimens. Further, by the limitation of the present creep analysis by finite element method, a quantitative discussion can only be made on the material which undergoes neither change in the microstructure nor those in the deformation behavior and rupture properties in creep. This point was ambiguous in the previous studies, and it is necessary to take this into account in order to discuss on notch-strengthening of notch-weakening of materials.

In 21-4N austenitic engine valve steel, pearlitic

nodules at grain boundaries are formed by grain boundary reaction as well as general precipitation interior of the grain.⁷⁻⁹⁾ In creep rupture test in the temperature range from 600 to 700 °C, it was found that more than about 10 % of the grain boundary reaction (in area fraction) remarkably increased the ductility of steels and then increased a tendency to notch-strengthening, while notch-weakening occurred in the steel with the less amount of the reaction.¹⁰⁾ Further, cracks could not be observed up to the time from about 80 to 90 % of the rupture life, independently of the extent of the reaction in smooth bar specimen. This fact implies that most of the rupture life is spent on the deformation necessary for crack initiation.¹⁰⁾ Therefore, it is worthy to know the effect of microstructures on the creep strength of notched specimens not only from the investigative viewpoint but also from the practical one. In this study, an analysis of stress and strain of notched bar specimens during creep at 700 °C was performed on both typically notch-strengthened and notch-weakened steels by finite element method. The analysis was based on the results of creep rupture experiment using both smooth and notched bar specimens of 21-4N steels with various amount of the reaction. The relation between microstructures and creep rupture strength of notched bar specimens was then discussed.

II. Steels Used and Experimental Procedure

21-4N steel bars used in this study have standard chemical compositions of 0.51 % C, 0.40 % N, 20.22 % Cr, 3.90 % Ni, 8.75 % Mn and balance of Fe. These steel bars were heat-treated in order to obtain specimens of equal hardness (Hv 320) with various amount of grain boundary reaction and those of greater hardness (Hv 357). Those steel bars were machined into single-notched round bar specimens of 7.5 mm diameter with 60 deg notch (root radius: 0.5 mm) of 1 mm depth (diameter of the minimum cross section was 5.5 mm and $K_t=2.4$), double notched ones for microscopic observation and smooth bar specimens of 5.5 mm diameter and 30 mm gauge length. Creep rupture test was carried out for the most part at 700 °C using a creep rupture equipment of single lever type (capacity of 1.5 t). Further, initiation of microcracks was examined on the ruptured specimens principally by an optical microscope. The grain boundary reaction is simply denoted by "GBR" in this study.

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III. Outline of Calculations by Finite Element Method

The initial strain method¹¹⁾ which was applicable to creep deformation problem and was relatively easy to use was employed in this study, though several other kinds of methods¹¹⁾ were proposed on stress-strain analysis by finite element method. In 21-4N steel used in this study, a long steady-state creep with constant creep rate was observed in creep rupture test of smooth bar specimens, independently of the amount of GBR. Further, stress dependence of steady-state creep rate, $\dot{\epsilon}_s$, was well fitted to the power law, $\dot{\epsilon}_s = A\sigma^n$. Therefore, it was assumed that there is also the same relationship, $\dot{\epsilon}_{eqp} = A\sigma_{eq}^n$, between equivalent stress, σ_{eq} , and equivalent plastic strain rate, $\dot{\epsilon}_{eqp}$ of von Mises type in notched bar specimens. Non-dimensional creep equation used in actual calculations is the same as the one proposed by Ohji *et al.*⁶⁾ The outline of calculations by computer in this study is as follows, while the basic equations are given in Ref. 6) and 11).

(1) Initial stress and strain components are calculated in elastic state at $t=0$.

(2) Creep strain increment, $\{\Delta\epsilon_c\}$, is obtained using the relationship, $\dot{\epsilon}_{eqp} = A\sigma_{eq}^n$, in each element, provided that stress state is not changed during the time interval between $t=0$ and $t=\Delta t$.

(3) Increment of load is obtained at each node from the theory of elasticity regarding $\{\Delta\epsilon_c\}$ as initial strain, and increments in displacement, $\{\Delta u\}$, total strain, $\{\Delta\epsilon\}$, and stress, $\{\Delta\sigma\}$, are calculated in each element, respectively.

(4) These $\{\Delta u\}$, $\{\Delta\epsilon\}$ and $\{\Delta\sigma\}$ are added to the present values in each element, and displacement, strain and stress in new state are determined.

(5) Procedure from (2) to (4) mentioned above is repeated until steady state is almost reached.

Change in coordinates of nodes due to creep deformation is taken into account in the calculation of this work. Figure 1 shows finite element model of

Fig. 1. Finite element model in this work.

a quarter of the notched part with 141 elements and 87 nodes. Initial condition was determined to give rise to the equal displacement of loading points. This calculation was performed by the conjugate gradient (C-G) method¹²⁾ in order to obtain accurate elastic solution. The calculation in the subsequent steps of creep deformation was made by SOR method.¹³⁾ Errors in these iterative calculations were about 1 % at most. Stress components at notch root were obtained by extrapolation method using those values at center of gravity of elements. The values of Young's modulus ($E=14\,300\text{ kg/mm}^2$) and Poisson's ratio ($\nu=0.29$) of austenitic AISI316 steel¹⁴⁾ were used in the following calculation, because both values for 21-4N steel at 700 °C are unknown.

IV. Experimental Results and Discussion

1. On the Result of Creep Rupture Test

Figure 2 shows the result of creep rupture test of notched bar specimens at 700 °C. Steels with more than 8 % GBR have the same or a higher creep rupture strength compared with steels without GBR and those of greater hardness, and the rupture life has maximum in steels with about 8 % GBR. Rupture elongation in smooth bar specimen is larger in steels with more than 8 % GBR, and remarkable notch-strengthening is observed in those steels. For example, in the steel with 36 % GBR, rupture elongation is almost constant (about 18 to 22 %), and the rupture time ratio of notched specimen to smooth one

Fig. 2. Relationship between creep rupture properties at 700 °C and amount of the grain boundary reaction (GBR).

is in the range from 2.7 to 4.7. In the steel without GBR and the one of greater hardness, rupture elongation of smooth bar specimen is much smaller and is in the range from about 4.4 to 5.5 %. It is worthy of note that these steels exhibit strong notch-weakening according to an increase in nominal stress. No changes in microstructures and hardness were detected on all of the specimens in this study.

Thus, creep rupture strength is strongly affected by differences in the amount of GBR and hardness. In this study, typically notch-strengthened material with 36 % GBR (Hv 320) is denoted by "ductile steel", while notch-weakened one of greater hardness (Hv 357) with 4 % GBR is described as "brittle steel". Finite element method is hereafter denoted by "FEM".

The experimental values of A and n in $\dot{\epsilon}_{eqp} = A\sigma_{eq}^n$ are $A = 1.11 \times 10^{-13}$, $n = 7.31$ for the ductile steel and $A = 9.72 \times 10^{-15}$, $n = 7.50$ for the brittle steel. The result of stress-strain analysis of notched bar specimen by FEM will be stated on these two kinds of steels.

2. Creep Analysis of Notched Specimens by FEM

Figure 3 shows change in axial stress, σ_z , equivalent stress, σ_{eq} , and mean stress, $\sigma_m = (\sigma_r + \sigma_\theta + \sigma_z)/3$, where σ_r and σ_θ are radial and tangential stresses, respectively) at notch root during creep at 700 °C and nominal stress of 25 kg/mm². σ_z , σ_{eq} and σ_m decrease in the earlier stage of creep in the ductile steel than in the brittle steel. In both steels, the values of σ_z and σ_{eq} become smaller than nominal stress and approach to certain constant values during creep. σ_m of notched bar specimen is larger than that of smooth one even after long-term creep, though it decreases with creep deformation.

Figure 4 shows stress distribution in the minimum cross section in both elastic and almost steady states. This figure represents only the calculated stress values of the notched brittle specimen at the time when rupture occurred, because very little difference was found in stress distribution between two kinds of steels even in almost steady state. In elastic state, σ_z has a maximum value at notch root, and the value of stress concentration factor by the present calculation, K_{FEM} , is

Fig. 3. Change in axial stress, σ_z , equivalent stress, σ_{eq} , and mean stress, σ_m , at notch root during creep at 700 °C, 25 kg/mm².

2.70 and a little larger than that of theoretical one, $K_t (= 2.4)$. Moreover, distributions of σ_z , σ_θ and σ_r coincide with those in other reports.^{5,6)} In almost steady state, the maximum values of σ_z , σ_θ and σ_m are somewhat inside from notch root, and the value of K_{FEM} is about 1.29. It is obvious that the redistribution of stresses occurs during creep.

Figure 5 shows distributions of axial strain, ϵ_z , and equivalent plastic strain, ϵ_{eqp} , in the minimum cross section under 25 kg/mm² at the time when smooth specimen of the ductile steel ruptured and at that when notched specimen of the brittle steel ruptured. The axial elastic strain, ϵ_{zel} , is almost independent of material properties. ϵ_{eqp} and ϵ_z have maxima at notch root, while they are very small inside of specimen. This result shows the same tendency as the result obtained by Ohji *et al.*⁶⁾ Amount of plastic deformation is larger in the ductile steel than in the brittle one. In the notch-strengthened ductile steel, the value of ϵ_{eqp} at notch root is more than 3.3 % at

Fig. 4. Stress distribution in the minimum cross section at notch root during creep at 700 °C, 25 kg/mm².

Fig. 5. Steady-state strain distribution in the minimum cross section at notch root during creep at 700 °C, 25 kg/mm².

the rupture time of smooth specimen (35.8 h), but cracks were not yet observed. However, in the brittle steel, notched specimen ruptured at the time when the value of ϵ_{eqp} at notch root was 1.52 % (44.6 h), and this value was smaller than the rupture strain of smooth specimen of the same steel.

3. On the Notch-strengthening and Notch-weakening of Steels

Figure 6 shows change in equivalent strain (sum of equivalent plastic strain, ϵ_{eqp} , and equivalent elastic strain, ϵ_{eqe}) at notch root in notched specimens during creep. Straight line in this figure indicates the value of smooth specimen which is sum of elastic strain and plastic one calculated by steady-state creep model using a power relation, $\dot{\epsilon}_s = A\sigma^n$ for both ductile and brittle steels. In the notch-strengthened ductile steel, equivalent strain at notch root becomes much smaller than that of smooth specimen owing to rapid decrease in creep rate with an increase of time, while they are both greater than those of smooth specimens in the early stage of creep deformation. In the notch-weakened brittle steel, creep rate at notch root also decreases with an increase of time, but equivalent strain at notch root is always greater than that of smooth specimen under nominal stress greater than 25 kg/mm². These results are essentially consistent with those obtained by Ohnami *et al.*¹⁵⁾ In the brittle steel, as shown in Fig. 7, creep strain (equivalent plastic strain, ϵ_{eqp}) at notch root at fracture is in the range from about 1.1 to 1.9 %, and is close to about 2.2 %, the value of experimentally obtained strain at crack initiation of smooth specimen under nominal stress of 25 kg/mm², while it is much smaller compared with the rupture elongation of smooth specimen (about 4.4 to 5.5 %). In this figure, calculated creep strain of smooth specimen (ϵ) at the time when fracture of notched specimen occurs (t_{rn}) is given by $\epsilon = \epsilon_s t_{rn} = A\sigma^n t_{rn}$ according to steady-state creep model using power law. Creep strain at notch root of this steel increases more noticeably with an increase of nominal stress in comparison with that of smooth specimen calculated by steady-state creep model. This result explains that notch-weakening is more remarkable under higher nominal stresses. Figure 8 shows

Fig. 6. Change in the equivalent strain at notch root in the ductile and the brittle specimens during creep at 700 °C.

that creep strain at notch root in notched specimen of the ductile steel is in the range from 3.0 to 4.6 % at the time corresponding to the rupture life of smooth specimen, and this value is in the range from about one third to a half of smooth one calculated by a steady-state creep model. In this figure, calculated creep strain of smooth specimen is given by $\epsilon = \dot{\epsilon}_s t_r = A\sigma^n t_r$, where t_r is rupture life of smooth specimen. This result is in accordance with the notch-strengthening of this steel (Fig. 2). Creep strain at crack initiation of smooth specimen in this steel is about 9.2 % when nominal stress is 20 kg/mm², and is much larger than the strain in the brittle steel. As already reported,¹⁰⁾ this is due to the fact that large plastic deformation is necessary for the initiation and growth of cracks in steels with the grain boundary reaction nodules. Further, mean stress at notch root is larger than that of smooth specimen in the ductile steel, as shown in Fig. 3. As is well known, constraint of plastic deformation due to stress triaxiality in notched specimen is also considered to contribute to notch-strengthening.

In the brittle steel, mean stress at notch root is considerably greater than that of smooth specimen even at the time immediately before the rupture of notched specimen, while it is maximum at a little inside of notch root (Fig. 4). Relationship between mean stress and initiation of crack in notched specimen has already been reported by other investigators.⁵⁾ Also in Fig. 7, creep strain at notch root at rupture decreases a little with increasing value of

Fig. 7. Creep strains at notch root and of smooth specimen of the brittle steel at 700 °C.

Fig. 8. Creep strains at notch root and of smooth specimen of the ductile steel at 700 °C.

mean stress owing to an increase of nominal stress. However, such a change in the creep strain is considered to be not so large, because an analysis was made on creep deformation behavior simulated by steady-state creep model. Therefore, it is considered that crack may occur in the brittle steel when creep strain at notch root amounts to a certain value ranging from 1.1 to 1.9 % under nominal stress range from 20 to 30 kg/mm², and it may propagate rapidly to cause rupture under higher mean stress than that of smooth specimen. This is the most important reason why this steel exhibits noticeable notch-weakening under higher stresses at 700 °C. On the contrary, equivalent stress at notch root in the ductile steel becomes lower than nominal stress owing to rapid accommodation of stress concentration at notch root by creep deformation, and crack initiation is retarded by constraint of plastic deformation in comparison with smooth specimen due to stress triaxiality. This explains notch-strengthening in the ductile steel.

4. Initiation of Creep Crack in Notched Specimen

In this study as well as in many works by other investigators, differences in deformation behavior and ductility have great influence on creep rupture strength of notched specimen. Photograph 1 shows optical microstructure at notch root of unruptured part in the double notched specimen ruptured under nominal stress of 25 kg/mm². In the brittle steel, long and straight crack can be found at grain boundary near the surface of notch root where creep strain is maximum, as shown in Photo. 1(a), whereas a crack in the ductile steel is apt to be formed at the interface of the nodule as reported in previous paper¹⁰⁾ and a lot of small cracks can be observed in the wide area of notch root in Photo. 1(b). Further, dimple and grain-boundary fracture surface were observed in the ductile and brittle steels by means of scanning electron microscopy, respectively. Ohtani and Itoh⁵⁾ have suggested that preferred initiation of creep crack occurs at the point of maximum mean stress in notched round bar specimen. However, the value of mean stress is maximum not at notch root but somewhat inside of notch root in almost steady state of both brittle and ductile steels, while equivalent stress has max-

imum value at notch root. Ohnami *et al*¹⁵⁾ considered mean stress as well as equivalent stress at notch root as one of controlling factors of crack initiation in notched specimen, but mean stress at notch root in almost steady state is the same in both steels in this study. From the results of this study, it is considered that controlling factors of crack initiation in both steels are equivalent stress and ductility of steel to crack initiation, and the effect of mean stress is relatively small. In notched specimen as well as in smooth one, crack occurred at about 80 to 90 % of rupture life time (in tertiary creep), independently of ductility of steel, however, detailed observation of crack propagation in notched specimen was not made. This fact suggests that rupture life of notched specimen is determined for the most part by crack initiation life. Crack at notch root is easy to occur by a small amount of creep deformation in the brittle steel with greater hardness, while a large amount of plastic deformation is necessary for crack initiation in the ductile steel with 36 % GBR. Such a difference in ductility to crack initiation has a great influence on the rupture strength of notched specimen.

V. Conclusion

An analysis of stress and strain during creep was made on the notched round bar specimens of austenitic 21-4N steel by finite element method, and the effect of material properties on the creep rupture strength of this steel was then discussed on notched specimen of this steel. The results obtained are summarized as follows.

(1) Axial, equivalent and mean stresses (σ_z , σ_{eq} and σ_m) at notch root decreased in the earlier stage of creep in the notch-strengthened ductile steel (Hv320, 36 % GBR) than in the notch-weakened brittle one (Hv357, 4 % GBR) at 700 °C. The value of axial stress was maximum at notch root and stress concentration factor by finite element method, K_{FEM} , was 2.70 in elastic state, while the maximum value of axial stress was somewhat inside of notch root and the value of K_{FEM} was about 1.29 in almost steady state under nominal stress of 25 kg/mm². Maximum value of mean stress in this state was also a little inside from notch root, but its value at notch root was still larger

(a) Brittle specimen (Hv357, 4 % GBR)

(b) Ductile specimen (Hv320, 36 % GBR)

Photo. 1. Grain boundary cracks at notch root occurred during creep at 700 °C, 25 kg/mm².

than that of smooth specimen, independently of material properties.

(2) Equivalent strain (sum of equivalent plastic and equivalent elastic strains) and creep rate at notch root were both smaller than those of smooth specimen by steady-state creep model except in the earlier stage of creep in the ductile steel, while they are always greater than those of smooth one in strongly notch-weakened specimen of the brittle steel under higher stress. Further, amount of creep deformation at notch root increased more rapidly compared with that of smooth specimen with an increase of nominal stress in the brittle steel.

(3) Notch-strengthening in the ductile steel was caused by retardation of creep deformation in comparison with smooth specimen owing to a rapid decrease of stress concentration and stress triaxiality at notch root during creep. On the contrary, in the brittle steel, creep deformation of notched specimen occurred rapidly under high stress concentration before it ruptured at a certain amount of creep strain at notch root.

(4) Long and straight crack was found at grain boundary near the surface of notch root in the brittle steel, while a lot of microcracks in the ductile steel were observed in the wide area of notch root. From the results of this microscopic observation and creep analysis by finite element method, it was considered that controlling factors of crack initiation in both steels are equivalent stress and ductility of steel to crack initiation, and the effect of mean stress is relatively small. This result was different from those by other investigators. In the ductile steel, crack was apt to be formed at the interface of the nodule, and its initiation required a large amount of plastic deformation, whereas crack in the brittle steel was easy to occur after a small amount of it. Such a difference in ductility to crack initiation was considered to greatly affect the rupture strength of notched specimen. Rupture life of notched specimen was determined for the most part by crack initiation life, because crack occurred at about 80 to 90 % of rupture life time (in tertiary creep), independently of ductility

of steel.

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