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Effect of Temperature on Ratcheting Behaviour of 316LN SS

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Abstract

Ratcheting experiments were carried out on 316LN stainless steel as a function of temperature ranging from 523 -923 K for different mean stress (σm)-stress amplitude (σa) combinations. The effect of temperature on ratcheting strain accumulation as well as cyclic life is found to be anomalous due to occurrence of Dynamic Strain Aging (DSA). While the peak DSA temperature is at 823 K for all mean stress-stress amplitude combinations, the temperature regime in which DSA operates varied for different σm - σa combinations.

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Nomenclature

| Symbol | Description |
|--------|-------------|
| σm    | mean stress |
| σa    | stress amplitude |
| σmax  | peak stress/maximum stress |
| δr    | ratcheting strain |
| δrf   | maximum ratcheting strain |
| Nf    | cycles to failure |

1. Introduction

Ratcheting is the progressive directional accumulation of deformation due to asymmetric loading in structures. Piping components in nuclear power plants are especially vulnerable to ratcheting. In Sodium Cooled Fast Reactors (SFRs), high amount of strain accumulation due to ratcheting can thin down the structural components in the primary sodium circuit leading to buckling. Therefore ratcheting is one of the prime considerations in the design of those components [1]. Ratcheting has been extensively studied on austenitic stainless steels in the last decade. Although the effects of mean stress (σm) and stress amplitude (σa) on ratcheting behavior have been studied on austenitic stainless steels at ambient temperature [2,3], studies on the effect of temperature on ratcheting behavior including the dynamic strain aging (DSA) regime are very limited.

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Since DSA regime encompasses the operating temperature of SFRs (~820 K), it is essential to investigate the manifestations of DSA in ratcheting. The present study is an attempt to explore the ratcheting behavior of 316LN SS which is the currently favored structural material for primary side components in SFRs, over a wide range of temperature from 523 to 923 K for different \( \sigma_m - \sigma_a \) combinations. The main focus is to bring out the effect of temperature on ratcheting strain accumulation and to analyze the shift in DSA temperature regimes with respect to different \( \sigma_m - \sigma_a \) combination.

2. Experimental

The material used for the present study was 316LN stainless steel with 0.14 wt. %N. The chemical composition (in wt. %) of this material is Fe-0.025C-17.5Cr-12.1Ni-2.53Mo-0.14N-1.74Mn-0.0041S-0.017P. The material was subjected to solution annealing at 1363 K/1h followed by water quenching. Cylindrical low cycle fatigue (LCF) specimens of 25 mm gauge length and 10 mm gauge diameter were machined from the heat treated blanks. The tests were carried out on a servohydraulic fatigue testing machine equipped with a resistance heating furnace under a uniaxial, stress controlled mode using a triangular waveform at a constant stress rate of 50 MPa s\(^{-1}\) (Fig. 1). Axial strain was measured using axial extensometers.

Tests were not continued till complete separation of the specimen. Crack formation towards the end of life increases cyclic strain increment. When this increment reached 40% of the average strain throughout the cycles, tests were terminated. To perform tests over a wide range of temperature from 523 to 923 K, \( \sigma_m - \sigma_a \) combinations viz. (1) \( \sigma_m : 25 \) and 75 MPa at a fixed \( \sigma_a : 180 \) MPa and (2) \( \sigma_a : 180 \) and 230 MPa at a \( \sigma_m : 75 \) MPa are chosen, so that at higher temperatures, the maximum stress/peak stress (\( \sigma_{\text{max}} \)) lies well below the ultimate tensile strength to nullify chances of geometrical softening during cycling. However, for a combination of \( \sigma_a : 230 \) Mpa, \( \sigma_m : 75 \) MPa, tests were carried out in the temperature range of 823 to 873 K only, due to the above reason. Even though some researchers have carried out true stress controlled tests [6], in the present investigation, all tests were engineering stress controlled since geometrical softening is avoided by choosing proper \( \sigma_m - \sigma_a \) combinations. It may also be noted that failure due to necking was not observed under any testing condition.

3. Results and discussion

3.1. Effect of temperature on ratcheting strain accumulation

Figures 2(a)-(c) presents the ratcheting strain plotted against cycles to failure for different \( \sigma_m - \sigma_a \) combinations for a wide range of temperature varying from 523 to 923 K. Ratcheting strain is defined as the arithmetic mean of the maximum and minimum axial strain in a particular cycle i.e., \( \varepsilon_r = \frac{1}{2}(\varepsilon_{\text{max}} + \varepsilon_{\text{min}}) \). Strain was seen to accumulate in the tensile direction owing to the tensile mean stress applied. The progressive buildup of strain during cyclic loading caused fatigue damage leading to failure. It is observed in Fig. 2(a) (\( \sigma_m : 75 \) MPa, \( \sigma_a : 180 \) MPa) that elastic shakedown has occurred throughout the temperature range of 523-823 K. With increase in temperature yield stress and ultimate tensile stress decreases. So for the same \( \sigma_m - \sigma_a \) combination, with increase in temperature, the peak stress in a cycle during ratcheting reaches a higher fraction of yield stress which essentially implies an increase in \( \varepsilon_{\text{rf}} \) and decrease in \( N_f \) with increase in temperature. However the reason for the anomaly as observed in the figure is due to the high deformation resistance caused by the locking of mobile dislocations by solute atoms [7] because of strong dynamic strain aging operating in that temperature range [8]. However at 523 K, \( \sigma_{\text{max}} \) is only slightly higher than yield stress. So ratcheting strain accumulation is very slow and gets saturated after around 2000 cycles leading to elastic shakedown. Similar result is reported by Sivaprasad et al [9] where early shakedown occurred at room temperature for SA 333 Gr. 6 steel when \( \sigma_{\text{max}} \) is slightly above the yield stress. This is different from what happened at 623 K and 823 K where shakedown is observed from the beginning of the cycling due to pronounced hardening caused by DSA. This is also corroborated by Table 1 where plastic strain amplitude and hysteresis loop area at half-life (\( \sigma_m:75 \) MPa,\( \sigma_a:180 \) MPa) is seen to be decreasing gradually with temperature taking a dip at 823 K depicting that DSA operates mostly in the range of 623 -823 K. Beyond 823 K the effect of DSA seems to be weaker when \( \varepsilon_r \).
accumulates much more and \( N_f \) decreases. This fact is substantiated from Table 1 where plastic strain amplitude and hysteresis loop area which are known to be strong function of cyclic damage, both increases manifold from 873 to 923 K leading to decrease in \( N_f \).

From Fig. 2(b) (\( \sigma_m; 75 \text{ MPa} \), \( \sigma_a; 230 \text{ MPa} \)), a very slow ratcheting is observed at 823 K due to occurrence of DSA at that temperature while ratcheting strain accumulation increases greatly at 873 K where no effect of DSA is found. Increase of \( \varepsilon \) and decrease in \( N_f \) outside DSA regime is due to the reasons discussed above. More or less similar trends is found out in Fig. 2(c) where the ratcheting strain accumulation is slow with lesser \( N_f \) compared to Fig. 2(b) owing to a higher reversible plastic deformation due to a lower \( \sigma_m \). This is also evident from \( \varepsilon_f \) and \( N_f \) data for different temperatures in Table 1 (\( \sigma_m; 25 \text{ MPa} \) \( \sigma_a; 230 \text{ MPa} \)). This is in affirmation of the earlier experiments [10] which elucidates the effect of \( \sigma_m \) and \( \sigma_a \) on ratcheting behavior of austenitic stainless steels.

![Fig. 1. Loading path for a ratcheting experiment.](image)

Table 1. Maximum ratcheting strain, cycle to failure, plastic strain amplitude and hysteresis loop area at half-life with variation in temperature for different \( \sigma_m - \sigma_a \) combination.

| Stress Amplitude (MPa) | Mean Stress (MPa) | Temperature (K) | Plastic strain amplitude, % | Hysteresis loop area (MJ/m³) | Maximum Ratcheting strain, % | Cycles to failure |
|------------------------|-------------------|-----------------|----------------------------|-----------------------------|-----------------------------|-----------------|
| 180                    | 75                | 523             | 0.02                       | 128                         | 1.77                        | shakedown       |
|                        |                   | 623             | 0.02                       | 120                         | 4.13                        | shakedown       |
| 230                    | 75                | 823             | 0.01                       | 115                         | 6.22                        | shakedown       |
|                        |                   | 873             | 0.03                       | 201                         | 24.86                       | 6665            |
|                        |                   | 923             | 0.04                       | 260                         | 9.973                       | 26220           |
|                        |                   | 823             | 0.05                       | 197                         | 7.915                       | 10188           |
| 230                    | 25                | 873             | 0.07                       | 273                         | 23.965                      | 7681            |
|                        |                   | 823             | 0.10                       | 300                         | 7.31                        | 6507            |
| 230                    | 25                | 873             | 0.12                       | 325                         | 8.8                         | 5130            |
|                        |                   | 923             | 0.17                       | 354                         | 19.9                        | 2492            |

3.2. Effect of \( \sigma_m \) and \( \sigma_a \) on DSA temperature range

Increase in \( \sigma_m \) causes more hardening during ratcheting for austenitic stainless steels [10] thereby assisting DSA. So, for the same \( \sigma_a \) at a lower \( \sigma_m \) (25 MPa), DSA has almost negligible influence on ratcheting strain accumulation throughout 823-923 K whereas for a higher \( \sigma_m \) of 75 MPa, DSA is manifested as slow ratcheting at 823 K (\( \sigma_a; 180 \text{ MPa} \)). This is evident from Figs. 1(b)-1(c). On the other hand, DSA is much more prominent on decreasing the \( \sigma_a \) (\( \sigma_a; 75 \text{ MPa} \), \( \sigma_a; 180 \text{ MPa} \)) and the zone in which DSA operates moves to a wider domain ranging from 623 to 823 K (Fig. 1a). Decrease in \( \sigma_a \) causes the tensile as well as compressive part of a cycle to decrease causing lesser plastic deformation. But when \( \sigma_a \) is increased to 230 MPa for the same \( \sigma_m \) (75 MPa),
resistance to DSA increases and apart from 823 K, considerable amount of ratcheting strain gets accumulated. Hence, the zone of operation of DSA is narrowed down to 823 K in that case.

Fig. 2(a). Variation of $\varepsilon_r$ with $N_f$ for different temperatures ranging from 523-923 K ($\sigma_m$: 75 MPa, $\sigma_a$: 180 MPa).

Fig. 2(b). Variation of $\varepsilon_r$ with $N_f$ at 823 and 873 K ($\sigma_m$: 75 MPa, $\sigma_a$: 230 MPa).

Fig. 2(c). Variation of $\varepsilon_r$ with $N_f$ at 823, 873 and 923 K ($\sigma_m$: 25 MPa, $\sigma_a$: 230 MPa).

4. Conclusions

- With increase in temperature maximum ratcheting strain increases and cyclic life decreases due to higher plastic deformation.
- An anomaly in ratcheting strain accumulation as well as life endurance is observed in the DSA regime.
- Temperature regimes of DSA vary based on mean stress-stress amplitude combination. Elastic shakedown is observed as a manifestation of DSA throughout 623-823 K for cycling with low stress amplitude, whereas, on increasing the stress amplitude, slow ratcheting due to DSA is found to occur only at 823 K.

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