Low and high cycle fatigue behavior of Nickel-base Alloy at High Temperatures

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Abstract

Low and high cycle fatigue behaviors of Alloy 690 have been investigated at temperatures up to 330°C and number of cycles up to 2 × 10^9. Two interesting phenomena were observed. At high temperature, the alloy shows a secondary strain hardening in the cyclic stress-strain response. Formation of nano-twins and interactions between moving dislocations and stacking faults or interstitial atoms could contribute to this secondary strain hardening. For very high cycle fatigue, subsurface fatigue crack initiation at grain boundaries has been observed. EBSD investigation shows that strain accumulation is much localized. The fatigue damage is a localized plasticity exhaustion process.

Keywords: Nickel base alloy; dynamic strain ageing; low cycle fatigue; high cycle fatigue; cyclic deformation; plasticity exhaustion

1. Introduction

Nickel base alloy, Alloy 690, is mainly used as steam generator tubing in nuclear power plants. This alloy is considered to be immune to primary water stress corrosion cracking and has equal or superior stress corrosion cracking resistance to other steam generator tubing materials. They are used in the environments where the temperature can be up to 330°C. The material in the environment can also undergo strain controlled fatigue [1] and a vibration with a frequency from 30-40 Hz [2]. Although the stresses introduced in the tubes due to the vibration is relatively small, the fatigue properties of the SG tubing in very high cycle regimes (higher than 10^8 cycles) have been of concern.

Temperature has been found to have a significant influence on the strain controlled fatigue behaviours [3-5]. Three temperature regions have been defined. At low temperatures (about 0.25Tm, Tm-melting temperature), a rapid cyclic hardening is followed by a softening until a saturation peak stress is attained, or followed by a nearly stable stress response. At intermediate temperatures (<0.5Tm), this softening is replaced by stable stress response, and the saturation peak stress is increased [3, 5]. For some alloys, however, a monotonic cyclic hardening can be observed. At high temperatures (>0.5Tm), a rapid cyclic hardening is followed by cyclic softening, or only cyclic softening occurs [3].

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The purpose of this study is to investigate the influence of temperature and strain amplitude on the cyclic deformation behaviour and very high cycle fatigue behaviour of Alloy 690. The mechanisms of the observed secondary cyclic strain hardening have been discussed.

1.1. Material and experimental

The material used was hot extruded Alloy 690 (Sandvik Sanicro 69) material and SG tubing material with chemical composition and tensile property shown in Table 1 and 2.

| C   | Si  | Mn  | Cr  | Ni  | Ti  | Fe  | N   |
|-----|-----|-----|-----|-----|-----|-----|-----|
| 0.018 | 0.24 | 0.26 | 29.5 | 59.2 | 0.28 | 10.48 | 0.026 |

| Rp0.2 (MPa) | Rm (MPa) | A (%) |
|------------|---------|------|
| 210        | 716     | 47   |

Low cycle fatigue tests were conducted using a computer controlled servo-hydraulic 50 kN Instron machine. The tests were performed under total strain control at both RT, 204°C and 330 °C. The strain was measured using a high temperature extensometer with a gauge length of 25mm. A symmetric push-pull mode with a sinusoidal waveform and a frequency of 0,15Hz was applied. The test was stopped when 20% of the loading was reduced.

Two types of stress controlled fatigue tests were carried out. One was performed using an Amsler machine with a frequency of about 150 Hz. The sample used was a cylindrical sample with diameter of 3.5 mm and actual SG tubing with a length of 250 mm. Pulsating tensile stresses with a stress ratio R=0.1 were applied. Another test with same stress ratio was performed using an ultrasonic (Piezo) fatigue testing machine with a frequency of 20 kHz. A round sample with a diameter of 6 mm was used.

The origins of fatigue crack initiation and fatigue pre-initiation damage (dislocation slip bands) were investigated using a JEOL 840 scanning electron microscope (SEM). In order to investigate the fatigue crack initiation mechanism and material damage process after the fatigue, the dislocation structures were studied using a JEOL 2000-FX analytical transmission electron microscope (TEM/STEM) operating at 200 kV. In this study, the electron back-scattering diffraction (EBSD) technique has been used to study the microstructures related to deformation (misorientation and stress/strain fields).

2. Results and discussion

2.1. Low cycle fatigue properties at high temperature

The results from the strain controlled fatigue tests are summarised in Fig. 1a. If only plastic strain is concerned, the influences of strain amplitude on the fatigue properties at these two temperatures are comparable. The cyclic stress-strain responses at these two temperatures, however, vary differently (Fig. 1b). At room temperature, Alloy 690 shows a normal cyclic hardening and softening response. Increase in strain amplitude increases both hardening and softening rate. At 204°C, however, the stresses in the beginning increase with increasing number of cycles as expected. It then changes depending on strain amplitude. At small strain amplitude, it comes to a nearly stable stress at 10 to 100 cycles, and then the stress increases again with further cyclic strain until the specimen fails. This indicates that the alloy exhibits a secondary cyclic hardening. At a high strain amplitude, however, a softening instead of stable stress has also occurred before the secondary
cyclic hardening appears. The phenomenon of the secondary cyclic hardening at high temperature has rarely been reported in the literature [6].

![Graph showing cyclic strain hardening](image1)

In order to investigate the possible mechanisms for secondary cyclic strain hardening, a TEM investigation was performed. It was found that dense micro-twins with a width of ~100 nm and distance between two micro-twins of ~2 μm have been formed in the specimen with high strain amplitude in the secondary strain hardening region (Fig. 2a). According to Murr et al. [7], micro-twins can initiate in Ni based alloy when the critical pressure is higher than 30 GPa. On the other hand, micro twinning can also initiate when easy dislocation glide is hindered [8]. In the present investigation, the formation of micro-twins at high strain amplitude and elevated temperature may be attributed to the occurrence of dynamic strain ageing and the interaction between the moving dislocations and the stacking faults, which causes plastic deformation to become more difficult. Dynamic strain ageing behavior in this alloy has been observed during the static tensile testing at the same temperature as shown in Fig. 2b. This phenomenon during the cyclic loading at high temperature has been reported earlier [6]. The formation of micro-twins will increase plasticity and contribute to most of the localized deformation and consequently the softening, which can consequently be favorable to the fatigue life. On the other hand, once the micro-twins are formed, they will become the barriers for dislocation movement due to the increase of the boundaries, which may cause cyclic strain hardening again. Another contribution to the secondary hardening is the interaction between the moving dislocations and the stacking faults (Fig 2c), which causes plastic deformation to become more difficult. This can also give an explanation why Alloy 690 shows a high fatigue life at higher temperature.

### 2.2. High cycle fatigue properties at high temperature

Figure 3a shows the results of the fatigue tests up to 5x10⁸ cycles for Alloy 690 material at temperature up to 330°C. The fatigue life of the material at 330°C is slightly lower than that at RT, but the difference is small. This is mainly due to the fact that the high cycle fatigue properties are related to the strength of the material. However, when the stresses applied are near the fatigue endurance, the fatigue properties at 330°C are comparable with that at RT. The fracture investigation shows that the fatigue crack initiation in this alloy started mainly at the specimen surface. However, subsurface fatigue crack initiation in the matrix was observed in the VHCF regime. They are not from an inclusion, but from the matrix and have a facet microstructure. This is a type of subsurface crack initiation phenomenon typical for a pure material in VHCF regime. In this work, the crack initiation started at the boundaries of crystal planes (probably grain boundary) (Fig. 3b).
In order to investigate the possible mechanisms for subsurface non defect fatigue crack initiation in the very high cycle regime, an EBSD investigation was performed. With the EBSD technique, the local strain of each individual grain could be mapped through the image analysis of all the grains [9]. Fig. 4 shows the relative strains (strain contouring) for the specimens before and after the very high cycle fatigue test. Since the as delivered material (AD) is in an annealed and water quenched condition, it contains certain residual stresses and consequently strains (Fig. 4a). During cyclic loading with a stress range of below the yield strength, strain...
localising has occurred. Two phenomena could be observed. The localised highest strain was increased and the lowest strain was decreased although the average strain was increased. This indicates that some localised stress relaxation could also have occurred. For a lower stress range (270 MPa) and a very long fatigue life ($5.45 \times 10^8$ cycles), this tendency becomes more obvious (Fig. 4b). The difference between the highest strain and the average strain increases greatly. This indicates that dislocation accumulation during very high cycle fatigue is highly localized, where the plasticity of the material is exhausted and localized stress or strain concentration is formed. This leads to fatigue damage or fatigue crack initiation.

![Strain contouring mappings obtained from EBSD analysis of the specimen before and after fatigue test. (a). Specimen in AD condition, (b). Fatigue tested specimen with a stress range of 270 MPa for $5.45 \times 10^8$ cycles.](image)

3. Conclusions

The influence of temperature on both high cycle and low cycle fatigue of hot extruded Alloy 690 material and SG tubing in the temperature range of RT to $330^\circ C$ is relatively small.

The secondary cyclic strain hardening occurred in Alloy 690 at elevated temperature is attributed to the dislocation multiplication, the interaction between moving dislocations and stacking faults, the dynamic strain ageing effect and formation of nano twins. In the VHCF regime, dislocation or strain accumulation in the specimen is highly localized, which leads to the exhaustion of local plasticity and the formation of stress concentration. This consequently causes fatigue damage or crack initiation.

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