Paragraph Ran in the Queries

Paper Title: Mechanical-thermal coupling fatigue failure of CoCrFeMnNi high entropy alloy

Content :

Results and Discussion

The parameters involved in correcting the stress-strain curve are shown in Table 1. Fig. 2a and b shows the corrected engineering stress-strain curves and the mechanical properties of the alloy. Fig. 2a shows that the yield stress decreased from 317 MPa at RT to 158 MPa at 500 °C, similar to previous research results [34]. As the temperature increased, the percentage elongation after fracture increased. Fig. 2b shows that the modulus of the alloy decreased from 203 GPa at RT to 165 GPa at 500 °C, and the tensile strength decreased from 626 MPa at RT to 212 MPa at 500°C. Although the yield stress under RT was slightly higher than that under 340 °C, it could not be considered that the yield stress under RT was lower than that under 340 °C. Such minor differences might be caused by uneven zeroing of the force sensors. In addition, the differences in pores inside the material caused by sintering could also lead to changes in the macroscopic mechanical properties of the specimens. Alloys would fatigue fail under cyclic loading. The fatigue life of alloys is a vital index for evaluating fatigue performance [35]. As shown in Fig. 2c, under a constant cyclic load of 76–380 N, the fatigue life of the fatigue specimen decreased from 16.7 × 104 (±2.0 × 104) at RT to 6.7 × 104 (±0.8 × 104) at 500 °C. The fatigue life comprises the crack nucleation and propagation life [36]. The number of loading cycles from the beginning of loading to the initiation of fatigue crack was called the crack nucleation life, and the number of loading cycles from the formation of fatigue cracks to instantaneous fracture was called the crack propagation life. The previous uniaxial tensile test showed that the yield and tensile strength of the alloy gradually decreased with increasing temperature. Under the same loading conditions, the decrease in yield strength led to the increased occurrence of dislocations and slip, accelerating crack nucleation and propagation [37], and thereby reducing the fatigue life of the alloy [33]. In contrast, a decrease in the tensile strength would probably reduce the crack propagation life by reducing the area of the crack propagation region. Therefore, the decrease in the fatigue life of alloys caused by higher temperatures was directly related to a decrease in the strength of the alloy induced by higher temperatures. The fatigue fracture surface consisted of the instantaneous fracture and the crack propagation region. The proportions of the instantaneous fracture region to the entire fracture surface at different temperatures are shown in Fig. 2c. The proportion of the instantaneous fracture region increased from 61.1% (±4.9%) at RT to 85.8% (±5.5%) at 500 °C. This meant that the area of the crack propagation region decreased with the increasing temperature, thus reducing the crack propagation life.The parameters R and n at RT, 340 °C, and 500 °C were obtained through fitting based on the engineering stress-strain curves. In contrast, the parameters σ_s and E could be directly calculated from the curve. Considering the limited number of constitutive model parameter groups obtained through fitting, to reduce errors, the parameters at temperatures in the range of RT to 500 °C were obtained through a linear interpolation method based on the parameters at RT, 340 °C, and 500 °C. The calculated constitutive model parameters at temperatures ranging from RT to 500 °C.Based on the calculated constitutive parameters, the maximum stresses at the bottom of the notch at the temperatures ranging from RT to 500 °C were calculated through finite element analysis to be 357 MPa, 358 MPa, 358 MPa, 359 MPa, 299 MPa, and 341 MPa, respectively. The changing trend of the calculated stress concentration coefficient with increasing temperature is shown in Fig. 2d, and the stress cloud map of the yield region calculated by simulation under different temperature conditions is also shown in the figure. The stress concentration coefficient first decreased and subsequently increased with the increase in temperature, and the area of the yield region increased with the increased temperature. The increase in the stress concentration factor in the static simulation was due to more significant lateral deformation exacerbating the notch tearing effect. However, under actual fatigue loading, the actual deformation of the specimen might be less than that under static mechanical simulation, due to the hardening effect of the strain rate on the alloy. The engineering stress-strain curve in Fig. 2a shows that the higher temperatures or the more significant the yield degree of the alloy resulted in a lower rate of stress change relative to the strain and the trend of stress homogenization and strain differentiation. The decreased strength induced by higher temperatures resulted in more areas in the minimum cross-section of the specimen reaching the yield stage and the increased yield degree under the same loading conditions. Therefore, the increase in temperature could lead to stress homogenization and strain differentiation in adjacent areas of the fatigue specimen [32,33]. The minimum cross-section of the fatigue specimen bore tensile-bending composite stress [35], and the stress gradually increased from the notch to away from the notch at the minimum cross-section of the specimen. The increased temperature would also weaken the nonuniformity of the bending stress [33]. Ignoring other factors, such as the decrease in strength, the trend of stress homogenization caused by higher temperature might lead to delayed fatigue failure.

To systematically evaluate the effect of temperature on fatigue failure, the flank morphology of the fatigue specimens near the fracture surface at temperatures ranging from RT to 500 °C was collected through optical microscopy, as shown in Fig. 3a. The fatigue crack nucleated from the notch on the right and gradually propagated to the left until the load-bearing cross-section of the specimen was insufficient to withstand the fatigue load and instantaneously fractured. The fracture edge at each temperature consisted of a relatively flat right fracture edge, which was a mark left during the crack propagation stage, and a relatively uneven left edge, which was the impact area of instantaneous fracture. At RT to 200 °C, the fracture edges near the notch of the upper and lower specimens (right area) were almost parallel or exhibited a slight angle. From 200 °C to 500 °C, the angle between the fracture edge near notch α of the upper and lower specimens (in the right area) gradually increased. The previous finite element analysis results indicated that the yield area of the fatigue specimen increased with increasing temperature. Compared to those under RT conditions, the tearing propagation of fatigue cracks caused by higher temperatures was more pronounced, indicating that higher temperatures resulted in alloy softening and strengthening of plasticity, which was consistent with the decrease in modulus and increase in elongation after fracture of the alloy with increasing temperature, as shown in Fig. 2a. Simultaneously, the axial displacement along the specimen caused by material softening might accelerate the nucleation of potential cracks. The crack nucleation life accounted for the majority of the fatigue life. The phenomenon of the crack nucleation stage could best reveal the mechanism of fatigue life reduction induced by higher temperatures [36]. Therefore, the morphology of the crack nucleation region at RT and 500 °C was collected through SEM, as shown in Fig. 3b and c. More cracks appeared at the crack nucleation region of the fracture near the notch at 500 °C than that at RT. Once the first crack formed in the crack nucleation region, stress concentration would occur at the crack tip, and the stress in other areas at the bottom corner of the notch would be partially released. Therefore, the second crack was formed in a lower-stress state under higher-temperature conditions, indicating that crack nucleation was easier under higher-temperature conditions than that under RT conditions, and the same situation was for the main crack. As shown in Fig. 3b, the nucleation point of the crack was concentrated at the protrusion on the right edge of the crack. Both the nucleation point of the crack and the secondary cracks on the surface of the specimen are concentrated at the protrusion at the bottom of the notch, as shown in Fig. 3b. Due to more significant tensile stress, the crack nucleation tendency at the protrusion was stronger [30], so the crack nucleation points were concentrated at the protrusion. In addition, the spacing between the fatigue striations at RT seemed more minor than that at 500 °C, corresponding to the stress homogenization and strength reduction induced by higher temperatures. Simultaneously, wider fatigue striations might correspond to faster crack propagation rates. At RT, the angle between the fracture surface and the bottom of the notch was close to the right angle, while at 500 °C, the angle between the fracture surface and the bottom of the notch was obtuse, indicating that higher temperatures induced more significant plastic deformation at the bottom of the notch and that higher temperatures caused softening and plastic enhancement of the alloy, consistent with the results of tensile testing.