Effect of Temperature on Low-Cycle Fatigue Behavior of Alloy 625 Welded Joints: Postprint

Authors: Wang Yuanyuan, Wang Baosen, Chen Lijia

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Abstract

The low-cycle fatigue behavior of Inconel 625 nickel-based alloy welded joints was investigated at temperatures of 25 ℃ and 760 ℃. The cyclic strain-fatigue life data and stress-strain data at the aforementioned two temperatures were analyzed, and the fatigue parameters of Inconel 625 alloy in this temperature range were subsequently presented. The results indicate that the relationships between elastic strain amplitude and load reversal cycles, as well as between plastic strain amplitude and load reversal cycles, after low-cycle fatigue at different temperatures can be described by the Basquin and Coffin-Manson equations, respectively; at 25 ℃, the cyclic stress response behavior of the alloy is primarily cyclic softening; while at 760 ℃, it mainly exhibits cyclic hardening. These behaviors are attributed to the interactions among dislocation-dislocation, dislocation-twin boundary, and dislocation-precipitate during cyclic deformation.

Full Text

Influence of Temperature on Low-Cycle Fatigue Behavior of Inconel 625 Nickel-Based Superalloy Welding Joint

Yuanyuan Wang^{1}), Lijia Chen^{1}), Baosen Wang^{2})
^{1}) School of Materials Science and Engineering, Shenyang University of Technology, Shenyang 110870
^{2}) Institute for Welding and Surface Technology, Research & Development Center, Baoshan Iron & Steel Co., Ltd., Shanghai 201900
Correspondent: Lijia Chen, Professor, Tel: (024)25497699, E-mail: chenlisut@163.com
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Abstract

The low-cycle fatigue behavior of Inconel 625 nickel-based superalloy welding joints was investigated at 25°C and 760°C. The strain-fatigue life data and cyclic stress-strain data were analyzed to determine the strain fatigue parameters of the alloy welding joints. The results showed that the relationships between elastic strain amplitude, plastic strain amplitude, and reversals to failure at different temperatures can be described by the Basquin and Coffin-Manson equations, respectively. During fatigue deformation at 25°C, the welding joint primarily exhibited cyclic softening, whereas cyclic hardening occurred at 760°C. Low-cycle fatigue cracks initiated transgranularly at the free surface of fatigue specimens. At 25°C, fatigue cracks propagated in a transgranular manner, while at 760°C they propagated in a mixed transgranular and intergranular mode.

Keywords: Inconel 625 alloy, welding joint, low-cycle fatigue, dislocation, twin boundary

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Introduction

Inconel 625 is a solid-solution strengthened nickel-based wrought superalloy with Mo and Nb as the main strengthening elements, exhibiting high strength, high toughness, and resistance to Cl^- stress corrosion from cryogenic temperatures up to 980°C. These properties make it widely used in the nuclear and aviation industries. Under actual service conditions, components experience high temperatures and high stresses, causing localized plastic deformation and resulting in low-cycle fatigue that severely affects service life. Consequently, research on the performance stability and low-cycle fatigue behavior of superalloys has received extensive attention.

Recent studies on the low-cycle fatigue behavior of commercial superalloys for industrial applications have shown that the primary factors affecting the high-temperature low-cycle fatigue life of nickel-based superalloys are experimental parameters such as strain rate, hold time, and waveform. Superalloys may exhibit cyclic softening or cyclic hardening during cyclic deformation, or may initially harden and subsequently soften (or vice versa), with the specific cyclic behavior determined by the alloy' s microstructural state. Cyclic frequency affects the cyclic stress response behavior of alloys, and the applied strain amplitude determines the degree of this influence. When the plastic strain amplitude is below 0.5%, frequency has a significant effect on cyclic softening; generally, lower frequencies result in greater softening. However, when the plastic strain amplitude exceeds 0.5%, the influence of frequency on cyclic stress response behavior becomes weaker. Experimental temperature affects the degree of cyclic softening; during the initial stress drop stage of cycling, the magnitude of stress reduction increases with increasing test temperature, while during the stable cycling stage, the corresponding number of cycles decreases with increasing temperature. Based on the formation of misfit dislocation networks, Hwang et al. proposed that the fundamental cause of cyclic softening is the loss of coherency of primary γ precipitate particles due to shearing and partial dissolution of secondary γ precipitate particles. The primary γ particles lose their coherency through interaction with dislocations rather than by self-coarsening. Since the process of γ precipitate particles losing coherency requires thermal activation, the degree of cyclic softening exhibits obvious temperature dependence. The excellent properties of nickel-based wrought superalloys primarily derive from the precipitation strengthening effect of the γ phase; therefore, the composition, size, morphology, and distribution of the γ phase significantly influence alloy performance.

This work primarily investigated the low-cycle fatigue properties of Inconel 625 nickel-based alloy welding joints at 25°C and 760°C. Based on these results, the cyclic stress response behavior, strain-fatigue life relationship, and cyclic stress-strain relationship were analyzed to provide a reliable theoretical basis for the fatigue-resistant design of such welding joints.

Experimental Methods

The chemical composition of the experimental Inconel 625 nickel-based superalloy (mass fraction, %) was: C 0.1, Cr 23, Co 1.0, Si 0.5, Mo 10.0, Mn 0.5, Ni 58, Al 0.4, Nb 4.15, Fe 5, Ti 0.4. Fatigue specimens were machined from cast rods with a diameter of 8 mm, with a total length of 110 mm and a gauge length of 15 mm. Specimen surfaces were finely polished with 1200-grit SiC sandpaper to eliminate interference from surface machining defects. All low-cycle fatigue tests were conducted on a PLD-50 fatigue testing machine using an axial tension-compression fully reversed total strain amplitude control mode. At 25°C, the nominal total strain amplitude ranged from 0.4% to 1.2%; at 760°C, it ranged from 0.2% to 0.5%. A strain ratio of R = -1 and a cyclic frequency of 0.5 Hz were employed. All fatigue tests were terminated when the cyclic stress amplitude dropped to 80% of the peak stress amplitude achieved during the entire fatigue deformation process, with the corresponding number of cycles defined as the fatigue life.

Fracture surface morphology was examined using an S-3400N scanning electron microscope (SEM). Microstructures of fatigued specimens were observed using a JEM-2100 transmission electron microscope (TEM). TEM samples were prepared as follows: slices approximately 0.5 mm thick were cut perpendicular to the loading axis at approximately 1 mm from the fracture surface using an SYJ-150A low-speed diamond cutter. These slices were then ground to about 50 m thickness using 1000, 1500, and 2000-grit sandpapers. Final thinning was performed using a TenuPol-5 twin-jet electropolishing unit with a mixed solution of 10% $HClO_4$ + 90% C_2H_5OH (volume fraction) at -20°C and 30 V.

2.1 Cyclic Stress Response Behavior

Figure 1 [Figure 1: see original paper] shows the cyclic stress response curves of the Inconel 625 nickel-based alloy welding joint at 25°C and 760°C. At 25°C and an applied total strain amplitude of 0.4%, the welding joint first underwent cyclic strain hardening, followed by cyclic stability until final rapid stress drop due to crack initiation and propagation. At total strain amplitudes (Δ /2) of 0.6%, 0.8%, 1.0%, and 1.2%, the joint exhibited cyclic stability during the initial stage of fatigue deformation, followed by cyclic strain softening until final rapid stress drop. At 760°C and an applied total strain amplitude of 0.2%, the welding joint showed essentially stable cyclic stress response throughout the fatigue deformation process. At a total strain amplitude of 0.25%, cyclic strain hardening occurred first, followed by cyclic stability in the middle and later stages until rapid stress drop. At total strain amplitudes of 0.3%, 0.4%, and 0.5%, the welding joint exhibited cyclic strain hardening throughout the entire fatigue deformation period until rapid stress drop due to crack initiation and propagation.

2.2 Low-Cycle Fatigue Life Behavior

The strain amplitude-fatigue life relationship curves for the Inconel 625 alloy welding joint at 25°C and 760°C are shown in Figure 2 [Figure 2: see original paper]. Within the applied total strain amplitude range of 0.3%-0.5%, the fatigue life of the welding joint after low-cycle fatigue at 760°C was significantly lower than that at 25°C. This indicates that high-temperature low-cycle fatigue reduces the fatigue life of Inconel 625 nickel-based alloy welding joints.

Figure 3 [Figure 3: see original paper] presents the relationship curves between strain amplitude and load reversal cycles to failure (2Nf) for the Inconel 625 alloy welding joint during low-cycle fatigue at 25°C and 760°C. The plastic strain amplitude Δ /2 and 2Nf showed a linear relationship at both temperatures, which can be described by the Coffin-Manson equation:

$$\Delta\ /2 = \ f\ (2Nf)\hat{}c$$

where f is the fatigue ductility coefficient and c is the fatigue ductility exponent. Similarly, the linear relationship between elastic strain amplitude Δ /2 and reversals to failure 2Nf at both temperatures can be described by the modified Basquin equation:

$$\Delta\ /2 = (\sigma\ f/E)\ (2Nf)\hat{}b$$

where σ f is the fatigue strength coefficient, b is the fatigue strength exponent, and E is Young' s modulus. Using linear regression analysis of the data in Figure 3, the strain fatigue parameters for the Inconel 625 nickel-based alloy welding joint at both temperatures were determined, as summarized in Table 1 . The results show that f, b, and c values are higher at elevated temperature, while σ f is lower.

2.3 Cyclic Stress-Strain Behavior

The cyclic stress-strain curve reflects the true stress-strain characteristics of a material under low-cycle fatigue loading, with the relationship expressed as:

$$\Delta\sigma/2 = K\ \ (\Delta\ \ /2)\hat{}n$$

where $\Delta\sigma/2$ is the cyclic stress amplitude, K is the cyclic strength coefficient, and n is the cyclic strain hardening exponent. Figure 4 [Figure 4: see original paper] shows the cyclic stress-strain relationship curves for the Inconel 625 alloy welding joint during low-cycle fatigue at 25°C and 760°C. The cyclic stress amplitude $\Delta\sigma/2$ and plastic strain amplitude $\Delta\ \ /2$ were obtained from cyclic hysteresis loops at half-life under different strain amplitudes. A roughly linear relationship between $\Delta\sigma/2$ and $\Delta\ \ /2$ was observed at both temperatures. Using linear regression analysis of the data in Figure 4, the strain fatigue parameters were determined, with specific values listed in Table 1. The K and n values for the Inconel 625 alloy welding joint at 760°C were lower than those at room temperature.

2.4 Low-Cycle Fatigue Fracture Behavior

Figure 5 [Figure 5: see original paper] shows the low-cycle fatigue fracture morphology of the Inconel 625 alloy welding joint at 25°C with an applied strain amplitude of 0.8%. At 25°C, low-cycle fatigue cracks primarily initiated transgranularly at the free surface of fatigue specimens (Figure 5a). In the crack propagation region, very clear fatigue striations were observed (Figure 5b), indicating that fatigue cracks propagated transgranularly during low-cycle fatigue deformation of the Inconel 625 alloy welding joint at 25°C.

Figure 6 [Figure 6: see original paper] presents the low-cycle fatigue fracture morphology of the Inconel 625 alloy welding joint at 760°C under different applied total strain amplitudes. Cracks initiated transgranularly at the free surface of fatigue specimens, and the fatigue crack propagation region appeared relatively rough. At an applied total strain amplitude of 0.25%, fatigue cracks propagated in a mixed transgranular and intergranular mode, with secondary cracks observable on the fracture surface (Figure 6c). At a total strain amplitude of 0.4%, fatigue cracks also propagated in a mixed transgranular and intergranular mode, but no obvious secondary cracks were observed (Figure 6d). During high-temperature fatigue deformation, intergranular fracture occurs because grain boundaries are favorable sites for oxygen penetration and oxidation. This oxidation damage at high temperature is responsible for the significantly reduced low-cycle fatigue life at 760°C compared to 25°C.

3 Analysis and Discussion

As mentioned previously, the cyclic stress amplitude of the Inconel 625 nickel-based alloy welding joint gradually decreased with increasing cycle number during cyclic deformation at 25°C, exhibiting cyclic softening, whereas cyclic hardening occurred during fatigue deformation at 760°C. Dislocation motion is the primary cause of plastic deformation in materials, and deformation behavior is mainly influenced by the state of dislocation motion. Therefore, the aforementioned cyclic stress response behavior can be explained based on interactions between dislocations and between dislocations and twin boundaries during deformation.

TEM observations revealed that during cyclic deformation at 25°C with an applied total strain amplitude of 0.4%, strong interactions occurred between dislocations and twin boundaries. Twin boundaries effectively obstructed dislocation motion, causing numerous dislocations to pile up at twin boundaries (Figure 7a [Figure 7: see original paper]). The introduction of twin boundaries reduced the total interfacial energy of the system, allowing dislocations to glide on twin boundary planes, with twin interfaces storing a large number of mobile dislocations. Additionally, strong interactions between dislocations formed dislocation tangles and locks that hindered subsequent dislocation motion, impeding deformation. Consequently, the Inconel 625 nickel-based alloy welding joint exhibited cyclic hardening during fatigue deformation. However, with increasing total strain amplitude, dislocations became uniformly distributed (Figure 7b), without tangling, and dislocation reconfiguration resulted in simpler dislocation configurations that reduced resistance to dislocation motion, causing cyclic softening during fatigue deformation.

During cyclic deformation at 760°C with an applied total strain amplitude of 0.25%, dislocations bypassed precipitates (Figure 8a [Figure 8: see original paper]), ensuring the availability of mobile dislocations and resulting in cyclic stability during the middle and later stages of fatigue deformation. With increasing applied total strain amplitude, interactions between dislocations formed dislocation tangles, while strong interactions between dislocations and twin boundaries occurred simultaneously (Figure 8b), reducing dislocation mobility and causing cyclic hardening of the Inconel 625 nickel-based alloy welding joint during fatigue deformation.

Comparison of Figures 7 and 8 indicates that changes in temperature and strain amplitude did not significantly affect the size or quantity of precipitates. Clearly, precipitation hardening is not the primary hardening mechanism for Inconel 625. Instead, dislocation pile-up at twin boundaries and the effective obstruction of dislocation motion by twin boundaries enhance the alloy’ s hardening capacity, making twin boundary strengthening the main hardening mechanism.

4 Conclusions

1. The Inconel 625 alloy welding joint exhibited cyclic softening during low-cycle fatigue deformation at 25°C and cyclic hardening at 760°C.
2. The low-cycle fatigue life of the welding joint at 760°C was significantly shorter than that at room temperature. Both elastic and plastic strain amplitudes showed linear relationships with reversals to failure, which can

be described by the Basquin and Coffin-Manson equations, respectively.

3. Cyclic hardening during low-cycle fatigue deformation of the alloy welding joint was primarily related to interactions between dislocations and between dislocations and twin boundaries, while cyclic softening was mainly caused by dislocation reconfiguration.
4. Low-cycle fatigue cracks initiated transgranularly at the free surface of fatigue specimens. At 25°C, fatigue cracks propagated transgranularly, whereas at 760°C they propagated in a mixed transgranular and intergranular mode.

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