Effect of Pt on the Stress-Rupture Properties of Nickel-Based Single Crystal Superalloys: Post-print

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Abstract

The creep properties of nickel-based single crystal superalloys with different Pt contents were investigated under conditions of 1100 ℃, 180 MPa and 1000 ℃, 310 MPa, and the effects of Pt on the creep deformation microstructure and dislocation morphology of the alloys were analyzed using SEM, TEM and other methods. The results show that Pt slightly reduced the creep life of the alloy at 1100 ℃, 180 MPa, and significantly reduced the creep life at 1000 ℃, 310 MPa. Creep fracture in alloys with different Pt contents under various conditions all exhibited ductile fracture, with numerous microvoids and microcracks observable near the fracture surface. After creep deformation, dense dislocation networks formed on the g/g' interfaces in all alloys with different Pt contents. The main reason for Pt' s effect on the creep properties is that Pt promoted TCP phase formation, and the interfaces between TCP phases and the matrix absorbed a large number of vacancies generated during deformation, leading to void nucleation; as deformation continued, these voids became crack sources.

Full Text

Influence of Pt on the Creep Rupture Properties of Ni-Based Single Crystal Superalloys

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Abstract
This study investigated the creep rupture properties of Ni-based single crystal superalloys with different Pt contents under conditions of 1100 °C/180 MPa and 1000 °C/310 MPa. The effects of Pt on the creep deformation microstructure and dislocation morphology were analyzed using SEM and TEM. The results show that Pt slightly decreased the creep rupture life at 1100 °C/180 MPa and

significantly reduced the rupture life at 1000 °C/310 MPa. All alloys exhibited ductile fracture under both conditions, with numerous microvoids and microcracks observed near the fracture surfaces. Dense dislocation networks formed at the γ/γ interfaces after creep deformation. The primary reason for Pt' s detrimental effect on creep properties is its promotion of TCP phase formation. The TCP phase/matrix interface absorbs vacancies generated during deformation, leading to void nucleation that subsequently becomes crack initiation sites.

Keywords: Pt, Ni-based single crystal superalloy, creep rupture property

Introduction

Since the 1980s, the chemical compositions of single crystal superalloys have continuously evolved to improve their service limits. Notably, the addition of Re—a hallmark refractory element of second- and third-generation single crystals—has increased the temperature capability by approximately 30 °C per generation and enhanced creep performance to meet the demands of advanced aero-engines. However, with increasing alloying levels, ensuring microstructural stability during long-term service without detrimental phase precipitation has become a primary concern for advanced single crystal superalloys.

Recent studies have found that adding Ru to superalloys can improve microstructural stability in Re-containing alloys by suppressing the precipitation of harmful topologically close-packed (TCP) phases, while simultaneously strengthening the alloy and further improving creep resistance. The unique role of Ru in single crystal superalloys has drawn attention to other platinum group elements, including Rh, Pd, Pt, and Ir. Although it is recognized that platinum group elements can significantly influence the properties and service limits of single crystal superalloys, understanding of their mechanisms remains limited. Most research has focused on the effects of Pt, Pd, and Ir on solidification behavior and microstructural stability, with few reports on their influence on mechanical properties, particularly high-temperature creep performance. Van Sluytman et al. studied the compressive creep behavior of platinum group element-containing single crystal alloys at 1000 °C, but this differs from the tensile creep deformation experienced by actual single crystal blades. Therefore, systematic investigation of high-temperature creep in novel platinum group element-containing single crystal superalloys is necessary.

To clarify the influence of platinum group elements on high-temperature creep performance, this work used a third-generation single crystal superalloy containing 5% Re (by mass) as a base alloy, with different Pt contents added to study the effects on creep rupture properties, deformation microstructure, and dislocation configurations.

Experimental Methods

The nominal compositions of the experimental alloys are shown in Table 1 . Based on the 5% Re alloy, 1.5% and 3.0% Pt were added respectively, while other elements such as Co, Cr, W, and Ta remained unchanged. These three alloys are designated as 0Pt, 1.5Pt, and 3Pt alloys. First, alloy ingots were melted in a 5 kg vacuum furnace. Single crystal rods with a diameter of 14 mm were then produced in a ZDG-2 industrial directional solidification furnace using the spiral grain selection method at a withdrawal rate of 5 mm/min. The deviation angle of the rods from the (001) orientation was measured using electron backscatter diffraction (EBSD) in an S-3400N scanning electron microscope (SEM), ensuring the deviation was no greater than 10°. The heat-treated single crystal rods were machined into standard creep rupture test specimens as shown in Figure 1 [Figure 1: see original paper]. High-temperature creep rupture tests were conducted at 1100 °C/180 MPa and 1000 °C/310 MPa.

Fracture surface morphologies after rupture testing were observed using an S-3400N SEM. Longitudinal microstructures were examined using an INSPECT F50 field emission scanning electron microscope (FESEM). Microstructural samples were etched with a solution of 100 mL HCl + 20 g $CuSO_4$ + 100 mL H_2O for 5–10 s. Samples approximately 3 mm from the fracture surface were sectioned along the transverse direction to a thickness of 500 m, ground with sandpaper to below 50 m, and thinned by twin-jet electropolishing using a 10% perchloric acid + 90% ethanol electrolyte at temperatures below -20 °C and a current of 20 mA. Dislocation configurations after fracture were observed using a JEM-2100 transmission electron microscope (TEM).

Results

2.1 Creep Rupture Properties The creep rupture properties of the different alloys under various conditions are summarized in Table 2 . Compared with the 0Pt alloy, increasing Pt content slightly decreased the creep rupture life at 1100 °C/180 MPa with minimal effect on elongation. At 1000 °C/310 MPa, however, increasing Pt content significantly reduced both rupture life and elongation.

2.2 Fracture Morphology Figure 2 [Figure 2: see original paper] shows the fracture morphologies of different alloys after rupture testing at 1100 °C/180 MPa. The overall fracture surfaces were essentially perpendicular to the stress axis (Figures 2a, c, e). At higher magnifications, the fracture surfaces consisted primarily of irregular-shaped facets connected by tear ridges, with microvoids at the centers of the facets (Figures 2b, d, f). With Pt addition, the facet size tended to decrease while the number of microvoids increased, particularly in the 3Pt alloy compared to the 0Pt alloy.

Figure 3 [Figure 3: see original paper] shows the fracture morphologies after rupture testing at 1000 °C/310 MPa. The overall fracture appearances were similar to those at 1100 °C/180 MPa (Figures 3a, c, e). At higher magnifications

(Figures 3b, d, f), the 0Pt alloy fracture surface also consisted of facets and tear ridges, but the facets were more regularly shaped and square-like compared to the 1100 °C condition, with fewer microvoids and some facets lacking microvoids entirely. The 1.5Pt alloy exhibited larger, irregularly shaped facets, while the 3Pt alloy showed the largest facets with few containing microvoids.

2.3 Longitudinal Microstructure The longitudinal microstructures near the fracture surfaces after rupture testing at 1100 °C/180 MPa are shown in Figure 4 [Figure 4: see original paper]. Numerous microcracks and microvoids were distributed near the fracture surfaces, with microcracks spaced at intervals approximately equal to the primary dendrite arm spacing (Figures 4a, c, e). The microcracks in the 0Pt alloy were slightly coarser but less numerous than those in the 3Pt alloy, while the 3Pt alloy showed significantly more microvoids, consistent with the fracture surface observations (Figure 2). Higher magnification images revealed TCP phases near the microcracks in all alloys, indicating that TCP phases are an important factor in crack nucleation and growth. The amount of TCP phase increased with Pt content, with the 3Pt alloy showing the highest TCP phase density near microcracks (Figures 4b, d, f).

Figure 5 [Figure 5: see original paper] shows the longitudinal microstructures after rupture testing at 1000 °C/310 MPa. The 0Pt alloy exhibited numerous microvoids but fewer microcracks. With Pt addition, the number of microvoids decreased while microcracks increased in both number and size (Figures 5a, c, e). Similar to the 1100 °C condition, microcracks were distributed at intervals approximately equal to the primary dendrite arm spacing. Higher magnification observations revealed small amounts of TCP phases near microvoids in the 1.5Pt and 3Pt alloys (Figures 5d, f). Therefore, the creep performance at 1000 °C/310 MPa depends not only on TCP phase formation but also on other factors such as γ phase rafting.

2.4 Dislocation Configurations Nickel-based single crystal superalloys undergo creep deformation through dislocation motion, so the dislocation configurations during creep and their interaction with the γ phase determine the creep deformation mechanism. Figure 6 [Figure 6: see original paper] shows the dislocation configurations after rupture testing at 1100 °C/180 MPa. Dense dislocation network structures formed at the γ/γ interfaces, with some dislocations cutting into the γ phase. Figure 7 [Figure 7: see original paper] shows the dislocation configurations after rupture testing at 1000 °C/310 MPa, which were similar to those at 1100 °C/180 MPa, with dense dislocation networks at the γ/γ interfaces and numerous dislocations cutting into the γ phase. The 3Pt alloy showed more dislocations cutting into the γ phase than the 0Pt alloy.

Discussion

The above results demonstrate that the addition of the precious metal element Pt significantly affects the high-temperature creep rupture properties, deforma-

tion microstructure, and fracture mode of the 5%Re-containing single crystal superalloy. Previous research has shown that Pt can promote the segregation of refractory elements Re and W, increasing their enrichment in dendrite cores. Since these elements are TCP phase formers, Pt addition increases the tendency for TCP phase formation. This study confirms that Pt-containing alloys formed TCP phases during high-temperature creep deformation, with the amount of TCP phase and creep voids increasing with Pt content, thereby reducing creep rupture life and increasing the number of voids observed on fracture surfaces.

Single crystal alloys undergo cuboidal γ phase rafting during high-temperature creep, with dislocation networks forming at the γ/γ interfaces (Figures 6 and 7). Regular dislocation networks can effectively relax coherency stresses at the γ/γ interfaces, further hindering dislocation motion in the γ channels and effectively resisting creep deformation. Generally, the dislocation network spacing D is inversely proportional to the absolute value of lattice misfit δc: $D = |b|/|\delta c|$, where b is the magnitude of the Burgers vector. Alloys with larger absolute lattice misfit values have smaller dislocation spacings and denser dislocation networks, which within a certain range correlates with superior creep rupture properties. Since Pt primarily segregates to the γ phase, its addition may increase the γ lattice parameter more than the γ phase lattice parameter, thereby decreasing $|\delta c|$. This change in lattice misfit could be another reason for the reduced creep rupture life.

The primary mechanism by which Pt degrades creep rupture properties is through promoting TCP phase formation during high-temperature creep. The incoherent TCP phase/matrix interfaces have high energy and serve as vacancy sinks. Meanwhile, dislocation motion via glide and climb at high temperatures continuously generates vacancies, which are absorbed at TCP phase/matrix interfaces to form voids that become crack initiation sites during subsequent deformation. Since Pt promotes segregation of Re and W and consequently TCP phase precipitation, Pt-containing alloys exhibit more TCP phases and creep voids, resulting in reduced creep rupture life.

Conclusions

1. Pt affects the high-temperature creep rupture properties of Re-containing single crystal superalloys. Pt slightly decreases rupture life at 1100 °C/180 MPa without significantly affecting ductility, but markedly reduces both rupture life and ductility at 1000 °C/310 MPa.
2. The mechanism for Pt' s influence on creep properties is that Pt promotes TCP phase formation during high-temperature creep. The TCP phase/matrix interface absorbs vacancies generated during deformation, leading to void formation and crack initiation.

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Note: Figure translations are in progress. See original paper for figures.