

Effect of Temperature on Tensile Behavior of High Tungsten Content K416B Nickel-Based Alloy Postprint

Authors: Xie Jun, Yu Jinjiang, Xiaofeng Sun, Jin Tao, Yang Yanhong

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Abstract

Tensile property testing and microstructural morphology observation were conducted on K416B nickel-based alloy with high tungsten content at different temperatures to investigate the influence of temperature on the tensile behavior of the alloy. The results indicate that within the range of 20–800 °C, the yield strength and tensile strength of the alloy increase with rising temperature, while above 800 °C, the tensile properties gradually decrease. The characteristic of tensile deformation at room temperature involves dislocations shearing the γ phase or bypassing the γ phase via the Orowan mechanism, and dislocations entering the γ phase can decompose to form stacking faults. As the temperature increases, the dislocation density within the alloy matrix gradually increases; notably, during tensile testing at 800 °C, high-density dislocation tangles form within the alloy matrix, which can produce deformation strengthening effects and constitute the primary reason for the alloy's high tensile strength. With further temperature elevation, the number of dislocations shearing into the γ phase increases, leading to a gradual decrease in alloy strength. Under medium- and low-temperature conditions, cracks primarily nucleate and propagate at large-sized M₆C carbides, resulting in brittle fracture of the alloy. During high-temperature tensile testing, the alloy mainly undergoes connection cracking along the $\gamma+\gamma$ eutectic interface via a microvoid coalescence mechanism, which is the main cause of ductile fracture in the alloy.

Full Text

Preamble

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Influence of Temperature on Tensile Behaviors of K416B Ni-Based Superalloy with High W Content

XIE Jun, YU Jinjiang, SUN Xiaofeng, JIN Tao, YANG Yanhong
Institute of Metal Research, Chinese Academy of Sciences, Shenyang 110016

Correspondent: YU Jinjiang, professor, Tel: (024)23971713, E-mail: jjyu@imr.ac.cn

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Abstract

Ni-based superalloys with high tungsten content are widely used for manufacturing gas turbine vanes and high-temperature forging dies due to their excellent high-temperature capabilities and cost-effectiveness. The microstructure of these alloys typically consists of a γ matrix, γ precipitates, and various carbides. Deformation mechanisms generally involve dislocation loop formation, shearing of dislocations into the γ phase, and the formation of anti-phase boundaries (APBs) and stacking faults. Although the deformation mechanisms of Ni-based superalloys have been extensively studied, the relationship between tensile properties and deformation mechanisms in K416B superalloy across different temperatures remains unclear. This investigation examines the influence of temperature on the tensile behaviors of K416B Ni-based superalloy with high W content through systematic tensile testing.

The results demonstrate that both yield strength and tensile strength increase with temperature from 20 °C to 800 °C, beyond which they gradually decrease. At room temperature, deformation occurs primarily through dislocations shearing the γ phase or bypassing it via the Orowan mechanism, with shearing dislocations decomposing to form stacking faults. As temperature rises, the dislocation density in the alloy matrix progressively increases. Notably, at 800 °C, high-density dislocation tangles form in the matrix, providing significant deformation strengthening and contributing to the alloy's peak strength. At higher temperatures, the increased number of dislocations shearing into the γ phase leads to strength degradation. Under intermediate and low temperatures, cracks predominantly initiate and propagate along large M₆C carbides, resulting in brittle fracture. In contrast, at elevated temperatures, fracture occurs through microvoid coalescence along the $\gamma+\gamma$ eutectic interfaces, manifesting as ductile fracture.

Keywords: K416B Ni-based superalloy, tensile behavior, deformation feature, fracture mechanism

Introduction

High-W Ni-based superalloys are considered important materials for aero-engine guide vanes due to their excellent oxidation resistance and high-temperature mechanical properties. The microstructure primarily comprises a γ matrix, γ' phase, and carbides, where the size, morphology, and distribution of strengthening phases directly influence service performance. Tungsten is a critical solid-solution element that strengthens both γ and γ' phases while also serving as a primary carbide-forming element during solidification. Various types and morphologies of carbides form during casting, significantly affecting mechanical properties. Hu et al. reported that in Ni-Cr-W alloys, M₂₃C₆ carbides precipitate in the γ matrix along $\langle 110 \rangle \{111\}$ orientations with diverse morphologies: discrete granular M₂₃C₆ at grain boundaries enhances tensile strength, whereas plate-like precipitates reduce it.

Temperature directly affects the mechanical properties of Ni-based superalloys, with tensile performance closely related to deformation mechanisms. At intermediate and low temperatures, deformation mechanisms include dislocation bowing and loop formation, with dislocations shearing γ' phase and decomposing into stacking faults or anti-phase boundaries (APBs). As temperature increases, dislocation tangles, cross-slip, and climb become active. Studies on M951 superalloy revealed that low-temperature deformation features dislocation shearing of γ' phase and slip band formation, high-temperature deformation involves dislocation bypassing, and intermediate temperatures show a transition from shearing to bypassing. Liu et al. demonstrated that in Re-containing single-crystal alloys, deformation below 600 °C creates APBs and stacking faults, while above 800 °C, dislocations bypass γ' phase.

Fracture modes in Ni-based superalloys include intergranular, transgranular, and microvoid coalescence. Literature indicates that deformation twins cause serrated stress-strain curves and can enhance strength within certain temperature ranges. Yang et al. attributed the high yield strength and good ductility of K445 superalloy at 750 °C to secondary hardening effects. Research on K403 alloy showed that fracture transitions from quasi-cleavage to intergranular with increasing temperature. However, reports on tensile deformation characteristics and fracture mechanisms in high-W Ni-based superalloys remain scarce. Therefore, this work investigates the tensile properties of high-W K416B alloy across various temperatures and examines the microstructures of fractured specimens to elucidate temperature effects on tensile behavior, providing theoretical guidance for alloy application and development.

1. Experimental Methods

K416B master alloy ingots were remelted in a ZG-001 10 kg vacuum induction furnace and cast into equiaxed bars. The nominal composition (mass fraction, %) was: C 0.13, Cr 4.90, Co 6.82, Nb 2.06, Al 5.75, W 16.3, Ti 1.00, Hf 1.00, Ni balance. Bars were machined into cylindrical tensile specimens with a gauge length of 25 mm and diameter of 5 mm. Tensile tests were conducted at various temperatures using an AG-25KNE testing machine.

Fracture surfaces were examined using an S-3400N scanning electron microscope (SEM). Fractured specimens were sectioned along the axial direction, ground, polished, and etched with a solution of 20 mL HCl + 5 g CuSO₄ + 25 mL H₂O for cross-sectional microstructural observation and energy-dispersive spectroscopy (EDS) analysis of precipitates. Thin foils (0.5 mm thick) were sliced from fractured specimens, mechanically ground to 50 μ m, punched into 3 mm disks, and thinned by twin-jet electropolishing at -25 °C using a 10% perchloric acid ethanol solution. Microstructures were observed using a TECNAI-20 transmission electron microscope (TEM).

2. Results and Discussion

2.1 Microstructure

The as-cast microstructure of K416B alloy is shown in [Figure 1: see original paper]. Dendrites with various growth directions are clearly visible, with numerous γ + γ eutectic structures in interdendritic regions and large blocky carbides precipitated along interdendritic areas. The large carbides exhibit blocky and strip morphologies with sizes of 40–80 μ m. Grain boundaries appear straight with irregular carbides distributed discontinuously along them. The γ phase shows size and morphology variations: dendrite core γ particles are smaller (0.3–0.6 μ m) and granular, while interdendritic γ is larger (0.5–1.0 μ m) and irregularly distributed.

The XRD spectrum in [Figure 2: see original paper] identifies the alloy as consisting primarily of γ matrix, γ phase, M₆C, and MC carbides. EDS analysis reveals that blocky carbides are rich in W, Co, and C, while grain boundary carbides contain Nb, Ti, Hf, and C. Combined with XRD results, the blocky phase is identified as M₆C carbide and the grain boundary precipitates as MC carbide.

2.2 Tensile Properties

Tensile properties at various temperatures are presented in [Figure 3: see original paper]. Yield and tensile strengths increase with temperature from 20 °C to 800 °C, rising from 710 MPa to 865 MPa and from 900 MPa to 1020 MPa, respectively. Above 800 °C, both strengths drop sharply to 493 MPa and 602

MPa at 1000 °C. Ductility remains low between 20 °C and 800 °C, with elongation of approximately 6.5% at 800 °C, but improves significantly above this temperature.

Stress-strain curves in [Figure 4: see original paper] show that strain rate increases with applied stress. At a given stress, strain rate increases with temperature. Curves for 20 °C, 600 °C, and 700 °C are similar, while strain increment becomes more pronounced above 800 °C.

2.3 Tensile Deformation Characteristics

TEM images of specimens fractured at intermediate and low temperatures are shown in [Figure 5: see original paper]. After room-temperature fracture, limited slip dislocations are observed. Deformation dislocations form loops in the matrix under applied stress, with $\langle 110 \rangle$ superdislocations shearing γ phase and decomposing into stacking faults [Figure 5a: see original paper]. At 600 °C, dislocation density increases with long dislocation traces crossing γ particles [Figure 5b: see original paper]. The morphology at 700 °C is similar and thus omitted. At 800 °C, dislocation density further increases, forming dense tangles in matrix channels [Figure 5c: see original paper].

High-temperature deformation features are illustrated in [Figure 6: see original paper]. After 900 °C testing, grain boundaries are clearly visible with discrete granular MC carbides that impede dislocation motion. The number of dislocations shearing into γ phase increases. At 1000 °C, dislocation density rises significantly with pile-ups and tangles at γ/γ interfaces, indicating progressive increase in deformation dislocations with temperature.

2.4 Microstructure of Tensile-Fractured Alloy

Typical microstructures of fractured specimens are shown in [Figure 7: see original paper]. At room temperature, blocky M6C carbides and eutectic structures are evident on the fracture surface, with cracks initiating and propagating along large carbides. After 400 °C testing, cracks remain associated with blocky M6C carbides, accompanied by 少量 parallel slip traces nearby. At 600 °C, numerous slip traces terminate at blocky M6C carbides, creating stress concentrations that exceed the carbide strength, causing carbide fracture and crack initiation. This pattern persists at 800 °C, where carbide fragmentation occurs under stress, confirming that large blocky M6C carbides represent the weak link during intermediate and low-temperature tensile deformation.

At 900 °C, slip traces appear near grain boundary MC carbides and eutectic structures. Intergranular cracks exhibit rough features with tearing at eutectic interfaces, while large blocky M6C carbides remain on the fracture surface with prominent slip steps above them. At 1000 °C, extensive slip traces appear at $\gamma+\gamma$ eutectics, and cracks form through microvoid coalescence primarily along eutectic interfaces, indicating that the $\gamma+\gamma$ eutectic region becomes the weak zone at high temperatures.

Fracture surface morphologies are presented in [Figure 8: see original paper]. Room-temperature fracture surfaces are flat with cleavage facets and dendritic cleavage traces, featuring cracked large blocky M6C carbides with cleavage steps nearby. At 400 °C, fractured carbides show uneven surfaces with adjacent cracks. Similar flat morphologies occur at 600 °C and 800 °C, with river patterns and propagating cracks visible at 600 °C, and shallow dimples with clear cleavage steps at 800 °C, indicating predominantly cleavage fracture (brittle behavior). At 900 °C, fracture surfaces become uneven with irregular cleavage facets and microvoids, showing coalescence-connected cracks and small tearing dimples. The 1000 °C fracture features are similar, with cleavage facets, tearing dimples, and microvoid-connected cracks, demonstrating mixed cleavage and microvoid coalescence (ductile behavior) at high temperatures.

Deformation dislocation density increases with temperature. At room temperature, limited dislocations glide in the γ matrix, bowing out to form loops and bypassing γ phase via the Orowan mechanism. $\langle 110 \rangle$ superdislocations shearing into γ phase decompose into partial dislocations and stacking faults. At intermediate temperatures (600–800 °C), dislocation density increases, with dense tangles at 800 °C providing deformation strengthening and contributing to high yield and tensile strengths. At high temperatures, deformation dislocation density further increases with more $\langle 110 \rangle$ superdislocations shearing γ phase, causing strength reduction.

Large blocky M6C carbides and $\gamma+\gamma$ eutectic structures critically influence fracture behavior. The high-strength M6C carbides generate stress concentrations during intermediate and low-temperature tensile deformation, promoting crack initiation and propagation and causing brittle fracture. In contrast, the lower-strength eutectic regions undergo extensive plastic deformation at high temperatures, failing by microvoid coalescence along eutectic interfaces, particularly pronounced at 1000 °C. Thus, the crack initiation site shifts from large M6C carbides to $\gamma+\gamma$ eutectic regions with increasing temperature, resulting in ductile fracture.

During intermediate and low-temperature tensile deformation, dislocations primarily activate in the γ matrix with limited shearing of γ phase, preventing timely stress release. Combined with stress concentration at large blocky M6C carbides, this promotes crack propagation and results in low ductility. At 900 °C, increased dislocation density in the γ matrix creates pile-ups at γ/γ interfaces, forcing dislocations to shear γ phase and release stress effectively, enabling continued deformation. Elevated temperature also reduces γ phase strength, allowing more dislocations to shear and producing greater plastic deformation, which enhances ductility. At higher temperatures, although increased dislocation density in both γ matrix and γ phase releases some stress from tangles, the substantial strength reduction and high strain rate cause flow stress to exceed stress release capacity. When accumulated flow stress surpasses the yield strength, fracture occurs, reducing elongation.

Conclusions

- (1) The yield and tensile strengths of K416B alloy increase initially then decrease with temperature, peaking at 800 °C. Above this temperature, ductility improves significantly.
- (2) Dislocation density increases with temperature. At room temperature, dislocations primarily bypass γ phase via the Orowan mechanism, with shearing dislocations decomposing into stacking faults. Dense dislocation tangles formed at 800 °C provide deformation strengthening, accounting for the high strength. At higher temperatures, increased shearing of γ phase by dislocations leads to strength reduction.
- (3) During intermediate and low-temperature tensile deformation, stress concentrations at large blocky M₆C carbides promote crack initiation and propagation, causing brittle fracture. At high temperatures, cracks initiate in $\gamma+\gamma$ eutectic regions and propagate by microvoid coalescence, resulting in ductile fracture.

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