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Creep-Induced Nonlinear Acoustic Change in Nickel-based superalloy, Inconel 718

Toshihiro Ohtani[1†], Yutaka Ishii[1], Masayuki Kamaya[2], Takayuki Sakakibara[3] , Yutaro Ohta[4] and Keiji Kubushiro[4]
([1]Shonan Institute of Technology; [2]Institute of Nuclear Safety System; [3]Chuo Spring Co; [4] IHI)

1. Introduction

Ni-based superalloys have excellent mechanical properties, corrosion resistance, and oxidation resistance at high temperatures. They are widely used in jet engines for aircraft and gas turbines for power generation[1)] . While various Ni-based superalloys have been developed, Inconel 718 was developed as an alloy with excellent mechanical properties, microstructural stability, and weldability at high temperatures below 973 K. Inconel 718 is a precipitation-strengthened alloy, and the precipitation-strengthened phase consists of γ″ particles (Ni_3Nb) and γ′ particles (Ni_3Al) with a volume ratio of 4:1.[2)] The mechanical properties strongly depend on the grain size of the γ″ particles[2),3)].

The purpose of this study was to apply the evaluation method combining the nonlinear ultrasonic method, three-wave-interation,[4)] and the electromagnetic acoustic resonance (EMAR) method[5)] to the creep damage of a Ni-based superalloy, Inconel 718. The EMAR method is a measurement method that combines ultrasonic resonance with an electromagnetic acoustic transducer (EMAT) [5)] that can transmit ultrasonic waves without contact. We elucidated the relationship between microstructural change and the evolutions of nonlinear acoustic characterizations, three-wave interacting[4)], with EMAR throughout the creep life time. We observed microstructure with SEM, EBSD, dislocation density with X-ray and Vickers' hardness.

2. Experimental

The material investigated in this study is the Inconel 718 was subjected to solid solution treatment (ST) at 1253 K for 1 h, air cooling after holding, and the aging conditions were 991 K for 8 h, cooling rate after holding at 56 deg/h, and 894 K, air cooling after holding for 8 h. After that, creep specimen shown in **Fig. 1** was cut out. The gauge section of the creep specimen is 5 mm thick, 18 mm wide and 40 mm long Mechanical properties at room temperature were following; proof stress 1,176 MPa, tensile strength 1343 MPa, elongation17 %. To clarify the relationship between nonlinear acoustic

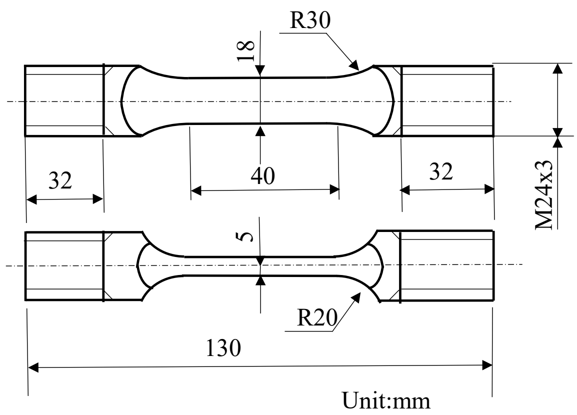

Fig.1 Shape and dimension of creep specimen in Inconel 718.

characterizations and the formation and evolution process of creep damage in Inconel 718, interrupted creep tests carried out at several steps of rupture life (tr) at 1033 K and 200 MPa, 973 K and 310 MPa for the specimen (tr=351 h, 1,780 h), where a failure was observed. Tests were interrupted at approximately 20, 40, 60, 80, 100% of rupture life.

We measured evolutions of the acoustic nonlinearities with the nonlinear three-wave-interaction method throughout the creep life in the gauge section with an electromagnetic acoustic transducer (EMAT). We used bulk-shear-wave EMAT, which transmits and receives shear wave propagating in thickness direction of a plate type specimen. Three-wave-interaction method is based on the fact that material nonlinearities cause interaction between two intersecting ultrasonic waves[5)]. Under certain conditions, this can lead to the generation of a third wave with a frequency and wave-vector equal to the sum or difference of the incident wave frequencies and wave-vectors, relatively. This is much less sensitive to system nonlinearities due to spatial selectively, modal selectively, and frequency selectivity. We developed a technic to measure with only one EMAT measured three- wave interaction method.

Different resonance frequencies; f_n, f_m (n, m: resonant modes, $m>n$) were generated by two coils, respectively. Resonant frequency appeared at an equal interval and was determined by the following

e-mail : ohtani@mech.shonan-it.ac.jp

equation; $f_n = nV/(2d)$, where n is the resonant mode, V the wave speed, d the thickness of the sample, f_n the n-th resonant frequency. The difference or sum frequency, $f_n \pm f_m$ was measured by one coil. Because material nonlinearity showed independence of the excitation level, the amplitude of the interaction resonant wave A_3, at $f_n \pm f_m$ was normalized to the product of the two input resonant amplitudes A_1 and A_2. In this study, we measured the amplitude, A_3 at the resonant frequency, $f_n \pm f_m$. In selection of resonance mode, n, m, the numbers were prime numbers or not with common divisor or common multiple. We measured resonant frequencies for resonant modes with using the systems for a nonlinear acoustic phenomenon (SNAP) manufactured by RITEC.

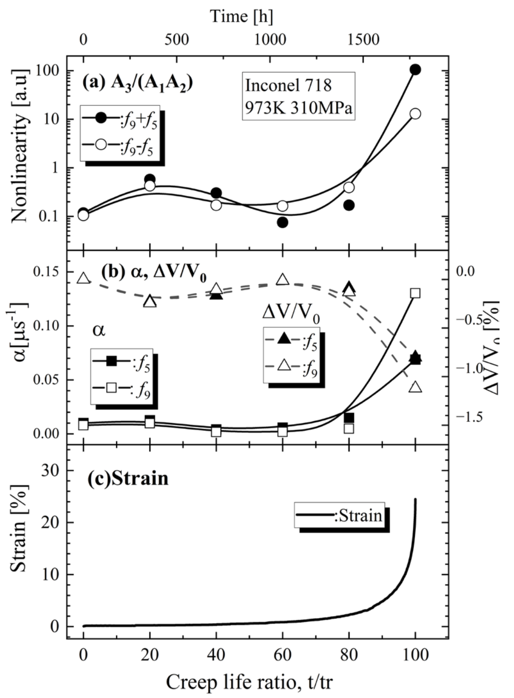

Fig.2 Evolution of (a) the nonlinearity with three-wave interaction (b) attenuation coefficients and relative velocities and (c) creep strain during creep in Inconel 718 (973K, 310MPa, tr=1,780h).

3. Results and Discussion

In this study, ultrasonic properties in the thickness direction were measured using the 5th- and 9 th-resonant frequencies, f_5, f_9, nonlinear three-wave interaction method and ultrasonic properties (attenuation coefficient, α and velocity:) with EMAR as creep progress in Inconel 718. In the nonlinear three-wave interaction method, the resonance frequencies of f_5 and f_9, were used as input resonant frequencies, the difference and sum modes (f_9-f_5 = f_4, f_9+f_5 = f_{14}) were measured, and these amplitudes were used to define $A_3/(A_1A_2)$s as the nonlinearities (A_1, A_2: amplitudes at resonant frequencies, f_9 and f_5 as input resonant frequencies, A_3s: amplitudes at the incident frequencies, f_9-f_5, f_9+f_5). Shown in **Fig. 2** are the evolutions of (a) the nonlinearities with three-wave interaction, $A_3/(A_1A_2)$s, (b) attenuation coefficients, αs, and relative velocities, $\Delta V/V_0$s at f_9, f_5 ($\Delta V = V - V_0$, V: velocity, V_0: initial velocity) and (c) creep strain during creep (973 K and 310 MPa). The nonlinearities, $A_3/(A_1A_2)$s increase rapidly from the beginning to t/tr=20%, then decreased to t/tr=60%, and then increased rapidly to the rupture(Fig. 1(a)). Similar to $A_3/(A_1A_2)$s, attenuation coefficients, αs increased from the start of creep, reaching a maximum value at t/tr =20%, and then increased from t/tr =60% to rupture. $\Delta V/V_0$s slightly decreased from the beginning to t/tr =80% and then rapidly decreased to the rupture. The maximum amount of change was about 1%. This phenomenon shows three-wave interaction methods nonlinearity $A_3/(A_1A_2)$, attenuation α, as creep progress was related to the microstructure change, especially, dislocation mobility, cohesion and coarsening of γ″ and precipitates during creep life.

3. Conclusions

We investigated the relationship between microstructural change and the evolutions of nonlinear acoustic characterization three-wave interaction, with EMAR throughout the creep life in the Inconel 718. Nonlinear acoustic parameter and ultrasonic attenuation showed peaks at t/tr=20% and increased from t/tr =60 % to rupture. We interpreted these phenomena in terms of dislocation recovery, recrystallization, and restructuring related to the γ″ (Ni_3Nb) phase collapse, with support from the X-ray diffraction observation, SEM and EBSD observations.

Assessment of creep damage advance and microstructural change of metals may potentially be facilitated by nonlinear acoustics measurement with EMAR.

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