Nondestructive Evaluation of the Creep Damaged Ni-Based Superalloy Using Ultrasonic Wave Method

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Abstract

The effects of microstructures during creep on the ultrasonic attenuation have been investigated for Ni based superalloy (IN738LC). The cuboidal γ′ precipitates in the virgin material became coarsened preferentially in the direction perpendicular to the applied stress axis as creep time increased. The length of γ′ precipitates increased with creep time, while the width increased slightly. The increase in the ultrasonic attenuation with increasing creep time was discussed with the increase in the equivalent size of γ′ precipitates, which was related to the scattering of ultrasonic. Ultrasonic attenuation was found to have a linear correlation with the equivalent size of γ′ precipitates. It is suggested that the ultrasonic attenuation can be used as a potential nondestructive parameter for assessing the degree of creep damage of IN738LC superalloy.

1. Introduction

The IN738LC Ni based superalloy has been widely used for gas turbine blade due to its high resistance to creep, oxidation and corrosion. The superiority in high temperature creep strength of the alloy is mainly attributed to large amount (volume fraction: approximately 40% [1]) of cuboidal γ′ precipitates ($Ni_3(Al,Ti)$) [2]. However, the alloy is known to result in directional coarsening (rafting) after long time use at high temperature under stress, which causes progressive loss of creep strength [2-5]. Some researchers [3,4] have attempted to quantify the degree of rafting in Ni based superalloy by metallographic examination. Matan et al. [3] reported that the length of γ′ precipitates increased linearly with increasing creep time. Paris et al. [4] observed the increase of aspect ratio of γ′ precipitates in creep damaged Ni based superalloy. In order to evaluate the damage to structure nondestructively using in-situ monitoring, ultrasonic [6,7], magnetic [8] and electrical resistivity [9] methods are currently used.

In the most of the previous research applying ultrasonic method to the evaluation of creep damage in steel [6] and Cu [7], the decrease of ultrasonic velocity due to the formation of creep cavity was reported. On the contrary, the most dominant microstructural change in IN738LC alloy during creep deformation is rafting of γ′ precipitates rather than creep cavity formation [5]. In this research, it was attempted to evaluate the rafted microstructure of artificially creep damaged IN738LC alloy by nondestructive ultrasonic attenuation measurement.

2. Experimental Procedure

A cast plate specimen aged at 780℃ for 24 hours after solution heat treatment at 1150℃ for 4 hours [5] was used, and its chemical composition is Ni: balance, C: 0.1, Cr: 16, Co: 8.6, Mo: 1.75, Ta: 1.8, Al: 3.1, Ti:3.1, W: 2.7, Si: 0.09, Mn: 0.03, Nb: 0.82 and Fe: 0.3 in weight %. The creep temperatures and stress ranges were determined from the Larson-Miller parameter so that the rupture time ranged 10-1000 hours. Creep test was interrupted after some fraction of life time (t/t_f = 0, 0.25, 0.5, 0.75, 1.0) [3] for microstructural examination and ultrasonic measurement. The γ′ precipitates were observed using FESEM (field emission scanning electron microscope) after electrolytic etching. The mean length and width were measured for 300-400 γ′ precipitates in each specimen using image analyzer. The equivalent size

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(value converted to the diameter of sphere) of γ′ precipitates, was calculated by using the following Equation [10] under the assumption that the shape of precipitates is oval:

$$d_E = (2a + b)/6 \quad (1)$$

where a is the length and b is the width of γ′ precipitates, respectively.

In order to identify the amount of cavity formed during creep, a density of the specimen was measured using Archimedes's principle [7].

An immersion test method was employed to minimize the errors due to contact couplant in measuring the ultrasonic attenuation.
The wide band piezoelectric transducer with the central frequency of 15 MHz was used for pulsating and receiving longitudinal wave. Attenuation coefficients were estimated by pulse echo method in time domain [11]. The results are the average values of five measurements. All the measurements including microstructural analysis in the fractured specimens were performed after removing 5mm thick surface.

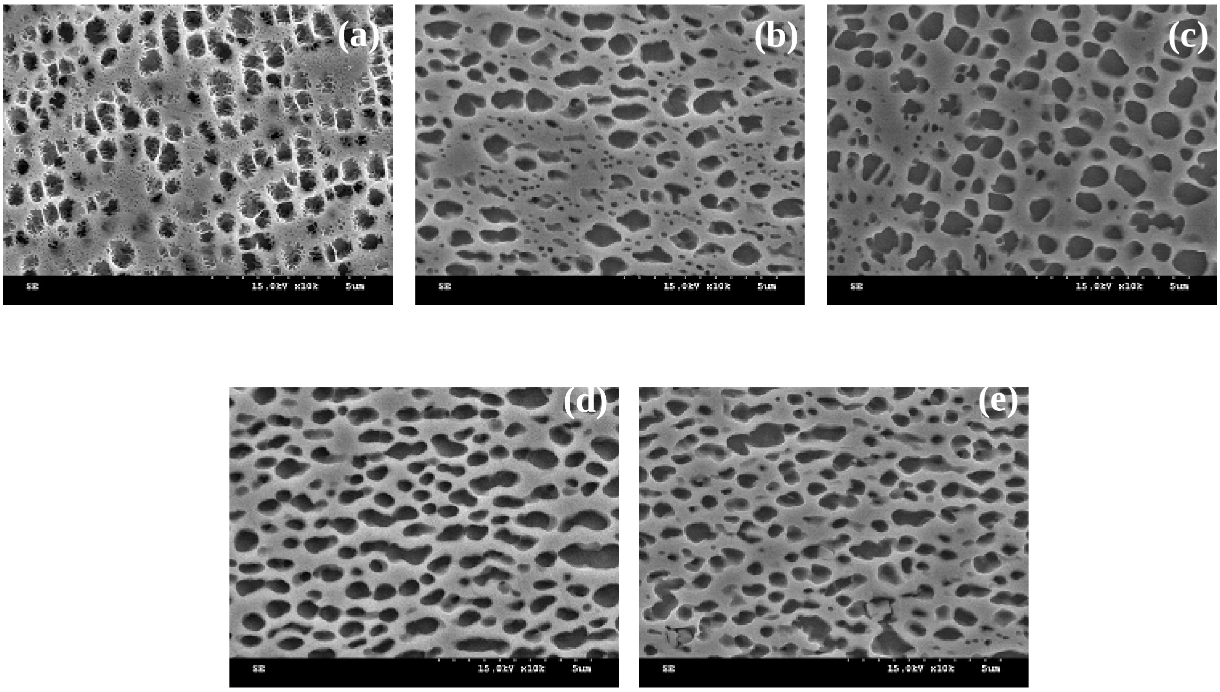

Fig. 1. Creep curve at 950℃ under 215MPa and typical FESEM images showing the rafted micro structure at various damage levels: (a) virgin, (b) 9 hrs, (c) 19 hrs, (d) 27 hrs and (e) fracture (38hrs).

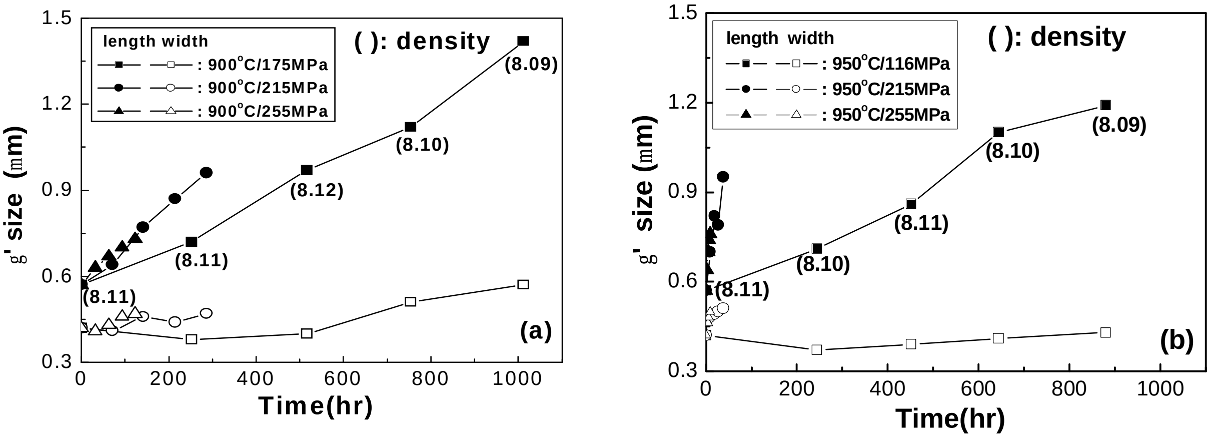

Fig. 2. Change of the mean size of γ′ precipitates with creep time at various creep conditions; (a) 900℃ and (b) 950℃.

3. Results and Discussion

Fig. 1 shows the rafted morphologies of γ′ precipitates at various damage levels. The cuboidal γ′ precipitates in the virgin material became coarsened preferentially in the direction perpendicular to the applied stress axis as creep time increased, which implies that there exists a negative misfit (the lattice parameter of γ is larger than that of γ′) between γ′ precipitates and γ matrix. Fig. 2 shows the change of mean length and width of γ′ precipitates with creep time at various creep conditions. The length of γ′ precipitates increased linearly with creep time, while the width increased slightly. The results shown in Fig. 2 agreed well with the Matan et al.'s ones [3] obtained from the crept CMSX-4 Ni based superalloy. Little decrease in the measured density was observed during creep as noted in Fig. 2, which indicate that almost no cavity formed in spite of creep deformation. Komazaki et al.' report [5] that creep cavity did not form until creep life fraction of 0.8 in Ni based superalloy with γ′ precipitates conforms the similarity to the present results.

Hardness was decreased with creep time as shown in Fig. 3 due to the coarsening and rafting of γ′ precipitates. Softening is the main physical phenomenon observed in materials after creep deformation and represents a decrease in hardness. The Vickers hardness exhibits a linear relation with the inverse of the size of the precipitates, as shown in Fig. 4. This linear relation corresponds to the particle looping mechanism [12] presented by E. Orowan and Ashby. Based on the result of the linear regression analysis, the above relationships can be represented by the following Equation.

$$Hv = 218.7 + 54 * (d_E^{-1}) \qquad (2)$$

where Hv is Vickers hardness and d_E is the size of precipitates, respectively.

Fig. 5 shows the change of ultrasonic attenuation with creep time at each creep condition. The attenuation coefficient tended to increase linearly with creep time. Ultrasonic energy is attenuated as the wave propagates through a material due to scattering and absorption. Absorption, which is caused by microstructural defects such as dislocation and point defect, takes only small part of the measured attenuation in metallic materials and usually assumed to be negligible [10]. The increase of ultrasonic attenuation in the crept specimens seems to be related to the rafted microstructure.

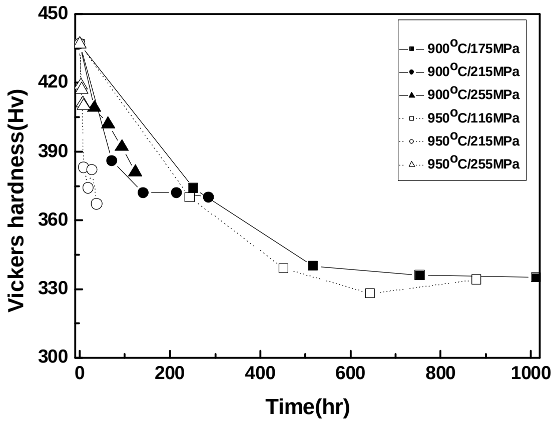

Fig. 3. Changes of Vickers hardness with increasing creep time at each creep conditions.

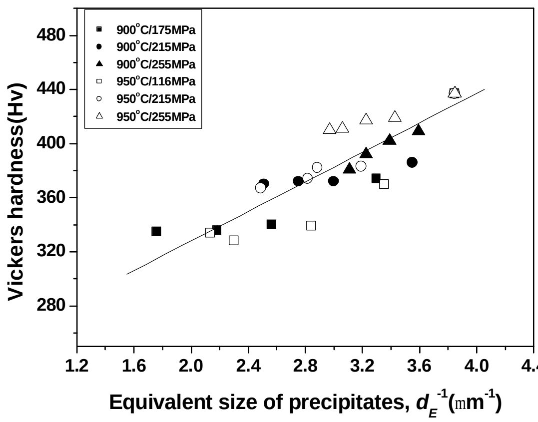

Fig. 4. Influence of size of precipitates on Vickers hardness.

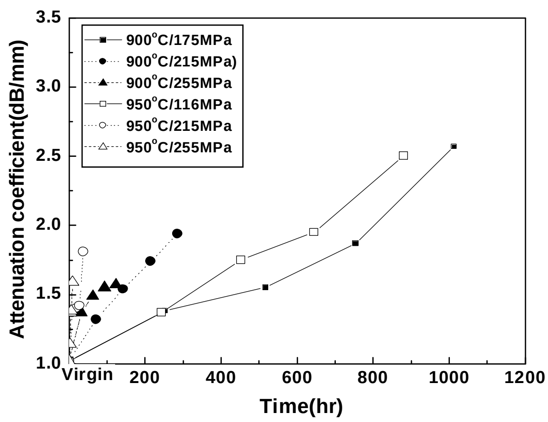

Fig. 5. Change of ultrasonic attenuation with creep time at each creep condition.

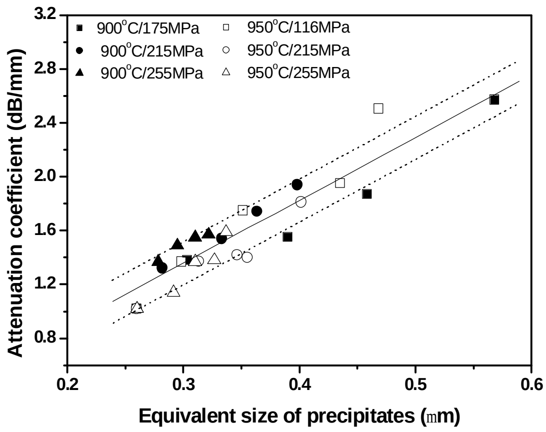

Fig. 6. Correlation between the equivalent size of γ' precipitates and the ultrasonic attenuation coefficient.

Fig. 5. Changes of ultrasonic attenuation coefficient with increasing creep time. The coarsening of spherical second phase particles with different acoustic impedance from the matrix is reported to increase ultrasonic scattering [13]. Similarly, the rafting (directional coarsening) of γ' precipitates is believed to increase ultrasonic scattering (attenuation), although the extent of scattering from rafted γ' precipitates might be different with that from spherical particles. Fig. 6 shows the change of attenuation coefficient with increasing equivalent size of γ' precipitates. It can be seen that there exist a linear correlation between them, implied that the degree of rafting in the creep damaged IN738LC superalloy can be evaluated by measuring ultrasonic attenuation nondestructively instead of time-consuming metallographic technique.

4. Summary and Conclusions

Both the equivalent size of γ' precipitates and ultrasonic attenuation were observed to increase linearly with creep time. A linear correlation was found between the equivalent size of γ' precipitates and the ultrasonic attenuation. Therefore, ultrasonic attenuation coefficient was suggested as a potential nondestructive evaluation parameter to assess the creep damage level of IN738LC superalloy.

5. References

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