SERVICE TEMPERATURE ESTIMATION FOR HEAVY DUTY GAS TURBINE BUCKETS

BASED ON MICROSTRUCTURE CHANGE

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Abstract

This paper studies the microstructure change of Ni-base superalloy IN738LC in the temperature range of 750°-900°C, and develops methods for predicting the service temperature of a gas turbine bucket operated for around 20,000 hours. Specimens of IN738LC were aged in the temperature range up to 24,000 hours to obtain the data of microstructure change. Growth rate of γ' diameter in IN738LC was proportional to the 1/3 power of aging time and γ' density was inversely proportional to aging time. Accuracy of predicted temperature based on the γ' diameter and density increased with increasing the aging time and temperature. Metal temperature of the actual 20,000 hours serviced bucket estimated by the microstructure change agreed with the thermal analyses at the leading edge portion which is a most reliable point for the analysis. This shows the availability of the proposed methods.

Introduction

To keep the reliability of gas turbine hot-gas-path components, it is important to know accurate metal temperature. Especially the buckets are rotated and current ones have an air cooled system under high temperature and complex gas stream, which increase difficulty to analyze the metal temperature. In the case of high temperature components, microstructure changes are occurred during service due to overaging of the materials. By using this phenomena, it is thought to be possible to estimate the metal temperature.

This paper describes the development of temperature estimation methods by using the γ' coarsening law of gas turbine bucket alloy IN738LC and investigation results of accuracy of these methods. These methods are applied to the actual serviced bucket and the availability are demonstrated. The effect of stress on the γ' coarsening rate is also described.

Test Methods

The chemical composition of the cast Ni-base alloy IN738LC used for this investigation is shown in Table 1. The slab material of 200 mm $\times$ 80 mm $\times$ 20 mm was made by an investment casting process in vacuum and specified heat treatments of 1,120°C for 2 hours and 843°C for 24 hours followed by gas cooling were conducted. After the heat treatments, the material was aged at temperatures of 750°, 800°, 850°, and 900°C for 1000, 3000, 10,000, and 24,000 hours. After the agings, microstructural observations were performed. Metallographic specimens were prepared from the unaged and aged samples. After being sectioned, mounted, and

polished, the specimens were etched using a marble's reagent consisting of 4g CuSO₄, 20ml HCl, and 80ml H₂O. Two stage replication technique was used for the observation of γ' phases by transmission electron microscopy (TEM). Quantitative image analysis was subsequently conducted to measure the mean diameter of γ' precipitates, number of precipitates per unit area (density), and area fraction by using a LUZEX IIIU NIRECO image analyzer.

Table 1 Chemical composition of IN738LC studied (mass %)

	C	Ni	Cr	Co	Al	Ti	W	Mo	Ta	Nb	B	Zr
Aging test material	.10	Bal.	15.82	8.60	3.58	3.40	2.90	1.68	1.83	.87	.011	.056
Creep test material	.09	Bal.	15.92	8.18	3.52	3.54	2.55	1.74	1.76	.89	.010	.034

Microstructural observation was conducted for new and around 20,000 hours serviced stage 1 buckets. Circumferential 12 points are observed on the mid-span cross-section of the airfoil of the buckets as shown in Figure 1. The surface observed is parallel to the centrifugal force.

Figure 1: Sectioning location and microstructure observation points of buckets studied.

Test Results

Effect of Aging on Microstructural Change

Observation results of transgranular γ' precipitates were shown in Figure 2. The microstructure of as-specified heat-treated IN738LC shows around 0.4 μm diameter cubical γ' with around 0.02 μm fine spherical γ' . During the agings, fine γ' dissolved and cubical γ' is observed to have been coarsened and spheroidized.

Figure 3 shows the image analyses results of transgranular γ' which are mean diameter, density, and area fraction of γ' . During the agings, the mean diameter is increased and density decreased. This tendency accelerated with the temperature increased.

Effect of Stress on Microstructural Change

Observation results of transgranular γ' precipitates were shown in

Figure 3: Image analysis results of γ' in aged IN738LC.

Figure 2: Microstructure of IN738LC aged at 850°C for (a) 0 hrs, (b) 1,000 hrs, (c) 10,000 hrs, and for 24,000 hrs at (d) 850°C, (e) 750°C, (f) 800°C, (g) 850°C, (h) 900°C.

Figure 4: Microstructure of IN738LC creep-tested at 900°C under 98MPa interrupted at (a) 0 hr, (b) 2,500 hrs, (c) 5,000 hrs, (d) 7,500 hrs, (e) 14,440.8 hrs (ruptured).

Figure 5: Microstructure of the new bucket at mid-span cross section of (a)leading edge portion, (b)mid-chord portion of suction side surface, (c)trailing edge portion, (d) mid-chord portion of pressure side surface, and of the 20,000 hrs serviced bucket at that of (e)leading edge portion, (f)mid-chord portion of suction side surface, (g)trailing edge portion, and (h)mid-chord portion of pressure side surface,

Figure 4. The microstructures of stress-free portion of the samples at the pre-tested and interrupted creep tested conditions was the same behaviors as aged samples. But, during creep testing, microstructures of stressed portions show a rafted structure which γ' grows at the direction perpendicular to the stress. This structure is growing with creep testing time increasing and most significant elongated one is observed in the ruptured sample.

Microstructural Observation Results of a Serviced Bucket

Figure 5 showed the microstructure at the airfoil surfaces of the new and around 20,000 hours serviced stage 1 buckets. Elimination of fine spherical γ' and coarsening of large cubical γ' are observed, but the degree of the coarsening in the serviced buckets are not so significant.

Discussions

γ' Coarsening Law of IN738LC

Coarsening of fine precipitates normally explained to be the volume diffusion-controlled coarsening theory formulated by Lifshitz, Slyozov (Ref.1), and Wagner (Ref.2). This model propose that the mean particle diameter increases according to the following equation

$$d^3 - d_0^3 = K \cdot t \quad (1)$$

$$K = \frac{64\gamma_s D C_s V_m^2}{9kT} \quad (2)$$

where,

d : average γ' mean diameter of pre-aged IN738LC

d_0 : average γ' mean diameter of aged IN738LC

γ_s : specific γ/γ' interfacial free energy

D : diffusion coefficient of γ' solutes in γ

C_s : equilibrium molar concentration of γ' solute in γ

k : Boltzmann constant

t : aging time

T : aging temperature

V_m : molar volume of γ'

The third power of the mean γ' diameter of the aging materials versus aging time are plotted as shown in Figure 6. The data of each aging temperature are scattered at the earlier stage of aging, but they are getting good linearity during aging, which indicates γ' coarsening of IN738LC follows the volume diffusion-controlled coarsening theory.

Figure 6: Change of γ' mean diameter in IN738LC during aging.

During aging, coarsening of γ' precipitates occurred with γ' density decreasing. In the equation (2), V_m is molar volume of γ' , C_s is equilibrium molar concentration of γ' solute in γ and d^3 is a mean volume of one precipitate, which induces the following equation.

$$N = \frac{V_m C_e}{d^3} \quad (3)$$

By using this equation, equation (1) can be modified to the following equation.

$$\bar{N}^{-1} - \bar{N}_0^{-1} = K't \quad (4)$$

$$K' = \frac{64\gamma_e DV_m}{9kT} \quad (5)$$

Inverse of density versus aging time is also plotted in the Figure 7. Density versus time also shows good linearity at the longer aging time as well as mean γ' diameter does.

Figure 7: Change of γ' density in IN738LC during aging.

In both the equations of (2) and (5), diffusion coefficient D in the proportional constant K and K' is explained by the following equation.

$$D = D_0 \exp(-Q_d / kT) \quad (6)$$

where,

D_0 : frequency factor

Q_d : activation energy of diffusion

$\ln(KT)$ and $\ln(K'T)$ versus $-1/T$ are plotted in Figure 8. Good linearity is also obtained and the activation energy is 192 kJ/mol, but the activation energy of Ti or Al in Ni is 257 to 270 kJ/mol (Ref.3). Those literal value is larger than the value we obtained.

By using $Q_d=192\text{kJ/mol}$, γ' diameter and density calculated from equation (1) and (4) are plotted in Figure 9 compared with measured value. Good correlation is obtained at the longer aging time and higher aging temperatures.

Effect of Stress on γ' Coarsening Rate

Figure 10 shows the image analyses results of transgranular γ' of the interrupted creep samples. Stressed (parallel portions in the test samples) and unstressed portions (attached portions) are separately

Figure 8: Temperature dependence of rate constant K and K' for γ' diameter and density in aged IN738LC.

evaluated to figure out the effect of stress on the microstructural change. No effects of stress on the area fraction, density, and mean diameter of γ' are observed, which concludes these microstructural methods can apply even to component materials which are under high stress and already has rafted microstructures.

Figure 9: Comparison of measured γ' mean diameter and density with calculated ones.

Accuracy of Microstructural Estimation Methods

Changes of γ' diameter and density during aging are explained by the equation (1) and (4). By using these equations, it is thought to be possible to estimate the metal temperature of the components if γ' diameter and/or density are obtained. Accuracy of these estimation methods is investigated in this section by using the results of aging materials.

Figure 10: Change of γ' volume fraction, mean diameter, and density during creep testing under 98MPa at 900°C.

Aging temperature is estimated from the γ' diameter, density, and aging time, and then change of deviation between true aging temperature T_a and estimated one T_{est} during aging is investigated, where furnace temperature for the aging is defined as true aging temperature. To evaluate the deviation, variation coefficient C_v which is derived from the deviation divided by true temperature is introduced to eliminate the effect of absolute value of aging temperature. Average value of the coefficient for each aging time versus aging time are plotted in Figure 11. The coefficient which is derived by using both estimation methods is decreasing with the aging time increasing and shows the following equation.

$$C_v = a \cdot t^b \quad (7)$$

where

$$C_v = \frac{|T_a - T_{est}|}{T_a}$$

a, b : constant

Those values of “a” and “b” are listed in Table II.

The solid line indicates a regression line made by the average coefficient derived by the estimation method from γ' diameter, and the broken line does a regression line made by the average coefficient derived from the method from γ' density. This figure shows that the estimation method by the γ' diameter is more accurate than the methods by γ' density up to 5,000 hours, but that by γ' density is more accurate over 5,000 hours. In the case of new and earlier aging time conditions, counting of fine γ' is thought

to induce more observational error than measuring of γ' diameter. But in the case of longer aging time, γ' size increases and population of γ' observed decreases, which is thought to result in less accuracy to measure the diameter.

Table II Material constants of “a” and “b” in equation (Ref.7)

	a	b
Estimation method by γ' diameter	1.19	-0.371
Estimation method by γ' density	5.05	-0.556

Figure 11: Effect of aging time on coefficient of estimated temperature variation.

Effect of aging temperature on accuracy of the temperature estimation methods is also investigated. By using equation (7), the value “a” is derived for each aging temperature and “a” versus aging temperature are plotted in Figure 12. No good relationship is observed at the 10,000 hours aging time, but at the 10,000 and 24,000 hours aging time, clear temperature dependency is observed and following equation is obtained. The value of “C” and “Q” are listed in Table III.

Figure 12: Temperature dependence of variation coefficient.

$$\ln a = C + Q / kT_a \quad (8)$$

$C, Q : \text{constant}$

Higher aging temperature shows less “a” value, which also means less variation coefficient. According to the temperature increasing, microstructure is getting homogeneous and observational error is thought to be decreasing.

The variation coefficient C_v is derived from aging time t and aging temperature T_a by using the equation (7), (8) as follows.

$$C_v = \exp(C + Q / kT_a) \cdot t^b \quad (9)$$

Table III Material constants of “C” and “Q” in equation (8).

	C	Q (J)
Estimation method by γ' diameter	-21.4	3.19×10^{-19}
Estimation method by γ' density	-11.4	2.07×10^{-19}

The scatter band of estimated temperature from these methods, therefore, is expressed as following equations.

$$T_{\max} = (1 + C_v) \cdot T_a \quad (10)$$

$$T_{\min} = (1 - C_v) \cdot T_a \quad (11)$$

In the case of the around 20,000 hours serviced bucket used in this investigation, both estimation methods indicate the same results, that is, $T_{\max} = 859$ and $T_{\min} = 841^\circ\text{C}$ if true metal temperature of the bucket is supposed to be 850°C and serviced time is 20,000 hours. Estimated temperature is thought to be within the scatter band of $\pm 9^\circ\text{C}$, which means that quite accurate estimation can be obtained by these method at longer service time.

Applicability to the Actual Bucket

Microstructural temperature estimation results (estimated temperature) of the around 20,000 hours serviced bucket are shown in Figure 13 with temperature analyses results (analytical temperature) by using three different airfoil surface heat transfer rate calculations.

The transfer rate on the surface of buckets are calculated using both the integral method of boundary layer and Reynolds average Navier-Stokes equation (RANS). Calculation for an integral method were performed for two cases. One is based on the criterion of transition from laminar to turbulent in boundary layer (Analysis 1) and the other assumes the boundary layer as a fully turbulent boundary layer (Analysis 2). The analysis code of RANS (Analysis 3) is that the base code is STAN5 and two-equation turbulent model is incorporated (Ref.4, 5). These total three cases are calculated here.

The three analyses results show good coincidence with each other at the leading edge portion of the bucket. At the suction side,

Analysis 2 shows higher temperature than the analysis 1 and 3 but almost the same values as estimated one. All the analysis results at the pressure side shows lower than the estimated one.

Temperatures estimated from the microstructure shows good coincidence at the leading edge portion, but higher values at the other portions. The applicability of the microstructural temperature estimation methods for the actual buckets is discussed hereafter.

The errors arisen from the microstructural estimations of the bucket are thought to be due to the differences of original microstructures and operating histories, and the microstructural measurement methods. To eliminate these error factors, the new bucket is also evaluated at the same locations as the serviced one. The accuracy of the bucket temperature estimation is, therefore, almost the same as that of the results from the aging material as we discussed in the previous section.

The accuracy of the analyses codes are also discussed here. The leading edge portion is regarded as a cylinder for calculation of the heat transfer rate. In this case, degree of acceleration due to the turbulence intensity is empirically known well, which means the accuracy of analyses is thought to be high. The good coincidence between analytical and estimated temperatures obtained at this point imply that this estimation method has quite high accuracy. The other portions shows analyses results are lower than the estimated ones. Turbine buckets are operated under the influences of the turbulence and the periodical fluctuations of wake which is generated from turbine nozzle vanes. This fluctuation of wake is also thought to accelerate the heat transfer rate. Recently, many researches on the influence of the wake to the heat transfer rate by using test turbines and the unsteady state analysis of nozzle vanes and buckets are performed. The enhancement effect for heat transfer rate on surface of a bucket have been recognized, but the accuracy of analysis is not so high. Large discrepancy between analytical and estimated values have been recognized at the surface regions from leading edge portion to the mid-chord of pressure and suction sides which are thought to be strongly influenced by the

Figure 13: Temperature distribution of serviced bucket surface estimated by γ' mean diameter (mid-span cross section of bucket airfoil).

wake of nozzle vane. This discrepancy is, therefore, thought not to be due to the microstructural estimation methods, but to be due to less considerations on this wake. This analyses code does not take surface roughness into account, but it is reported that the heat transfer rate increases significantly after the characteristic value defined by surface roughness exceeds the critical value (Ref. 6, 7, 8). Roughness of the bucket surface is observed to increase during service and the pressure side surface is observed to be roughen significantly. The analyses should, therefore, be considered the roughness effect in this region.

Summary and Conclusions

Metallurgical metal temperature estimation methods were investigated and were verified to be applicable to actual buckets. The results are summarized and described as follows.

- (1) Change of average γ' diameter in IN738LC is proportional to the one third power of aging time and density is inversely proportional to aging time.
- (2) Accuracy of the estimation methods is explained by the function of aging time and temperature and increases with aging time and temperature increasing.
- (3) Comparison between estimated and analyzed bucket surface metal temperature is conducted and good coincidence was observed at the most reliable analysis point, which verify these method are applicable to the actual bucket temperature estimation.
- (4) Comparison between estimated and analyzed bucket surface temperature implies some possibility to analyze the actual phenomena of the buckets and also clarify the problem of analyses code

References

1. M.Lifshitz, V.V.Slyozov, "The Kinetics of Precipitation from Supersaturated Solid Solutions," J.Phys. Chem. Solids, 19(1961), 35-50.
2. C.Wagner, "Theorie der Alterung von Niederschlagen durch Umlosen," Z.Electrochem., 65(1061), 581-591.
3. The Japan Institute of Metals eds., Metals Data Book, (Maruzen, 1984), 27-28.
4. D.Biswas, Fukuyama, Araki, "Calculation of Transitional Boundary Layer with an Improved Low-Reynolds Version of k- ϵ Model of Turbulence Part 2," Journal of the Gas Turbine Society of Japan, Vol.20, No.77 (1992), 68-75.
5. D.Biswas, Fukuyama, Araki, "Calculation of Transitional Boundary Layer with an Improved Low-Reynolds Version of k- ϵ Model of Turbulence Part 2," Journal of the Gas Turbine Society of Japan, Vol.20 No.78 (1992), 25-31.
6. M.F.Blair, "An Experimental Study of Heat Transfer in a Large-Scale Turbine Rotor Passage," ASME Paper 92-GT-195(1992), 1-15.
7. M.H.Hosni, H.W.Coleman, R.P.Taylor, "Heat Transfer Measurements and Calculations in Transitional Rough Flow," ASME Paper 90-GT-53 (1990), 1-9.
8. R.P.Taylor, J.K.Taylor, M.H.Hosni, H.W.Coleman, "Heat Transfer in the Turbulent Boundary Layer with a Step Change in Surface Roughness," ASME Paper 91-GT-266(1991), 1-8.