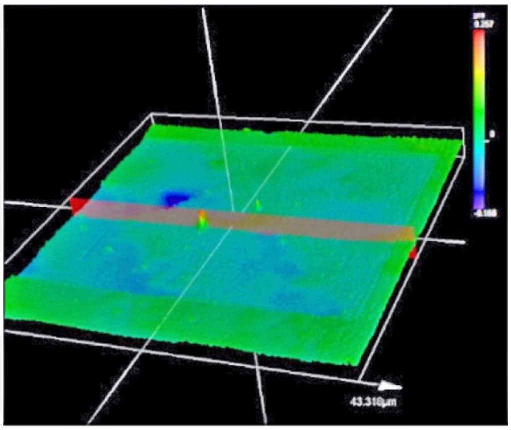
Creep Life Evaluation Techniques for Creep Enhanced Stainless Steel for Power Generation Boilers



KEITA HASHIMOTO[*1] **NOBUHIKO SAITO**[*2]

KO ARISUE[*1] **TADAAKI NAKAMURA**[*1]

NOBUYOSHI KOMAI[*3] **KIMIHIKO TOMINAGA**[*4]

Creep enhanced stainless steel containing 18 to 25% Cr is widely used as material for heat exchanger tubes in Ultra Super Critical boilers for thermal power generation, and the need to develop creep life evaluation techniques has increased. Mitsubishi Heavy Industries, Ltd. has developed a technique to evaluate the life of stainless steel heat exchanger tubes that accurately estimates the metal temperature of the tubes based on their microstructure, and this technique has already been applied to actual plants. In addition, to realize a life evaluation with higher accuracy, we have also been developing a new creep life evaluation method based on the amount of extremely small size creep void formation, which can directly evaluate damage without metal temperature estimation. This report describes the overview of these life evaluation techniques.

1. Introduction

Creep enhanced stainless steel containing 18 to 25% Cr, such as 18Cr-9Ni-3Cu-Nb-N steel (KA-SUS304J1HTB, ASME SA-213 S30432)(1) has excellent creep rupture strength and resistance to corrosion in high-temperature environments and is widely used as material for heat exchanger tubes in high-temperature environments over 600°C, such as in Ultra Super Critical (herein after referred to as USC) boilers, etc. Numerous USC boilers with heat exchanger tubes made of creep enhanced stainless steel have been in operation in excess of 100,000 hours. In recent years, several cases of steam leakage due to creep damage in heat exchanger tubes have been reported. Kimura et al.(2) conducted long-term creep tests on 18Cr-9Ni-3Cu-Nb-N steel and reported that the actual creep rupture strength of the steel might be lower than that assumed when the allowable stress was formulated according to ASME (The American Society of Mechanical Engineers). A large number of creep enhanced stainless steel tubes (1,000 or more/unit) are used for heat exchanger tubes in a USC boiler. Once a leakage occurs, it takes time to recover and causes significant impact. Therefore, it is necessary to prevent leakage in advance for the stable operation of electric power, and the development needs of the technology which can accurately evaluate creep residual life are increasing.

This report describes an overview of the metal temperature estimation based on microstructure(3),(4) and the creep life evaluation method based on the amount of extremely small size creep void formation(5) from MLAS-EX (**M**itsubishi Metallurgical **L**ife **A**ssessment **S**ystem for Heat **EX**changer tubes) which is a life evaluation technique package developed by Mitsubishi Heavy Industries, Ltd. (hereinafter referred to as MHI) for creep enhanced stainless steels.

[*1] Strength Research Department, Research & Innovation Center
[*2] Project Manager, Strength Research Department, Research & Innovation Center
[*3] Research Manager, Strength Research Department, Research & Innovation Center
[*4] Chief Manager, Engineering Department, Steam Power Maintenance Innovation Business Division, Energy Systems

2. Life evaluation technique by estimation of metal temperature

Creep life (rupture time) of creep enhanced stainless steel heat exchanger tubes depends on material grade, metal temperature and applied stress. Since the creep rupture characteristics (the relationship between metal temperature, stress and rupture time) of each material grade are known, the applied stress can be obtained from internal pressure and tube dimensions, and the cumulative operating time can also be determined. Consequently, if the temperature of the heat exchanger tubes during operation is known, residual creep life can be calculated. Due to the effects of combustion gas flow and heat radiation in the boiler furnace, it is difficult to estimate the local temperature of heat exchanger tubes accurately by calculation. And, since it is also difficult to measure the heat exchanger tube temperature in combustion gas over 1,000°C constantly by thermocouple, etc., it is desirable to be able to estimate the temperature of the said heat exchanger tubes during boiler operation by nondestructive method.

The microstructure of 18Cr-9Ni-3Cu-Nb-N steel changes with heating time in the practical metal temperature range (around 650°C) is shown in **Figure 1**(2),(6)~(10). In the initial 1,000 hours of heating, the Cu phase and Nb(C, N) precipitates in the grains and $M_{23}C_6$ precipitates on the grain boundaries. Then, at approximately 10,000 hours, Nb(C, N) gradually transforms NbCrN, and a relatively coarse σ phase and NbCrN are precipitated on the grain boundaries. Over tens of thousands of hours, the σ phase (intermetallic compounds composed mainly of Fe and Cr) and NbCrN on the grain boundaries become significantly coarser, and Precipitate-Free Zones (PFZ) are formed near the grain boundaries. It has also been reported that although trends in microstructural changes are generally the same in the practical metal temperature range even if the heating temperature differs depending on the location of the heat exchanger tubes, coarsening of the σ phase is more pronounced at higher metal temperatures and/or with longer heating times.(6) Focusing attention on the changes in particle size of the σ phase by heating, a technique to estimate metal temperature from particle size of the σ phase was developed by obtaining the relationship between the σ phase particle diameter (diameter approximated by a circle), metal temperature and heating time.

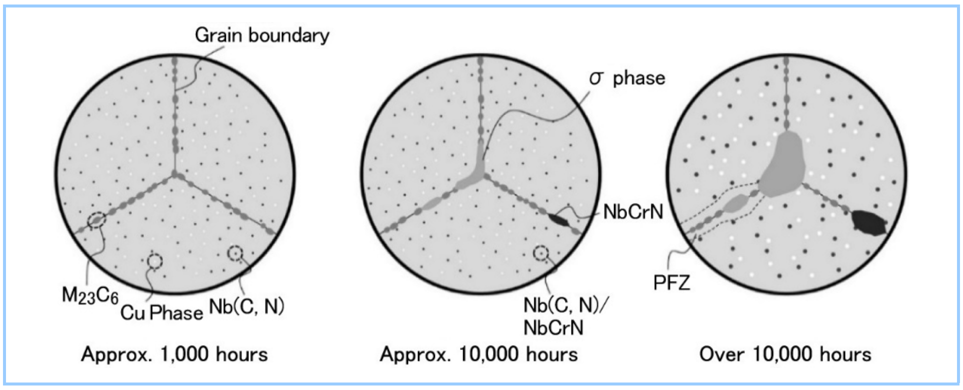


Figure 1 Microstructural changes of 18Cr-9Ni-3Cu-Nb-N steel at approximately 650°C

Representative SEM (scanning electron microscope) microstructures of the 18Cr-9Ni-3Cu-Nb-N steel, which was subjected to aging heat treatment at 650°C and 700°C for a maximum of 120,000 hours, is shown in **Figure 2**. The relatively coarse precipitates observed in gray contrast are the σ phase. The σ phase is shown to be coarser in material heated at higher temperatures and/or for longer periods of time. However, variation in particle size of the σ phase was observed even in the same SEM microstructure. This is thought to be due to nucleation and growth of the σ phase occurring at various times during heating. In other words, the σ phase with small particle size is considered to nucleate in the late stage of heating and does not grow sufficiently for the heating time. If the σ phase with small particle size is taken into evaluation, even particles that grew in a short time relative to the heating time are included, resulting in a reduction in prediction accuracy. Therefore, as shown in **Figure 3**, calculating average particle size only for the σ phase with large particle size was considered in order to avoid the above-mentioned problem. The master curve for material subjected to long-term aging heat treatment, which was created from the relationship between HJP (Hollomon-Jaffe Parameter), a parameter composed of temperature and time, and the average particle size of only coarse σ phase, is shown in **Figure 4**. In application to an actual plant, since operating time is known, the metal temperature can be estimated from the measured average particle size of the σ phase.

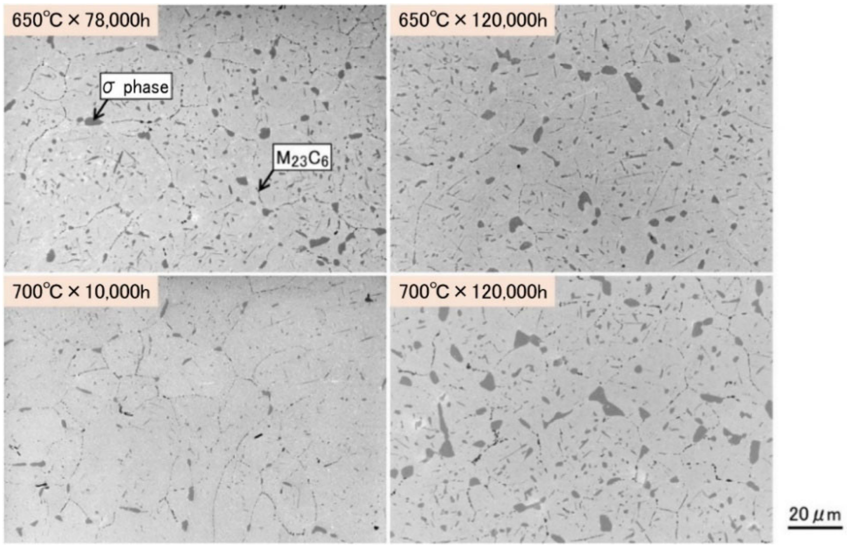


Figure 2 SEM images of 18Cr-9Ni-3Cu-Nb-N steel after aging heat treatment

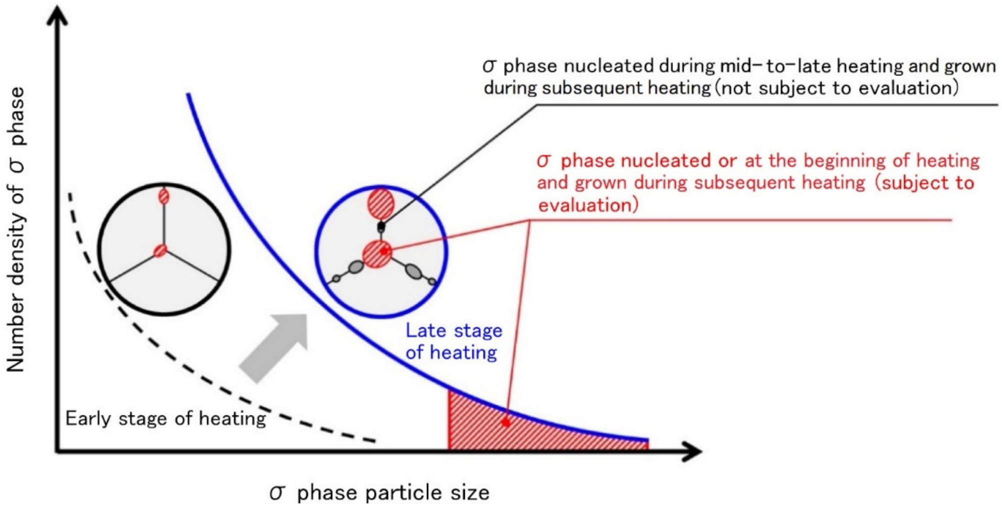


Figure 3 Schematic figure of selection of σ phase to be evaluated based on particle size Number density of σ phase particles

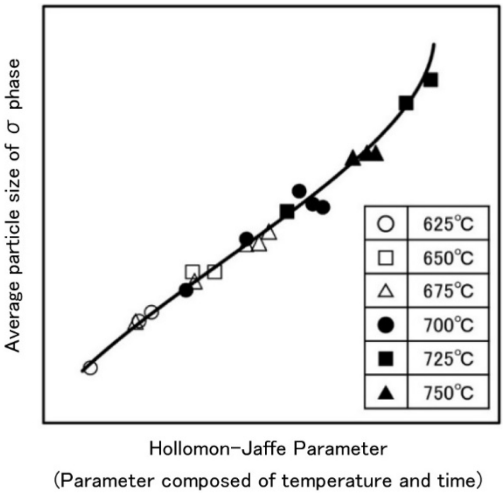


Figure 4 Master curve for metal temperature estimation

A comparison of actual metal temperatures and estimated metal temperatures from the created master curve, for which samples subjected to aging heat treatment in a laboratory were used, is shown in **Figure 5**. The metal temperature error estimated from the master curve was generally within ±10°C relative to the actual heating temperatures, and estimation of the metal temperature with high accuracy based on microstructure could be confirmed. In combination with the replica method, it is also possible to estimate the metal temperature with the same accuracy by an optical microscope observation of the microstructure transferred on the film, allowing multipoint evaluation quickly in an actual plant. It was confirmed that the metal temperature estimation result using this method is consistent with the temperature measurement result obtained by a thermocouple in actual plant, and it has already been applied to the life evaluation of several USC boiler heat transfer tubes.

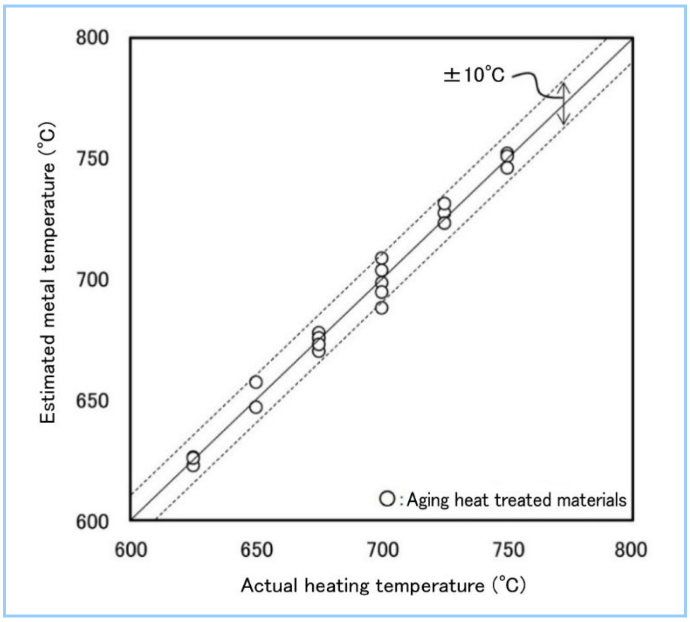


Figure 5 Comparison of actual heating temperature and estimated metal temperature

3. Life evaluation technique based on the amount of submicron void

In order to assess creep life more accurately, evaluating the remaining creep life by directly assessing the creep degradation state of the material used without the above-described metal temperature estimation is desirable. However, since the creep deformation resistance of creep enhanced stainless steel is higher than that of general ferritic heat-resistant steel, the swelling amount of the heat transfer tube (creep deformation amount) associated with creep damage up to the rupture is small, and the amount of creep void generation up to the end of creep life is also small. Therefore, it has been considered difficult to evaluate creep damage using these factors as indices. MHI has discovered that submicron size creep voids (submicron voids) occur adjacent to precipitates in the middle stage of the creep life of creep enhanced stainless steel as shown in **Figure 6** and has developed a life evaluation technique (submicron void method) focusing on these voids.

For observation of submicron voids, if general surface treatment processes, such as mirror polishing and etching using a corrosion solution, are conducted before microstructure observation, many precipitates are shed and observation of submicron voids becomes difficult. Therefore, an optimal polishing method was developed and applied. Spatial resolution of a conventional optical microscope is insufficient for observation, so an SEM or a laser microscope with higher spatial resolution, was employed and observation of submicron voids became possible. When the replica method is used in combination, it has been confirmed that submicron voids can be nondestructively evaluated with the same accuracy, even in the observation of the microstructure transferred from the heat exchanger tube surface to the film. Images of submicron voids observed using an SEM and laser microscopy by the replica method are shown in **Figure 7**.

The master curve created based on the relationship between the number density of submicron voids and the creep life consumption rate is shown in **Figure 8**, and the creep life consumption rate estimated by the submicron void method applied on trial to the 18Cr-9Ni-3Cu-Nb-N steel extracted after approximately 100,000 hours of use in an USC boiler is shown along with the creep life consumption rate estimated by a destructive test. The difference between the creep life consumption rate estimated using the submicron void method and the rate estimated by the destructive test was only 3-5%. These results confirm that the submicron void method can accurately estimate the creep life consumption rate, even in actual plants.

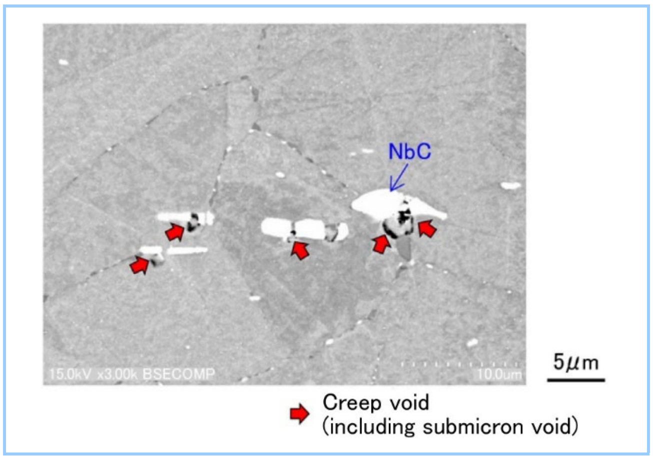
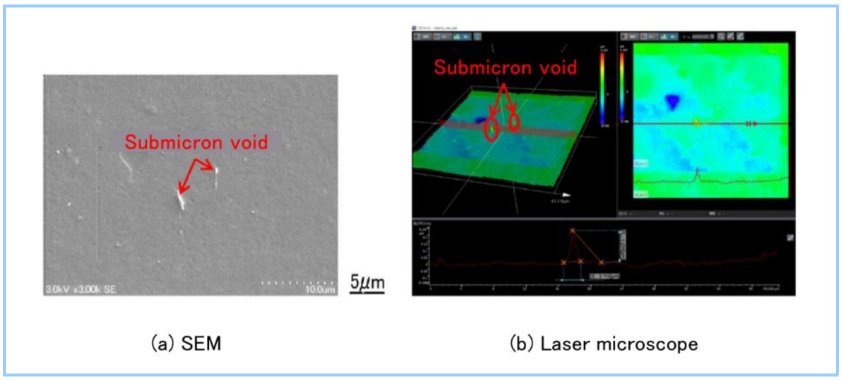


Figure 6　SEM image of the region around creep voids of 18Cr-9Ni-3Cu-Nb-N steel



(a) SEM　(b) Laser microscope

Figure 7　Images of submicron voids observed by the replica method

Location	Nominal tube dimensions	Operating time	Estimated creep life consumption rate	
			Submicron void method	Destructive test (creep test)
Superheater tube (1)	Φ45×t6.6mm	Approx. 100,000 hours	80%	77%
Superheater tube (2)	Φ45×t6.6mm	Approx. 100,000 hours	55%	60%

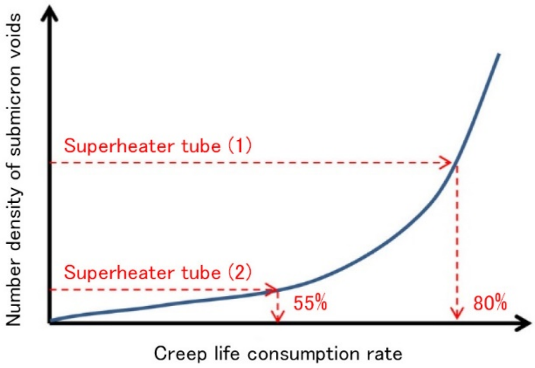


Figure 8　Relationship between the number density of submicron voids and the creep life consumption rate, and the estimated creep life consumption rates of materials used in an actual plant

4. Conclusion

In response to the increasing need to develop residual life evaluation techniques, two creep life evaluation techniques for creep enhanced stainless steel have been developed. The technology to estimate the metal temperature of the heat transfer tube from the microstructure with an accuracy within ±10°C which is necessary for the evaluation of creep life has been developed and is being applied to actual plants. This new method (submicron void evaluation method) developed with a focus on the amount of void of submicron size that generate adjacent to precipitates in the middle stage of the creep life allows life evaluation based on the directly observed creep damage state. As with the life evaluation technique by metal temperature estimation based on microstructure, this method was also confirmed to allow multipoint evaluation in actual plants by the combined use of the replica method. In addition to these methods, MHI has a lineup of other life evaluation methods for creep enhanced stainless steel, such as the outside diameter measurement method and the destructive testing method with sample tube extraction. MHI will continue to provide optimal solutions based on the actual state of the equipment and the needs of customers, in order to contribute to the stable operation and increased utilization of plants.

References

(1) Sawaragi, Y. et al, “The Development of a New 18-8 Austenitic Steel Tube (ST3Cu) with High Elevated Temperature Strength for Fossil Fired Boilers,” The Sumitomo Search, Vol. 43, No. 6 (1991), pp. 34-43.
(2) Kimura, K. et al., “Microstructural Evolution During Long-term Creep and Creep Rupture Strength of Super 304H Austenitic Stainless Steel” 11th International NIMS-MPA-IfW Workshop on Advances in Materials for Future Power Engineering, Germany, October 2016
(3) Japanese Patent No. 6853212
(4) Hashimoto, K. et al., Metal Temperature Estimation in High-Strength Austenitic Stainless Steels through Precipitation Analysis, Proc. of 10th int. conf. Advances in Materials, Manufacturing, and Repair for Power Plants (2024-10), p.335
(5) Japanese Patent Application No. 2022-055622
(6) Kimura, K. et al., “Creep Deformation Property and Creep Life Evaluation of Super304H” Pressure Vessel Technology, 144, 2(2022), 021507
(7) Kobayashi, S. et al., “THE DEGRADATION OF LONG-TERM CREEP STRENGTH AND MICROSTRUCTURE EVOLUTION IN SUPER304H” Proc. 3rd International ECCC Conf. Rome, Italy, May. 2014
(8) Kimura, K. et al., “Creep strength property and microstructural evolution during long-term creep of 18Cr-9Ni-3Cu-Nb-N (KA-SUS304J1HTB) austenitic steel” Proc. APCFS2016, Toyama, Japan, September 2016
(9) Sawada, K. et al., “Precipitation behavior during aging and creep in 18Cr-9Ni-3Cu-Nb-N steel” Materials Characterization, 141(2018), pp. 279-285
(10) Sawada, K. et al., “Microstructural changes and creep-strength degradation in 18Cr-9Ni-3Cu-Nb-N steel” Materials Characterization, 178(2021), 111286