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Recovery of Material Properties in Service-Degraded Gas Turbine Blades

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ABSTRACT

Gas turbine blades for power generation are generally made of Ni-base superalloys that feature excellent resistance to high temperature and corrosion. Since the blade material properties degrade due to long-term service operation of a gas turbine, the blades need to be replaced periodically. Using service degraded blades, we conducted research on the recovery of the blade material properties. To check whether the properties of the degraded blade materials had recovered or not, we applied hot isostatic pressing (HIP)-combined heat treatment technique in our research, and then inspected material properties before and after the heat treatment by various non-destructive and destructive tests. As a result, the heat treatment could recover metallurgical and mechanical properties of the degraded blades. After the treatment was applied to the degraded blades, those blades were reinstalled in a gas turbine, and the operation has restarted. At the time of regular periodical inspection, various non-destructive and destructive tests to verify their degradation showed no cracks or deformation in any of those blades, with very little change in microstructure and mechanical properties. No acceleration in degradation rate was revealed, and we further confirmed that those treated blades installed in the gas turbine were completely operational. Through our research, trial operation and subsequent damage inspection, it was confirmed that HIP-combined heat treatment could be a useful service-life extension method for gas turbine blades.

INTRODUCTION

Gas turbine blades are subjected to high temperature, large centrifugal force and thermal stress due to starts and stops of operation. The blades are generally made of Ni-base γ' phase (Ni_3Al) precipitation-strengthened superalloys to account for the creep rupture strength at high temperatures. Compared with the front stages, such as the first-stage, the operating environment is relatively moderate in the latter stages of gas turbines. For this reason, in some cases, the oxidation/corrosion resistant coatings are not applied to the latter-stage blades. In fact, it is not necessary to consider the coating-related damages, such as surface cracks, to those blades (Pallos, 2001). Considering material degradation due to the long-term operation, such as creep damages, it is necessary to replace those blades periodically (Viswanathan, 1989). Therefore, it is necessary to recover the material properties of degraded blades due to long-term operation in order to extend the service life of blades. Previously, many studies towards recovery of material properties in thermally exposed blades have been conducted. It is difficult to recover the material properties fully by applying conventional heat treatment (Susukida et al., 1980). Moreover, applying various heat treatment techniques resulted in partial recovery of material properties in the blades of aero engines (Drunen and Liburdi, 1977). On the other hand, the properties were recovered more remarkably by applying a hot isostatic pressing (HIP)-combined heat treatment compared to that of conventional heat treatment only (Liburdi and Wilson, 1981; Swaminathan et al., 1998). These reports, however, did not make the effects of the heat treatment clear with regard to gas turbine blades for power generation.

Therefore, in order to verify the applicability of the HIP-combined heat treatment to the gas turbine blades for power generation, we conducted the research on the recovery of blade material properties by using degraded second- and third-stage blades of a 1100°C-class gas turbine. We further conducted operational trials by reinstalling those blades in the commercial gas turbine to verify the effectiveness of this method, and checked the degradation in material properties two years later.

RESEARCH ON RECOVERY OF MATERIAL PROPERTIES

Sample blades and test methods

The sample blades used in this research comprised the second- and third-stage blades that had been installed in the 1100°C-class gas turbine (Model 7E made by GE) of the Yokkaichi Thermal Power Plant No.4 unit, and had been used for about 8 years, approximately 51,000h of operation with 1,000 starts and stops (hereafter referred to as the degraded blades). The sample blades are made of Ni-base γ' precipitation-strengthened superalloys. IN738LC is used for the second-stage blades, while U500 that is slightly weaker in strength than IN738LC is used for the third-stage blades. The blades of both stages are not coated. The chemical composition of the blades studied is shown in Table 1. Since the oxidation/corrosion resistant coating was used for the first-stage blades, and some coating-related damage was detected, the first-stage blades were excluded from the experiment.

As shown in Fig.1, HIP could make the coarsened spherical γ' phase dissolve in the matrix and eliminate creep voids and casting defects of the degraded materials (Honma, 1999). Thus, HIP followed by the solution and ageing heat treatment could recover the microstructure of the degraded materials. Applying high temperature exceeding the γ' phase solvus temperature, and high

Table. 1 Chemical composition of IN738LC and U500 studied (mass%)

	Ni	Cr	Co	Al	Ti	W	Mo	Ta	Nb	Fe	C
IN738LC	Bal.	15.94	8.37	3.53	3.33	2.68	1.85	1.62	0.78	0.20	0.10
U500	Bal.	17.81	16.82	2.96	2.88	—	3.78	—	—	0.09	0.07

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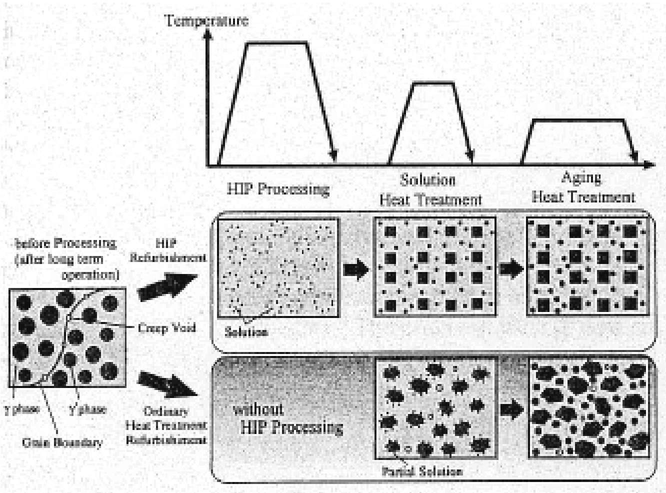

Fig. 1 Effects of HIP-combined heat treatment for degraded materials (Honma, 1999)

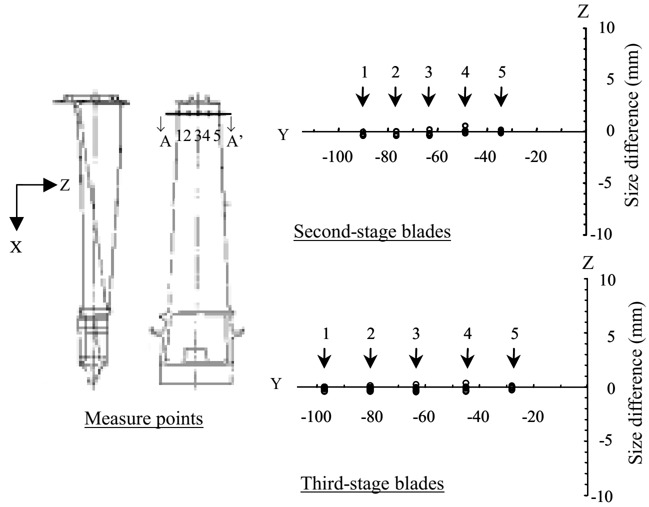

Fig. 2 Size difference between degraded and treated blades

Table. 2 Heat treatment conditions used in this research

	Solution heat treatment	Ageing heat treatment
IN738LC	1121°C×2h	843°C×24h
U500	1149°C×4h+1079°C×4h	760°C×16h

pressure exceeding 100MPa, HIP was first performed on the degraded blades for second and third stages. Then, the solution and ageing heat treatment was performed on the HIPed blades (hereafter referred to as the treated blades). The heat treatment conditions used in this research are summarized in Table 2. An unused blade was also examined in this research for the purpose of comparison. The degraded and treated blades were inspected with various non-destructive and destructive tests. The non-destructive tests consisted of visual observation, fluorescence penetrant tests and 3D size measurement on the airfoil section of the blades. The destructive tests consisted of microstructural observation in cross sections with optical and scanning electron microscopes (SEM), tensile tests, creep rupture tests and low-cycle fatigue tests. Specimens were taken from the same portion of the airfoil section in the sample blades for each stage. In the microstructural observation, we particularly focused on the γ' phase, which is the main precipitation-strengthened phase of the blade material. Tensile tests were conducted at 650°C and 845°C for the second-stage blades, and at room temperature and 620°C for the third-stage blades. Creep rupture tests were carried out at 815~900°C/245MPa for the second-stage blades, and at 800~850°C/333MPa for the third-stage blades. Low-cycle fatigue tests were performed by the compressive strain hold for two minutes at 815°C for the second-stage blades, and at 720°C for the third-stage blades. Then, to verify the effects of the treatment, we compared the test results of the treated blades to those of the degraded blades with the same operating history, and the unused blades.

Non-destructive tests

The airfoil sections in the degraded blades of both stages were discolored in dark brown, and some wear was found at the tip shroud of the blades. But in other portions, there was no crack or any other damage, confirming that the treatment has prevented the occurrence of damages. Fig.2 shows the size difference between the treated and degraded blades of the second and third stages. There were slight deformation and torsion in the blades of each stage. A concern was expressed initially that the strain accumulated during operation would be released by this treatment, causing large deformation of sample blades. But, the experiment revealed that the measured deformation was within the design tolerance. Uncoated cooling holes of the second-stage blades were not closed due to the treatment.

Destructive tests

Microstructural observation. Figs.3 and 4 show the optical micrographs in the cross section of the second- and third-stage blades, respectively. Casting defects, indicated by arrow marks in these figures, observed in the unused and degraded blades were not found in treated blades of each stage. Neither the degraded

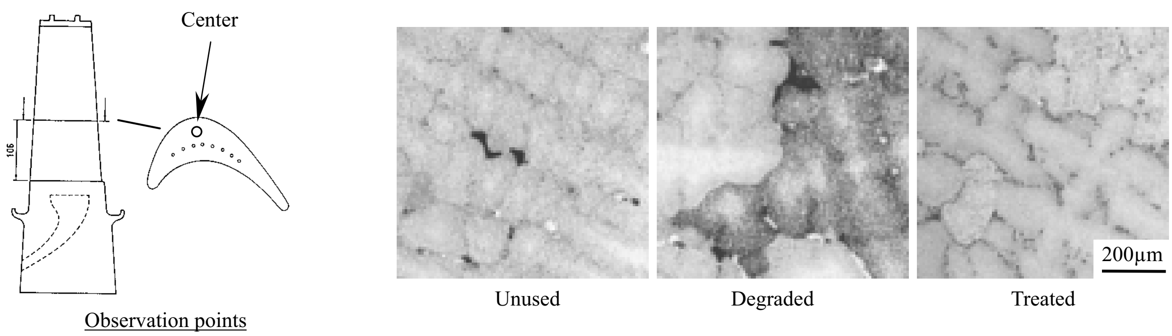

Fig. 3 Optical micrographs in the cross section of the second-stage blades

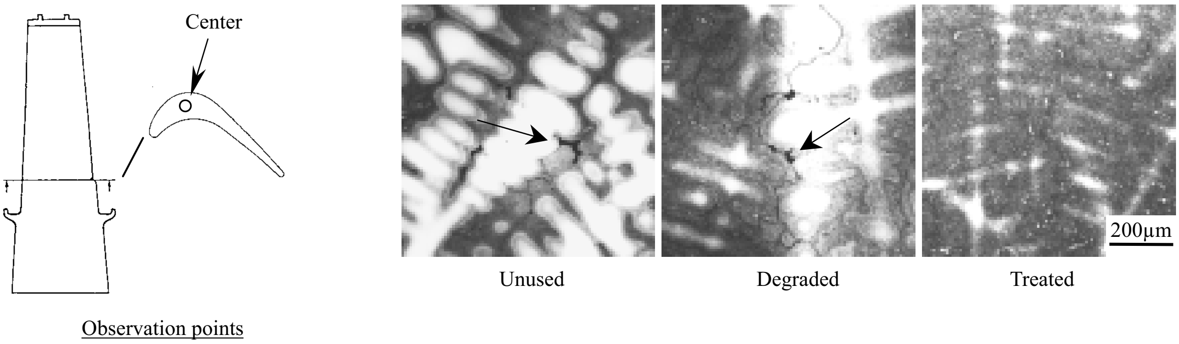

Fig. 4 Optical micrographs in the cross section of the third-stage blades

blades nor the treated blades had any crack in the cross sections observed. In addition, the treated blades did not feature strong microsegregation during casting. The oxide layer was detected in the degraded and treated blades of each stage. Furthermore, the γ' phase depleted layer was observed under the oxide layer. At the leading edge of second-stage blades, there was a corroded layer, indicating plate-like precipitates (AlN). The maximum depth of the oxide and γ' phase depleted layers detected in the degraded and treated blades of each stage was approximately 150μm. The maximum depth of the same combined layer was approximately 100μm on the cooling hole of the second-stage blades.

SEM micrographs in the cross section of the blades are shown in Fig.5. In the second-stage blades, the γ' phase coarsening and grain boundary γ' phase precipitation occurred at the leading edge. The treated blades featured a bimodal distribution of relatively large cuboidal and fine spherical γ' phase precipitates, which was the same microstructure as in the unused one. In addition, the grain boundary γ' phase precipitated was not observed in the treated blades, while that was found in the degraded blades. Because of applying the treatment, the grain boundary γ' phase would be dissolved in the matrix. Thus, the microstructure of the degraded blades could be recovered to that of the unused one. In the third-stage blades, the γ' phase slightly coarsened at the leading edge of the degraded blades as shown in this figure. There was, however, no such a remarkable metallurgical change as that found in the second-stage degraded blades. The cuboidal γ' phase of the treated blade was almost uniform. Thus, microstructure of the treated blades was the same as that of the unused one. No creep voids was found in the degraded blades of both stages.

Tensile tests. Fig.6 shows the results of tensile tests carried out. The results of the degraded and treated blades are described in comparison to the mean values of the unused one. For the second-stage blades, the tensile strength and proof stress of the degraded and treated blades were equal to those of the unused one. In terms of ductility, the degraded blades were inferior to the unused one, while the treated blades were superior to the degraded ones. In other words, the tensile properties of the degraded blades were recovered by applying the treatment to a degree of the unused one. For the third-stage blades, the tensile

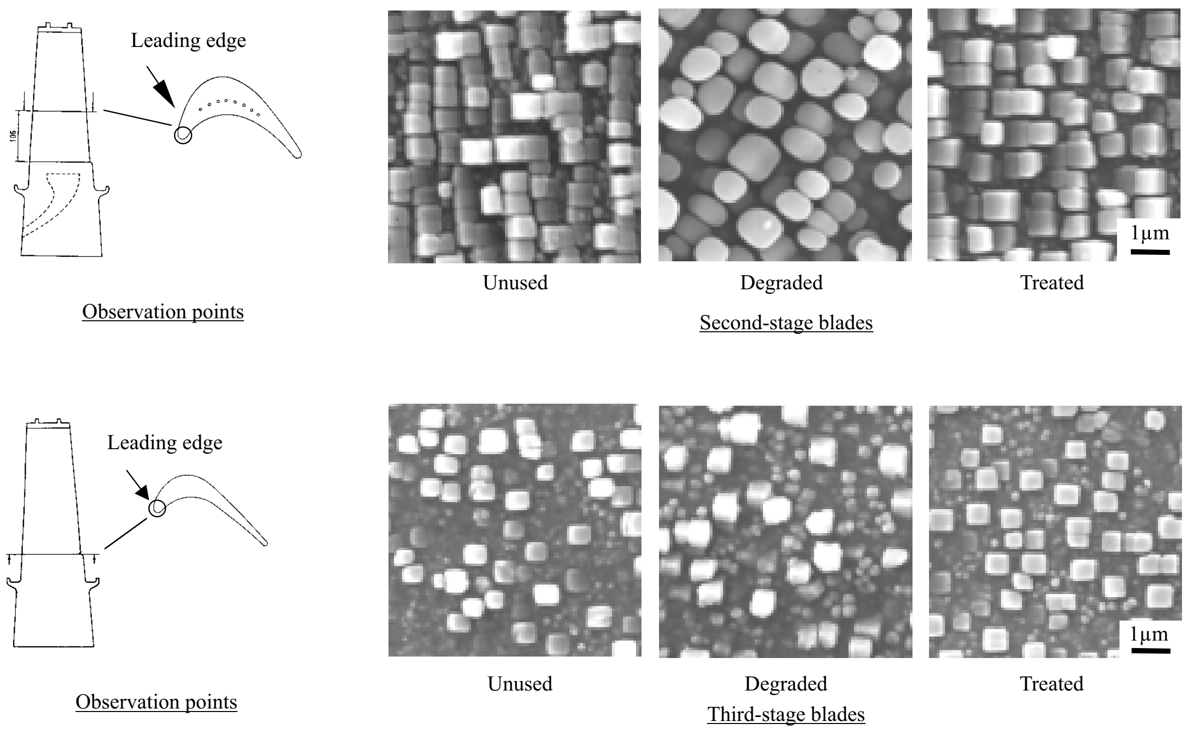

Fig. 5 SEM micrographs in the cross section of the second- and third-stage blades

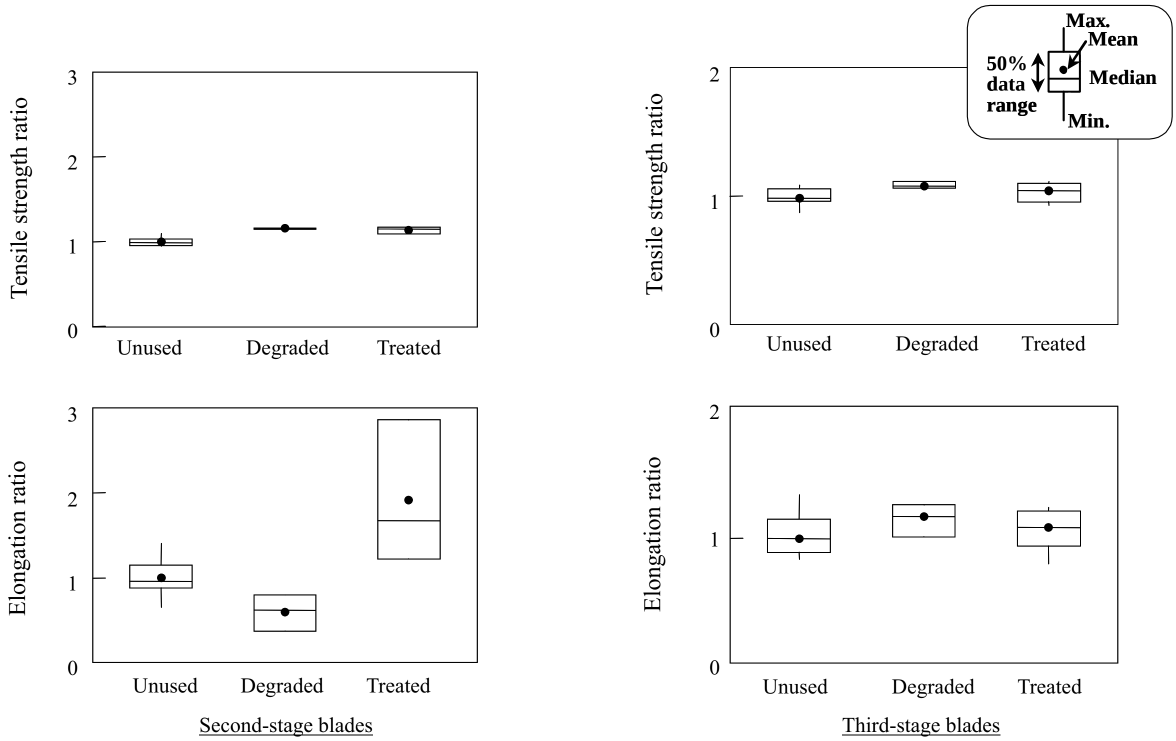

Fig. 6 Tensile properties of the second- and third-stage blades

strength and proof stress of the degraded and treated blades were almost the same as those of the unused one, so it can be said that there was no degradation in tensile properties of the third-stage blades due to their operation and/or the treatment.

Creep rupture tests. Fig.7 shows the results of creep rupture tests performed, comparing the results of the degraded and treated blades with the mean values of the unused ones. For the second-stage blades, creep rupture life of the degraded blades was shorter than that of the unused one, while that of the treated blades was equal to that of unused one. Thus, it could be said that the treatment recovered the creep rupture life of the degraded blades to a degree close to that of the unused one. In addition, the minimum values of the ductility have been improved in the course of the treatment, although the mean values of the treated blades were slightly inferior to the unused one. For the third-stage blades, there

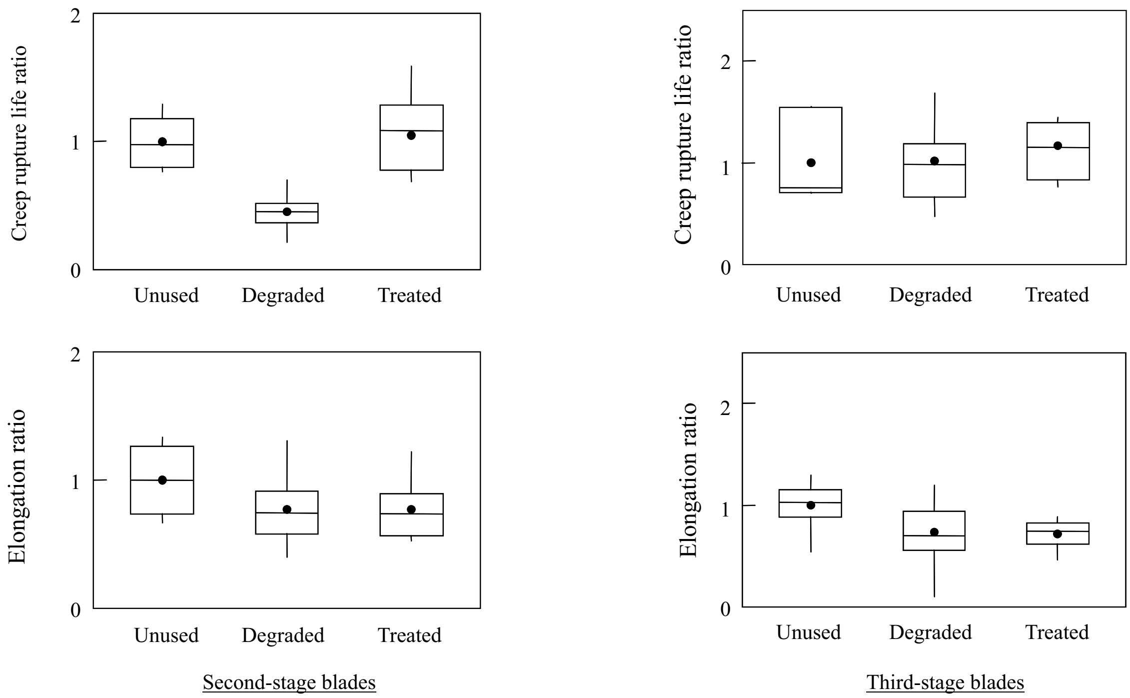

Fig. 7 Creep properties of the second- and third-stage blades

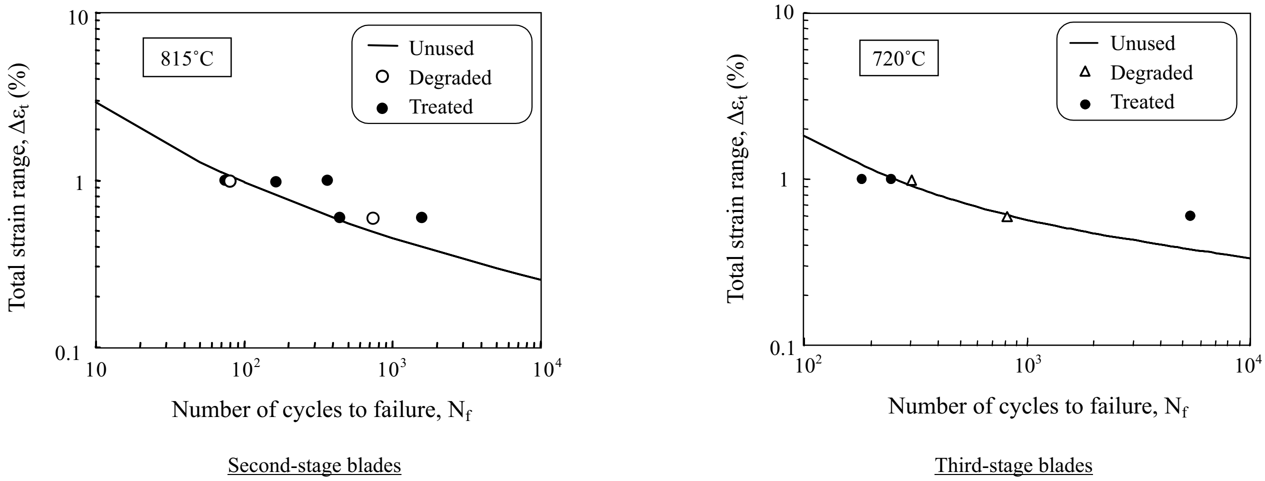

Fig. 8 Low-cycle fatigue life of the second- and third-stage blades

was no remarkable degradation in the mean values of creep rupture life and ductility for the degraded blades, as compared to the unused one. While creep properties featured a decline in the minimum values, those minimum values have been improved by the treatment.

Low-cycle fatigue tests. Fig.8 shows the results of the low-cycle fatigue tests performed, comparing the results of the degraded and treated blades with the mean values of the unused ones. Low-cycle fatigue life in degraded and treated blades of each stage indicates the same as that of the unused ones, except when total strain ranges are large. In other words, there was no degradation in fatigue life of the sample blades due to the operation and/or the treatment.

Evaluation of HIP-combined heat treatment's effects

We evaluate the applicability of the present HIP-combined heat treatment to recover material properties of degraded blades based on the results of the non-destructive and destructive tests. The non-destructive tests revealed no cracks due to the heat treatment on the surface of the blades for each stage. Moreover, the deformation and surface damage of the treated blades were negligible. The destructive tests revealed no cracks in the substrate of the treated blades in terms of macrostructure. Since the casting defects, detected not only in the degraded blades but also in the unused ones, were eliminated by applying the heat treatment. It can be said that the macrostructure of the degraded blades was improved to be even better than that of the unused ones. In terms of microstructure, the γ' phase of the degraded blades was recovered to a degree to that of the unused one through this treatment. Regarding mechanical properties, such as strength and ductility, the properties of the second-stage degraded blades were recovered to the level of the unused one. Thus, it can be confirmed that the heat treatment prolong the service life of each stage blades to a degree close to that of the unused one, although it was still necessary to verify that the treated blades had the same degradation rate as the unused ones.

TRIAL OPERATION

As a result of the above-mentioned research program, we confirmed that the degraded material properties of the blades due to service operation could be recovered by the present HIP-combined heat treatment. Also, assuming the heat treatment to be cost-effective, we installed the treated second- and third-stage blades for trial operation, three blades of each stage, in a 1100°C-class gas turbine of the Yokkaichi Thermal Power Plant No.4 unit to restart their operation in December 1999. Fig.9 shows the appearance of the treated blades installed in the turbine rotor before trial operation. For about two years, from the restart to September 2001, no troubles or irregularity has been experienced. Then, we conducted the follow-up damage inspection for every treated blade after trial operation.

DAMAGE INSPECTION

Sample blades and test methods

The sample blades used for the follow-up damage inspections were three blades of each stage (hereinafter referred to as the operated blades) installed in the gas turbine, as mentioned above. Those blades were removed at the time of regular periodic inspection, after about 2 years of operation (approximately 7,730h of operation with 380 starts and stops). While all blades were conducted to non-destructive tests, only one representative blade of each stage was performed to destructive tests. Non-destructive and destructive tests used in the follow-up damage inspection were the same methods as the above-mentioned research program. Material properties of the operated blades were compared with that of the unused and treated blades before the restart of operation in order to assess the damage and degradation rate.

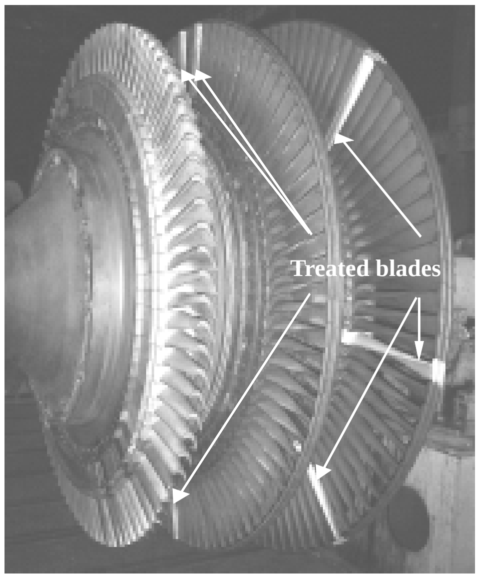

Fig. 9 Appearance of the treated blades installed in the turbine rotor before trial operation

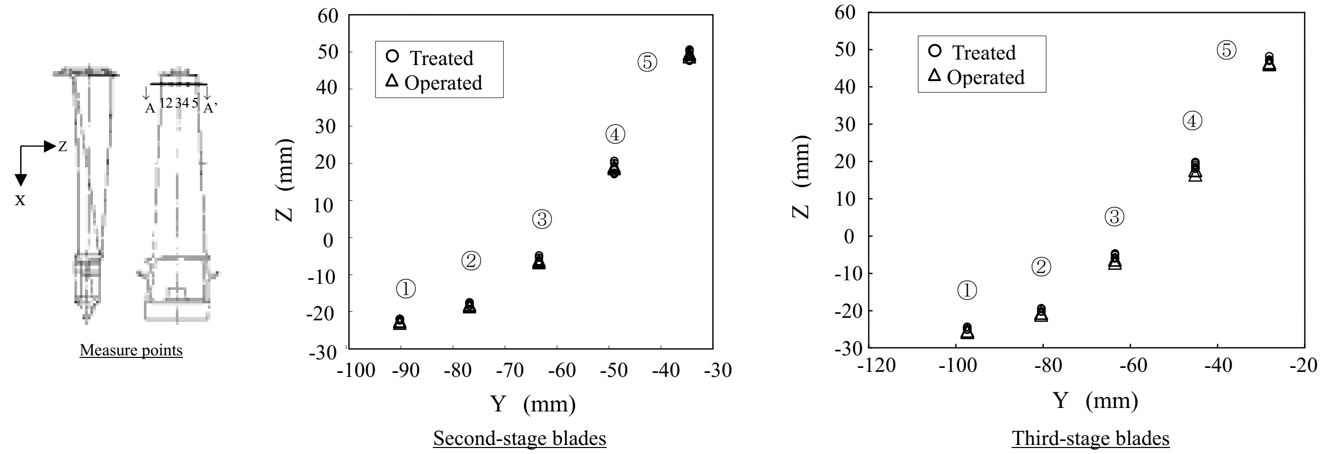

Fig. 10 Results of 3D size measurement of the operated and treated blades

Non-destructive tests

As in the case of the degraded blades, the airfoil area in the operated blades of each stage was discolored in dark brown, some wear was detected at the tip shroud of the blade. There was no crack or other damage observed.

Fig.10 shows the results of 3D size measurement for the treated and operated blades. Note that measure points are the same position of airfoil section shown in Fig.2. The operated blades of each stage almost did not differ dimensionally from the treated blades, and no deformation and torsion were detected in the airfoil section.

Destructive tests

Microstructural observation. Fig.11 shows the optical micrographs in the cross section. No cracks were observed in any cross section of the each-stage blades. And, no casting defects were detected in the each-stage blades, as in the case of the treated blades. Similarly to the degraded and treated blades, the surface of the operated blades had a corroded layer, consisted of the oxide and γ' phase depleted layers, but there was no plate-like precipitates (AlN). The maximum depth of the corroded layer was about 50μm at the tip shroud in the second-stage operated blades, while the maximum depth for the third-stage blades was approximately 20μm. The maximum depth of the corroded layer on the cooling hole of the second-stage blades was approximately 100μm, as in the case of the degraded and treated blades.

SEM micrographs in the cross section are shown in Fig.12. Coarsening of the cuboidal γ' phase and disappearance of the fine spherical γ' phase were occurred at the leading edge in the

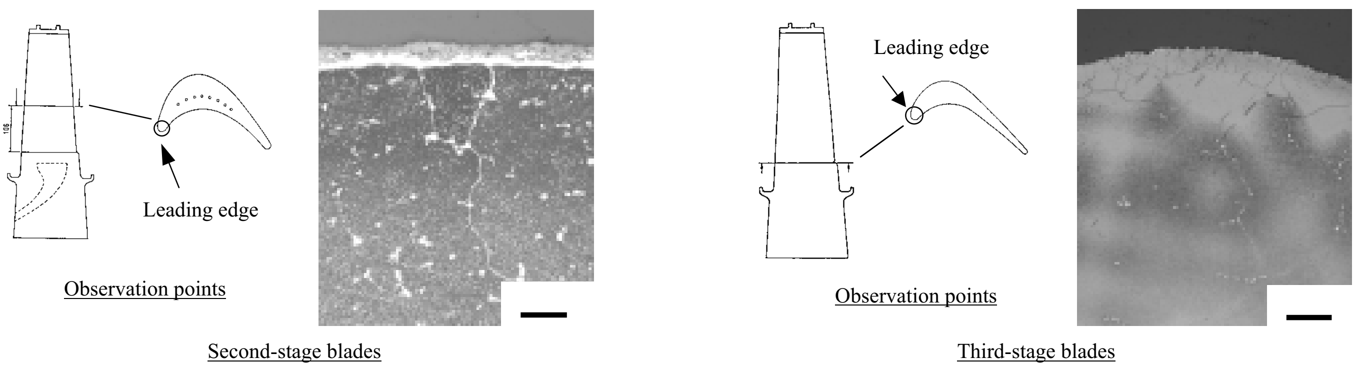

Fig. 11 Optical micrographs in the cross section of the operated blades

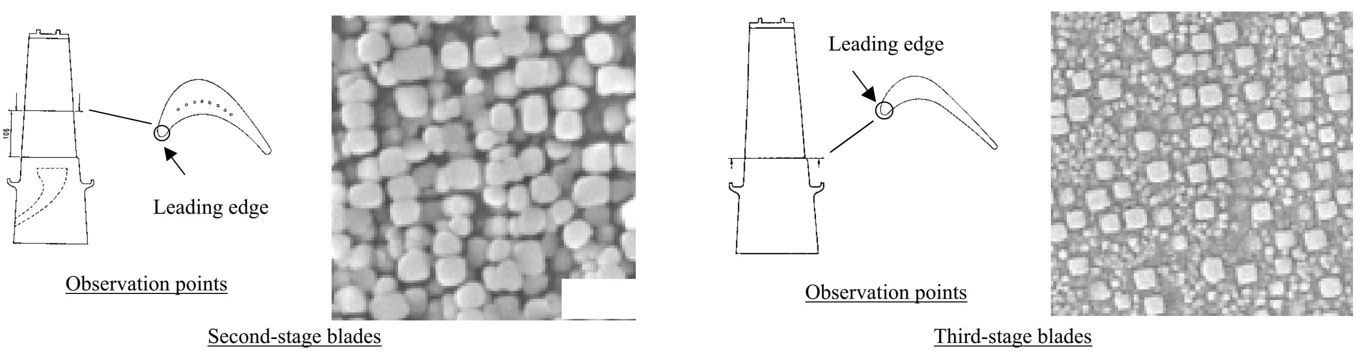

Fig. 12 SEM micrographs in the cross section of the operated blades

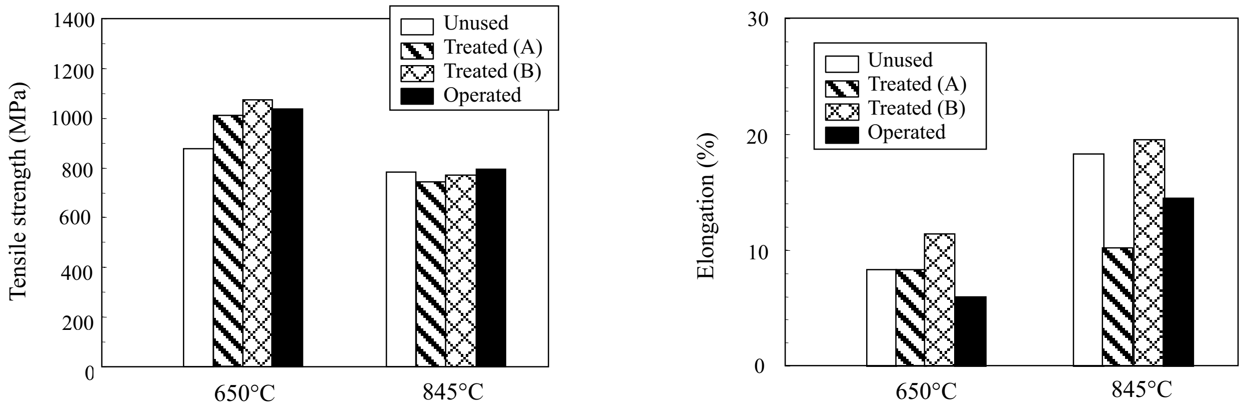

Fig. 13 Tensile properties of the second-stage operated blades

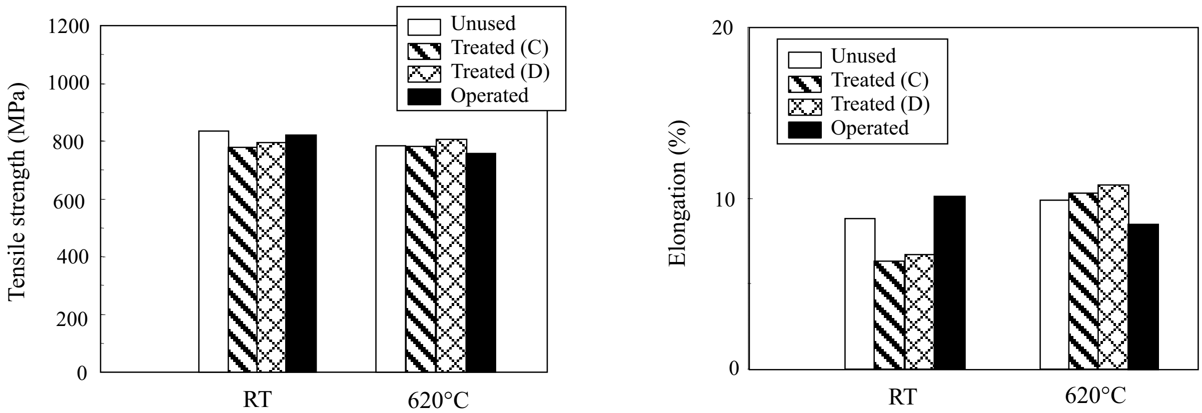

Fig. 14 Tensile properties of the third-stage operated blades

second-stage blades. The film-like grain boundary γ' phase precipitates were detected, but no creep void was found. The third-stage blades featured a slight γ' phase coarsening at the leading edge, as shown in Fig.12. Metallurgical changes were not as remarkable as those in the degraded blades.

Tensile tests. Figs.13 and 14 show the results of tensile tests performed at room and high temperatures on the second- and third-stage blades, respectively. The tensile properties of the operated blades are almost equal to those of the unused and treated blades. Thus, there was no degradation detected in tensile properties of the operated blades.

Creep rupture tests. Figs.15 and 16 show the results of the creep rupture tests performed at 900°C/245MPa and 825°C/245MPa on the second- and third-stage blades, respectively. The creep rupture life of the operated blades was slightly lower than that of the unused blade, but various creep properties were within the data range of the treated blades. Thus, there was no further degradation in those properties due to trial operation.

Low-cycle fatigue tests. As in the case of the degraded blades, there was no degradation in the low-cycle fatigue life of the operated blades for each stage as compared to that of the unused and treated blades.

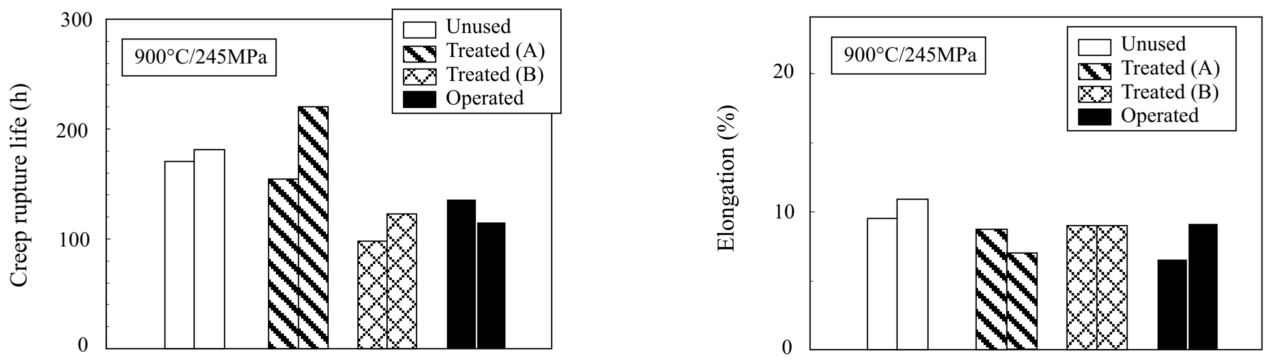

Fig. 15 Creep properties of the second-stage operated blades

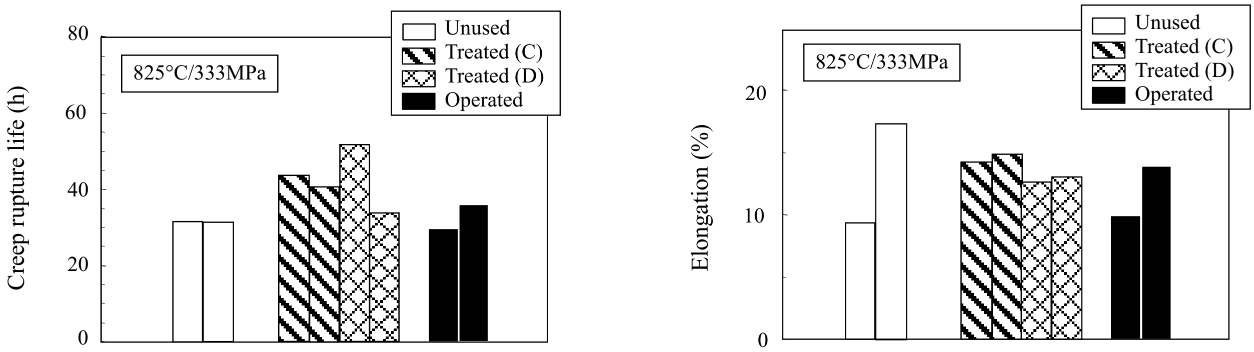

Fig. 16 Creep properties of the third-stage operated blades

Evaluation of Degradation

Based on the results of the above-mentioned non-destructive and destructive tests, we estimated the material properties of the treated blades after two-year operation.

The non-destructive tests revealed no cracks on the surface of the each stage blades. Moreover, the deformation and surface damage were negligible. The destructive tests revealed no cracks inside of the blades, confirming no damage to macrostructure. In terms of microstructure, a slight change in γ' phase was detected in each blade. Regarding the mechanical properties, such as strength and ductility, various properties of the operated blades were within the data range of the treated blades. Therefore, we have confirmed that the operated blades featured nearly the same mechanical properties as the treated blades before operation, without any acceleration in degradation rate, although there were some metallurgical changes due to the operation.

CONCLUSION

We studied the recovery of material properties through the HIP-combined heat treatment and verified its effectiveness by applying the treatment to the second- and third-stage degraded blades of a 1100°C-class gas turbine. We further conducted trial operations with the treated blades by reinstalling those in a commercial gas turbine to inspect their condition after the two-year operation. The results are summarized below:

(1) Metallurgical and mechanical properties of the service-degraded blades were recovered by applying the HIP-combined heat treatment.

(2) The trial operation, installed the blades applying the HIP-combined heat treatment, has finished smoothly without any trouble or irregularity.

(3) After the trial operation, the treated blades did not feature any further damage. The subsequent damage inspections did not reveal any acceleration in degradation rate due to the HIP-combined heat treatment.

(4) The present research, trial operation and subsequent damage inspection verified that the HIP-combined heat treatment could be a useful service-life extension method for gas turbine blades.

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