High-temperature strength of Ni-base superalloy coatings

M. Okazaki*

Department of Metallurgy, School of Engineering, The University of Tokyo, Hongo 7-3-1, Bunkyo-ku, Tokyo 113-8656, Japan

Received 29 September 2000; revised 27 November 2000; accepted 30 November 2000

Abstract

Recently considerable attention has been paid to large utility gas turbines, because of their high efficiency and many other advantages. This accelerates the introduction of advanced superalloys and coatings. While these technologies are traditionally from aero turbines, many novel challenges have arisen in their application, e.g. long operating time, weight, cyclic duty, environment using cheaper fuel, and size. This paper describes the mechanical properties and failures of the superalloys and the coatings used at the hot sections of utility gas turbines. Special focus is put on thermo-mechanical fatigue failure, and the collaborative test results by the Subcommittee of “Superalloys and Coatings” in The Society of Material Science, Japan, is introduced. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Gas turbines; Ni-base superalloys; Coatings; Reliability; High-temperature strength; Thermal stress; Thermo-mechanical fatigue; Failure; Life prediction; MCrAlY alloys

1. Introduction

Industrial gas turbines are used as electrical generators by both utilities and private industrial companies [1–12]. In the 1960s and 1970s, utilities primarily used them to provide peaking power, that is, electricity at the highest demand periods of the day. In the 1970s and especially the 1980s, combined cycle applications became widespread, in which exhaust gases were used to make steam in a boiler, and this was used to generate additional electricity with a steam turbine or was used in industrial process plants. In Europe, steam or hot water is used for district heating purposes. Today, many simple and combined cycle gas turbine plants are being built to provide additional power and to replace aging power plants all over the world. Nowadays the so-called 1500°C level combined cycle gas turbines have been developed, which can provide thermal efficiencies greater than 55% [4,11]. Industrial gas turbines are also advantageous in that they can be purchased in modular units to reduce the financial risk associated with building large, conventional coal-fired steam or nuclear plants. Smaller industrial gas turbines are used as mechanical drives for numerous applications and to provide electricity in remote locations.

The durability of a gas turbine is principally limited by those components operating at high temperatures in the turbine sections. In particular the first-stage nozzle and blades are usually subjected to severe service conditions. Although many efforts have been made to develop new heat resisting materials during the last few decades, Ni-base superalloys are still the most promising structural materials in advanced gas turbines (see Ref. [4]). Note that the turbine inlet temperatures in the advanced gas turbines are much higher than the endurance limits of superalloys; approximately 950°C in recent microstructurally controlled Ni-base superalloys. Accordingly, cooling schemes consisting of holes drilled through the span (Fig. 1) [6], as well as thermal barrier coatings (TBCs), are essential to reduce the metal temperature. The new, highest temperature gas turbines employ more advanced designs consisting of serpentine passages and film cooling, and the steam cooling system has been applied in the 1500°C level gas turbines. These sophisticated methods, on the other hand, expose the structural materials to more severe service conditions, as will be described later.

2. Why does failure occur?

Fig. 2 shows various damages experienced in the hot section components of a gas turbine [12]. Why does failure occur?

There are no materials which do not exhibit thermal expansion. Consider the simple case shown in Fig. 3, in which a bar is fixed at either ends between two immovable plates so that the length of the bar cannot increase. The bar is
assumed to be gradually heated from $T_0$ to $T_1$. If the bar was not fixed, it would expand as illustrated in Fig. 3b, but since expansion is prohibited it enters a state of compressive stress (Fig. 3c). This kind of stress is called thermal stress. The thermal stress may result even in cases where a temperature gradient exists. So long as engineering materials expand with temperature and their thermal conductivity is finite, engineers have to get along with thermal stress. It is the thermal stress as well as the mechanical loading that cause the components to fail. Fatigue due to the thermal stress is called thermal fatigue, and the failure resulting from the superimposition of both types of stress is called thermo-mechanical fatigue (TMF).

The gas path components of a gas turbine experience a complex thermal and mechanical history during a typical cycle of operation, consisting of start-up, steady-state operation, shut-down, and emergency shut-down, depending on the temperature gradient and the surrounding mechanical constraints. Fig. 4 illustrates the complexity of the thermo-mechanical cycle experienced at the leading edge of a first-stage blade during a normal start-up, shut-down cycle [2]. TMF should be recognized as one of the primary failure modes of hot components (Fig. 2d). Some typical damage items experienced in the hot section components are summarized in Table 1.

In addition to the thermal stress, rotating components such as turbine blades are subjected to high centrifugal loading. This situation exposes the component to creep, fatigue and wear. Moreover, in the case of utility gas turbines, in which long lifetime durability and cost reductions using clear fuel are required, the hot section parts are under environmentally severe conditions: high-temperature attacks from oxidation and hot corrosion (Fig. 2c and d). Thus, the protective coatings and thermal barrier coatings, which shield the underlying substrate materials from oxidation and corrosion attacks and reduce the temperature, respectively, are the essential requirements. Fig. 4 indicates the thermo-mechanical history regarding only the substrate. The coating induces an additional thermal stress, depending on the thermal expansion mismatch between the substrate and the film, as schematically illustrated in Fig. 5. Especially in TBCs, which reduce the underlying substrate material temperature, thermal stress may play an intrinsic role in components failure (Fig. 2a).

The mechanical properties of MCrAlY alloy coatings (see Section 3), which are widely used as protective coatings, are shown in Fig. 6 [11]. These coatings have ductile–brittle transition temperatures (DBTTs) depending on the alloy system, below which the ductility is remarkably low. From Figs. 4 and 5, it is easy to see the importance of the mechanical properties of the coating not only at higher temperatures but also at lower temperatures. The mechanical properties at lower temperatures have an important role in determining the TMF lives. Isothermal tests, e.g. the isothermal low-cycle fatigue (ILCF) test, may provide limited, or inadequate information. Despite many efforts to predict the TMF life from ILCF values in engineering monolithic materials, the results cannot always be applied.

Fig. 1. Cooling scheme consisting of holes drilled in blades [6].
Fig. 2. Some failures [12]: (a) TBC spallation of combustion liner; (b) trailing edge cracking in first-stage nozzle; (c) coating degradation at leading edge in first-stage blade; (d) crack in aluminized first-stage blade-transverse section.

to coatings. For this reason the TMF test has become an essential tool in recent years.

As shown in Fig. 4, the actual temperature–strain history experienced in the hot parts of gas turbines is too complicated to be exactly reproduced in the laboratory. The TMF test, in which mechanical strain is applied in synchronization with temperature cycling, has been recently developed and is widely used as a simulating test method (Fig. 7). Using this test, a wide variety of temperature–strain histories can be reproduced by selecting the phase difference between the strain and the temperature. For simulation of the temperature–strain histories of turbine blades, out-of-phase and diamond-phase TMF tests are often employed, in which the phase differences between strain and temperature are 180 and 135°, respectively (Fig. 7). Some articles relating to the TMF lives of the superalloy coatings will be introduced later.

Fig. 3. Illustration of thermal stress in constrained bar.
3. History of protective coatings

In the case of utility gas turbines, because of the long lifetime required, a base material and coatings with adequate resistance to corrosion and oxidation are generally regarded as essential. Alumina ($\text{Al}_2\text{O}_3$) is believed to be the most common choice for protective oxide. To form a protective alumina film, the surface concentration of aluminum in the underlying alloy must be increased. One of the standard methods to achieve this is the technique of pack aluminizing, or pack cementation (first generation, see Fig. 2c and d) [8,9,13–15]. In this process, the component is immersed in a bed comprising of an inert powder mixed with an aluminum rich powder to act as a source of aluminum. From a metallurgical point of view this process forms high-aluminum intermetallics, such as NiAl or Ni$_3$Al at the surface of the Ni-base superalloys. A modified aluminate coating has also been developed, incorporating platinum, or, later, platinum group metal (second generation) [9]. Usually a thin layer of Pt is electroplated on the substrate alloy, and then aluminized. This modification was aimed to improve the hot-corrosion resistance and adhesion strength [14,15]. Application of steam cooling in advanced gas turbines enhances this kind of protective coatings inside the components.

Third generation coatings began with the development of the so-called MCrAlY alloys (where M is Fe, Co, Ni, or a combination of these) [9–11,16]. Some typical MCrAlY alloys are summarized in Table 2 [16]. Until the 1980s, these were generally overlay-coated onto the substrate by using electron beam physical vapor deposition. Later a new deposition technique using plasma spray at low pressure (LPPS or VPS) made a considerable advance. The advent of MCrAlY alloys made a whole new industry from the stand points of: (i) flexibility in choice of coating composition [9], (ii) increased resistance to high-temperature corrosion and oxidation, (iii) flexibility in choice of coating thickness [6,8], and (iv) high ductility, compared with the first and second generation coatings [10,16]. Nowadays the coating by MCrAlY alloys plays an important role not only in protection but also by providing a bond coat between the substrate and the ceramics in TBCs [5,9,17]. Double, or multi-layers coatings, in which aluminate coating is additionally applied on the MCrAlY alloy.
coatings, have been recently begun to be applied in advanced gas turbines [18].

4. Research on strength of protective coatings

4.1. Resistance to corrosion, erosion and wear

MCrAIY coatings were found to be useful in improving the resistance to erosion, hot corrosion and wear [19–22]. For example, according to burner rigs tests, the corrosion resistance of superalloys is improved several times by application of these coatings [22].

4.2. Tensile and creep properties

Hebsur and Miner have measured the tensile properties of NiCoCrAlY alloy film at temperatures ranging from room temperature to 800°C, where the coating was performed by low-pressure plasma spraying [23]. They showed that the NiCoCrAlY alloy revealed high strength (approximately 950 MPa in 0.2% proof stress) and low ductility (approximately 2% in elongation) from room temperature to 600°C. The former property decreased and the latter increased with temperature. It was interesting that the alloy exhibited superplasticity phenomena above 850°C in which ductility was beyond 100%. Similar tests were carried out in the superalloy coatings with an aluminizing treatment. From these tests, it should be recognized that the protective coating films generally suffer from ductility below their DBTts [11,18,23]. Correspondingly, the creep strength of the Ni-base superalloy coatings was significantly influenced by temperature.

4.3. High-cycle fatigue strength

There are many studies on the high-cycle fatigue lives of
Ni-base alloys both aluminized [14,24–26] and overlay-coated with MCrAIY alloys [24,26,27]. The fatigue strengths revealed strong temperature dependence: whereas they were significantly lowered by the coating below the DBTT, they were still almost comparable to those of the bare materials. Some researchers have confirmed that the coating increases the life [26]. More recently the fatigue strength of the multi-layer coatings has also been explored [26].

4.4. ILCF strength

According to one study carried out by Totemeier and King, the ILCF strengths of aluminized nickel-based superalloy was lowered by 60% at 600°C compared with that of the substrate [28,29]. As the test temperature increased no reduction was noted. A similar trend has been confirmed by other research on MCrAIY-coated superalloys [30–32].

Low-cycle fatigue strength of monolithic materials is in general significantly influenced by creep effect, relating to strain waveshape. This is also the case in Ni-base superalloy coatings [33,34]. Minet et al. [33] studied the creep–fatigue strength of a single crystal superalloy, PWA1480, overlay-coated with NiCoCrAlY alloy by a low-pressure plasma spraying process at 1050°C under creep–fatigue interaction condition. This study showed that the lifetime of the coated material compared with the bare material was only reduced in tests with a strain hold on the tension side. Other researchers has confirmed the significant reduction of fatigue life by a strain hold on the compression side [32].

4.5. TMF strength

Research on the TMF strength of Ni-base superalloy coatings is very limited. According to research which cover the TMF lives of superalloys coated with aluminizing and with MCrAIY alloy, noticeable reductions were found to occur under out-of-phase condition [32,34] compared with the substrate life. Some more systematic results will be discussed in the next section.

4.6. Influence of long-term aging

Attention should be paid to long-term aging in metallic coatings, since the interdiffusion of the main alloying elements between the substrate and coating is generally significant, resulting in the changes to mechanical properties [34,35]. With respect to this, some researchers have observed only a slight reduction in long-term fatigue lives [35], whereas others have noted a beneficial effect on the inter-diffusion of alloying elements [26,36]. Some interesting examples are given in Refs. [37,38], which report that the TMF life is significantly changed by aging treatment through a change of adhesion strength between the coating and the substrate.

5. Activity in The Society of Materials Science, Japan (JSMS)

As introduced in the previous section, considerable
research has been conducted regarding the strength of coated materials. Nevertheless, the question still remains whether the results obtained by some researchers can be quantitatively compared with those by others. This is due to the fact that there are many process parameters in coating which may strongly influence the mechanical properties of the coatings, e.g. the coating material, thickness, substrate, the substrate temperature during coating, the previous surface finishing of the substrate, the coating gun used, etc. Round robin tests specifying common coating specimens must be the most promising way to systematize the information.

In an attempt to answer this problem, the Subcommittee on “Superalloys and Coatings” (chaired by Prof. M. Okazaki, The University of Tokyo, Japan), was established in The Society of Material Science, Japan (JSMS) in 1998. This subcommittee is engaged in collaborative research on the high-temperature strengths of superalloys and coatings, with special attention being paid to the interaction between the substrate and the coatings. The main objectives of the subcommittee are:

(i) to clarify quantitatively the mechanics and mechanisms of failure due to TMF, in comparison with ILCF-induced failure;
(ii) to clarify the effect of coating on TMF and ILCF lives;
(iii) to qualify the effect of substrate alloy on the TMF and ILCF lives; and

(iv) to develop life prediction method(s), summarizing items (i)–(iii).

Three typical types of Ni-base superalloys have been selected as the substrate: a polycrystalline alloy, IN737LC; a directionally solidified alloy, CM247LC; and a single crystal alloy, CMSX-4. CoNiCrAlY alloy overlay-coating was performed at a thickness of 250 μm by low-pressure plasma spraying and then the surface layer was aluminized to 50 μm in thickness by a pack diffusion method. These operations were carried out by Tocalo Co., Kobe, Japan. Round robin tests were carried out according to the test program given in Table 3.

Some of the results are summarized in Fig. 8, which covers the TMF and ILiCF lives of the IN738 substrate alloy specimen and those of the coated specimens. The following characteristics should also be pointed out (Fig. 8).

5.1. Regarding the substrate specimens

(i) The ILCF life of the IN738 substrate is strongly dependent on the strain waveshape: the life under the SS wave (in which the tension and compression going strain rates are low; see Table 3) is the shortest.
(ii) The TMF lives are generally longer than the ILCF lives at the highest temperature of the TMF test. The TMF life under the diamond phase condition (in which the phase difference between the strain and temperature is

| Specimen         | Test type | Strain waveform | Frequency (Hz) | Hold time (s) | Temp.–Strain phase difference, δ (°) | Maximum temperature (°C) | Minimum temperature (°C) |
|------------------|-----------|-----------------|----------------|---------------|--------------------------------------|--------------------------|--------------------------|
| Bare and coated  | LCF       | f-f             | 1/20           | 0             | –                                    | 900 and 400              | 900 and 400              |
|                  | s–s       | 1/480           | 0              |               |                                      |                          |                          |
|                  | Comp. hold| 1/620           | 600            |               |                                      |                          |                          |
| TMF              | Out-of-phase| 1/480        | 0              | 180           |                                      | 900                      | 400                      |
|                  | Diamond phase| 1/480     | 0              | 135           |                                      |                          |                          |
135°, see Fig. 7 and Table 3) is shorter than that under the out-of-phase condition (in which phase difference between the strain and temperature is 180°).

5.2. Regarding the coated specimens

(iii) The TMF life under the out-of-phase condition is the shortest. In addition, it is significantly reduced compared with the bare specimen.

(iv) In contrast to (iii), the ILCF life at 900°C is improved compared with the bare specimen.

These characteristics clearly demonstrate that the TMF life of the coatings can be hardly estimated from that of the substrate alone: i.e. the interaction between the substrate and the coating plays a significant role [28,32,36]. The role of the interface strength is also involved in this factor.

In order to explore the TMF life prediction method, how the interaction is quantified is a key point. Characteristics (iii) and (iv), of course, indicate that the ILCF test can provide only limited or inadequate information on TMF failure.

6. Summary and future work

As shown earlier, previous research on superalloy coatings has been carried out mostly on a fairly basic level. Research in this area is still infancy, but now is the time for a systematic approach to be undertaken.

The following are strongly recommended as future areas of research.

6.1. Development of an evaluation method

At present some difficulty exists thus preventing the
quantitative comparisons of the results of some researchers with those of others. There are many factors affecting the mechanical properties of coatings. For the life prediction the following information is essential: What are the elastic properties of this film? “How high is the residual stress?” “How can the mechanical properties of the coating film be evaluated?” “Are the properties obtained in the laboratory reproduced in the coated components?” and so on. There is a lack of standardized evaluation methods for the coating films; most of the experimental data are obtained according to the “individual” standards. Accordingly, world wide standardization of evaluation methods is essential, which must enable us to get good understanding on the failure process and the presentation method.

6.2. Recoating, repair and refurbishment technology

The direction of future development is not only the achievement of high thermal efficiency but also cost reduction in production and maintenance. Thus, repair, recoating and refurbishment of hot section components in service in extremely severe conditions will be inevitable part of this technology in the very near future, especially in the industrial gas turbines. At present, however, no sufficiently sophisticated technology has been established.

As an example, let us consider a simple refurbishment process in which single crystal alloys are subjected to actual damage (e.g. fatigue, creep–fatigue and thermo-mechanical fatigue) during the servicing period, after which reheat treatment is applied for damage recovery, which is the usual course of action for polycrystalline alloys. Which reheat treatment should be given? Is the same treatment condition as for the virgin material applicable? Is there a problem of local recrystallization in this case? There seems to be little understanding even for such a simple example. More recently, some researchers have been studying phenomena of local recrystallization and abnormal precipitation growth [39–41]. According to these investigations, when microstructurally controlled Ni-base superalloy substrates were subjected to damage associated with plastic deformation and then subjected to the normal reheat treatment methods for the virgin material, abnormally growing cellular microstructures were found to occur acceleratively, which could significantly reduce fatigue and creep properties. Note that the shot blasting procedures on Ni-base superalloys before coating, which are often conducted to improve adhesion between the film/substrate, are also straining processes. Thus the problem must be more complicated in coatings.

6.3. Nondestructive inspection

Urgent work is also required on nondestructive inspections of spallation of coating films and interface defects. Note that spallation is invisible from the surface in most cases. Many efforts have been made, employing ultrasonic wave, eddy current, thermography, and holography [5,17].

6.4. Control of interface and optimization

In coated components, attention should be paid not only to the chemical and mechanical properties of the coating film, but also to good compatibility with the substrates, with moderate adhesion between the substrate and the coating film. Of particular importance is that the strong adhesive strength does not always promise better strength of the composite system. For example, it has been pointed out from the analytical level that the control of the relative strength of the interface to the substrate is directly related to the optimization of the strength of the composite system [42]. Some experimental data supporting this have obtained [38], indicating that the TMF life of Ni-base superalloy coatings with MCrAlY alloys is strongly influenced by the interface strength. It is also desirable to develop a sophisticated method to evaluate the adhesion strength, based on interface mechanics [37,43,44].

6.5. Thermal barrier coatings

Thermal barrier coatings (TBCs) are extremely important for hot parts in advanced gas turbines, where TMF failure is a critical issue (Fig. 2). Usually the burner rig test is employed to evaluate the strength of TBCs under thermal cycling. Many workers have pointed out the importance of oxidation at the top/bond, or ceramics/metalllic coatings interface, resulting in spallation. Since the heat rate of the advanced industrial gas turbines is different from that of aircraft turbines, there is a lot of novel research to be done in this area. For more information on TBCs, see Refs. [9,17].

Acknowledgements

The author wishes to express his gratitude to the members of the Subcommittee “Superalloys and Coatings”, JSMS, for their cooperation in the round robin tests. Mr Namba, Matsu Engineering & Shipbuilding Co., is also thanked for supplying the valuable pictures. Fruitful discussions with Prof T. Yoshida and T. Suzuki are greatly acknowledged. This work is supported by the Financial supports from the Ministry of Education, Japan, as a Grant-in-Aid for Scientific Research (No. 10555023 and 10555242).

References

[1] A. Duret, A. Davin, R. Pichior, Recent approaches to the development of corrosion resistant coatings, in: R. Brunetaud (Ed.), High Temperature Alloys for Gas Turbines, Reidel, Dordrecht, 1982, p. 53.
[2] H.L. Bernstein, T.S. Grant, R.C. McClung, J.M. Allen, Prediction of thermal–mechanical fatigue life for gas turbine blades in electric power generation, in: H. Sehtiglu (Ed.), ASTM STP1186, ASTM, Philadelphia, 1993, pp. 212–238.
[3] National Research Council, Coatings for High Temperature Structural Materials — Trends and Opportunities, National Academy Press, Washington, DC, 1996.
[4] B.B. Seth, Superalloys: the utility gas turbine perspective, in: T. Pollock (Ed.), Superalloy 2000, TMS, Warrendale, 2000, p. 3.

[5] Y. Itoh, Protective coatings for gas turbine, Kikai-No-Kenkyu 44 (1992) 257 (in Japanese).

[6] Rolls-Royce plc., The Jet Engines, Japan Aeronautical Engineers Association, Tokyo, 1986 (chap. 9; translated to Japanese by Japan Aeronautical Engineers Association).

[7] H. Takeda, Heat resisting alloys, Kouyou Zairyou 33 (1993) 69–76 (in Japanese).

[8] K. Schneider, H.W. Grunling, Mechanical aspects of high temperature coatings, Thin Solid Films 107 (1983) 395–416.

[9] M.G. Hocking, V. Vasantasree, P.S. Sidky, Metallic and Ceramic Coatings, Longman, London, 1989.

[10] I. Shimitori, The trends of MCrAlX alloys for high temperature protective coatings, Tetsu-To-Hagane 69 (1983) 1229–1241 (in Japanese).

[11] J. Stinger, R. Viswanathan, Gas turbine hot section materials and coatings in electric utility applications, Proceedings of ASM 1993 Materials Week 93, ASM, Pittsburgh, 1993, pp. 1–21.

[12] K. Namba, K. Kamata, K. Miura, Damage and life evaluation for hot section components of Mitsu gas turbines, in: T. Tamaru (Ed.), Proceedings of the International Gas Turbine Congress 1999, Kobe, Gas Turbine Society of Japan, 1999, pp. 995–1001.

[13] L. Swadzba, B. Formanek, A. Maciejny, J. Biedron, Microstructure and resistance to cracking of modified protective diffusion coatings of Ni-base superalloys, Mater. Sci. Forum 102 (1992) 721–728.

[14] K. Schneider, H.W. Grunling, Influence of coatings and hot corrosion on the fatigue behavior of Ni-based superalloys, Thin Solid Films 84 (1981) 29–36.

[15] T.S. Sudrashan (Ed.), Surface Modification Technologies III TMS, Warrendale, 1990.

[16] T. Hasui, Thermal Spray Technology, Sanpou, Tokyo, 1996 (in Japanese).

[17] Y. Itoh, Thermal barrier coatings, Kikai-No-Kenkyuu 47 (1995) 746–751 (in Japanese).

[18] Y. Itoh, M. Saitoh, Y. Harada, Mechanical properties of alumelized MCrAlY alloy coatings, Trans. Soc. Mater. Sci. Jpn 44 (1995) 1361–1366 (in Japanese).

[19] R.W. Smith, H.M. Fox, Low pressure plasma-spray coatings for hot corrosion resistance, Trans. ASME 103 (1981) 146–153.

[20] M. Tikazaki, Hot corrosion resistance of alumelized and platinum aluminide coatings, Tetsu-To-Hagane 69 (1983) 1014–1021 (in Japanese).

[21] E. Khobaib (Ed.), High Temperature Coatings TMS, Warrendale, 1987.

[22] H.J. Ratzer, M.R. W instone, Hot corrosion resistance of coated single crystal superalloy under marine conditions, Mater. Sci. Technol. 9 (1993) 253–258.

[23] M.G. Hebsur, R.V. Miner, High temperature tensile and creep behavior of low pressure plasma sprayed NiCoCrAlY coatings alloy, Mater. Sci. Engng 83 (1986) 239–245.

[24] M. Okazaki, T. Sadasue, High-cycle fatigue failure modeling and the endurance prediction of Ni-base superalloy protective coatings, in: T. Tamaru (Ed.), Proceedings of the International Gas Turbine Congress 1999, Kobe, Gas Turbine Society of Japan, Tokyo, 1999, pp. 983–990.

[25] T. Sadasue, M. Okazaki, Y. Mutoh, Effect of aluminizing on high cycle fatigue strength of Ni-base superalloys at high temperature, Trans. Jpn. Soc. Test. Mater. 42 (1997) 32–39 (in Japanese).

[26] T. Sadasue, M. Okazaki, Y. Mutoh, Effect of aluminizing coating on fatigue strength of a Co–Ni–Cr–Al–Y coated Ni-base superalloy at ambient and high temperatures, in: H. Nakamura (Ed.), Proceedings of the International Conference on Materials and Mechanics’97, Japanese Society for Mechanical Engineers, Tokyo, 1997, pp. 155–161.

[27] M. Okazaki, T. Sadasue, Fatigue crack propagating across the interface in MCrAlY coated Ni-base superalloy, Trans. Soc. Mater. Sci. Jpn 46 (1997) 32–38 (in Japanese).

[28] T.C. Totemeier, J.E. King, Isothermal fatigue of an alumelized coated single crystal superalloy: part I, Metall. Trans. 27 (1996) 353–361.

[29] T.C. Totemeier, J.E. King, Isothermal fatigue of an alumelized coated single crystal superalloy: part II, Metall. Trans. 27 (1996) 363–369.

[30] P. Au, R.V. Danity, P.C. Patrik, Isothermal low cycle fatigue properties of alumelized coated nickel and cobalt base alloys, in: T.S. Sudrashan (Ed.), Surface Modification Technologies III, TMS, Warrendale, 1990, pp. 729–749.

[31] J. Gayda, R.V. Miner, Low cycle fatigue behavior of a plasma-sprayed coating material, Int. J. Fatigue 8 (1986) 217–223.

[32] M. Okazaki, Low cycle and thermo-mechanical fatigue strength of Ni-base superalloy protective coatings, Textbook on Symposium of Protective and Heat Resisting Coatings for Energy, The Japan Institute of Metals, Sendai, 2000, pp. 34–39 (in Japanese).

[33] R.V. Miner, J. Gayda, M.G. Hebsur, Creep-fatigue behavior of NiCoCrAlY coated PWA 1480 superalloy single crystals, in: H.D. Solomon (Ed.), ASTM STP942, ASTM, Philadelphia, 1988, pp. 371–384.

[34] H.W. Glunling, K. Schneider, L. Shingheiser, Interaction of coatings with base metals at high temperature, Mater. Sci. Engng 88 (1987) 177.

[35] M.I. Wood, Mechanical interactions between coatings and superalloys under conditions of fatigue, Surf. Coat. Technol. 39/40 (1989) 29–42.

[36] M. Okazaki, T. Sadasue, Y. Mutoh, Propose of a new life prediction method for protective coatings, Trans. Soc. Mater. Sci. Jpn 48 (1999) 181–187 (in Japanese).

[37] M. Okazaki, M. Okamoto, Y. Harada, Evaluation of adhesion strength of coating film on Ni-base superalloy for gas turbine, in: C. Berndt (Ed.), Thermal Spray 2000, ASM, Montreal, 2000, pp. 653–659.

[38] M. Okazaki, Y. Yamazaki, On a significance of adhesion strength on thermo-mechanical fatigue life of the CoNiCrAlY coated Ni-base superalloy, Proceedings of the Mechanics and Materials Meeting, JSME, 2000, No. 00-19, pp. 233–234 (in Japanese).

[39] W.S. Walston, J.C. Schaeffer, W.H. Murphy, A new type of microstructural instability in superalloys, in: R.D. Kissinger (Ed.), Superalloys’96, TMS, Warrendale, 1996, pp. 9–18.

[40] P. Portella, Influence of cellular recrystallization on the fatigue behavior of single crystal Ni-based superalloys, in: H. Mughabbi (Ed.), Mechanical Properties of Metallic High Temperature Materials, Deutsche Forschungsgemeinschaft, Berlin, 1999, pp. 441–453.

[41] M. Okazaki, Effect of local cellular transformation on fatigue small crack growth in CMSX-4 at high temperature — for refurbishment technology, in: T. Pollock (Ed.), Superalloy 2000, TMS, Warrendale, 2000, pp. 505–514.

[42] M.Y. He, J.W. Hutchinson, Crack deflection at an interface between dissimilar elastic materials, Int. J. Solids Struct. 25 (1989) 1053–1066.

[43] M. Niiyama, N.G. Shankar, Fracture mechanics approaches to coating strength evaluation, Engng Fract. Mech. 55 (1996) 235–248.

[44] R.H. Daussardt, M. Lane, N. Krishna, Adhesion and debonding of multi-layer thin film structures, Engng Fract. Mech. 61 (1998) 141–162.