CYCLIC FATIGUE CHARACTERISTICS OF 10%CR BLADE STEELS FOR ADVANCED STEAM TURBINE

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ABSTRACT

Modified 9 ~ 12%Cr ferritic steels have been used extensively as the structural materials at the temperature up to 600°C in thermal power plants. And also the steels are excellent candidate materials for the advanced steam turbine blades in high pressure and temperature. In this paper, the low cycle fatigue (LCF) and high cycle fatigue (HCF) characteristics of the high Cr steels (COST B2, DS2B2) in quenched and tempered conditions are presented. The steels were refined with the vacuum induction melting (VIM) furnace and/or electro slag remelting (ESR) process. From cyclic fatigue tests, it was known that fatigue life of DS2B2 was better than that of COST B2. HCF lives of two steels were almost same regardless of refining procedures. However, LCF characteristics of steels treated with VIM and ESR were better than those of steels treated with VIM only. It was estimated that these results were due to the reduction of harmful elements by ESR.

KEYWORDS

low cycle fatigue, high cycle fatigue, blade, advanced steam turbine, 9 ~ 12% Cr ferritic steel, electro slag remelting, vacuum induction melting

INTRODUCTION

Recently, to reduce the emissions of CO_2 and to increase the thermal efficiency, ultra-supercritical (USC) thermal power plant with the live steam temperature of 600°C or higher have been constructed. Turbine blade material has been improved continuously to be usable under the high temperature steam condition for its design life. Up to now, there are three candidate turbine blade materials such as COST B, COST E and TOS202 for steam temperature of 593°C. To improve the phase stability under long term high temperature and the creep strength, the authors have developed DS2B2 steel (11Cr1Mo1WCo) as the turbine blade material for USC thermal power plant.

Turbine blades are subjected to high cycle fatigue stress from turbine vibration and repeated thermal stress during start-up and shutdown procedures of thermal power plants. To verify the integrity against the fatigue damage under high temperature, it is necessary to evaluate the high and low cycle fatigue characteristics of the turbine blade materials. The objective of this paper is to evaluate fatigue life of new material, DS2B2 steel by comparing the fatigue characteristics between DS2B2 and COST B2 steels. Manufacture experience indicates that both low Si and low S are desirable by ESR[1]. In this paper, the effect of refining process on fatigue properties was discussed through comparing the fatigue characteristics between the material melted by VIM process only and the material refined by VIM furnace and ESR process.

1. EXPERIMENTAL PROCEDURE

Test materials, DS2B2 and COST B2 were refined by VIM furnace and/or ESR process, and then quenching and tempering for them were performed. Table 1 shows the chemical compositions of the test materials, where the VIM corresponds to the material refined by VIM process only and the ESR corresponds to the material refined by VIM and ESR process. DS2B2 contains 1% W and 1% Mo. Instead of adding W, more Mo of 1.5% was added to COST B2 based on the same Mo equivalent value (wt.% Mo + 1/2 wt.% W). The other elements of DS2B2 were adjusted to get the optimum physical properties required as the advanced steam turbine blade material

Table 1 Chemical compositions of test materials

Material		C	Cr	Mo	W	Co
DS2B2	ESR	0.14	10.80	0.99	1.06	0.86
	VIM	0.14	10.85	1.00	1.06	0.87
COST B2	ESR	0.17	9.53	1.50	0.04	0.17
	VIM	0.17	9.50	1.51	0.04	0.17

Strain-controlled low cycle fatigue (LCF) test was conducted using 10 ton servo-controlled hydraulic test machine with a box furnace at room temperature and 593°C. Total strain range was from 0.7 to 1.6% and from 0.5 to 1.0% for room temperature and 593 °C, respectively. Zero mean strain and a constant strain rate of 4 x 10^{-3}/sec were applied. The waveform of the strain cycle was triangular to simulate the fatigue history during operation of power plant. The fatigue life was defined as the cycle number corresponding to 20% drop of the peak stress of half life. Scanning electron microscope (SEM) analysis of the fractured surface and transmission electron microscope (TEM) analysis of the microstructure were performed.

High cycle fatigue (HCF) test was carried out under axial load control at room temperature and 593°C. Tensile stress amplitude was applied over the range from 50% to 80% of tensile strength. Fully reversed loading (R = -1), test frequency of 15Hz and sine waveform were adopted. S-N curve was obtained from the relation between applied stress amplitude and fatigue life. Fatigue limit was defined as maximum stress amplitude when specimen did not fail at 10^7cycles.

2. RESULTS AND DISCUSSION

2.1 LOW CYCLE FATIGUE CHARACTERISTICS

Fig. 1 shows LCF results of DS2B2 and COST B2 steels at room temperature. DS2B2 was superior to COST B2 at a low strain amplitude, whereas two steels were similar at a high strain amplitude in fatigue life. The comparison of VIM and ESR materials reveals that LCF characteristics of the materials treated by VIM and ESR were better than those of materials treated by VIM only. These results were due to the reduction of harmful elements such as sulfur and nonmetallic inclusions and small grain size enabled by the application of ESR.

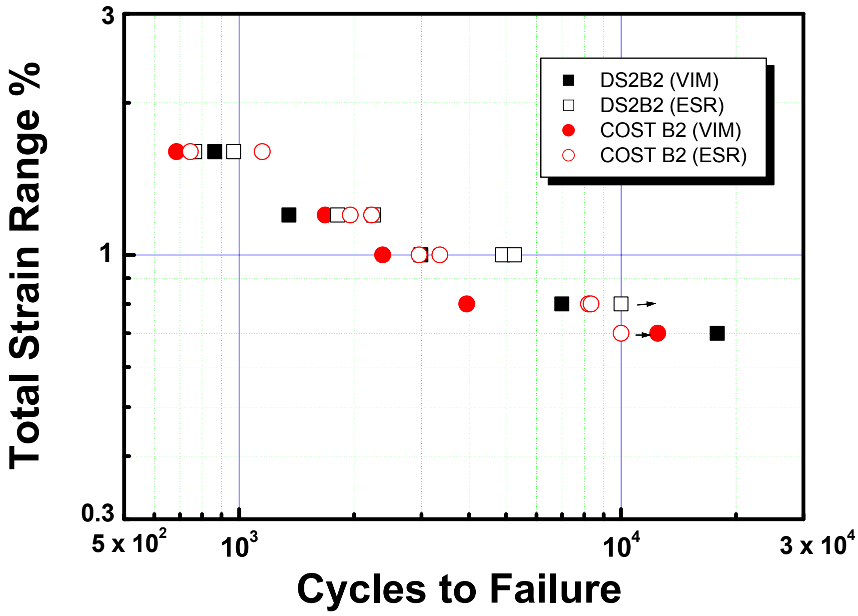


Fig. 1 Low cycle fatigue life of advanced steam turbine blade materials at room temperature

Fig. 2 illustrates the cyclic softening phenomena of BS2B2 and COST B2 steels at room temperature. The maximum stress dropped sharply after tens of cycles and then decreased slightly until specimen failure without stabilized stress region. COST B2 steel showed larger drop of the maximum stress at initial stage of cyclic loading than DS2B2 steel. It is reported that these softening phenomena resulted from the annihilation of dislocation during martensitic transformation and coarsening of precipitates [2,3]. Fig. 3 shows LCF results at 593°C for DS2B2 and COST B2 materials treated by ESR refining process. DS2B2 was superior to COST B2 at a low strain amplitude, whereas two steels were similar at a high strain amplitude in fatigue life as well as at room temperature.

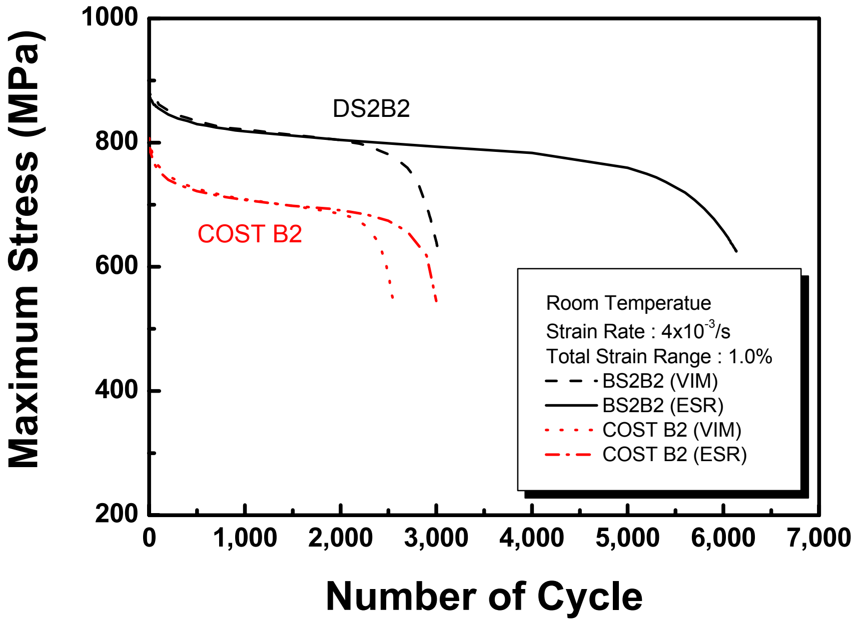


Fig. 2 The cyclic stress strain curve for DS2B2 and COST B2 steels

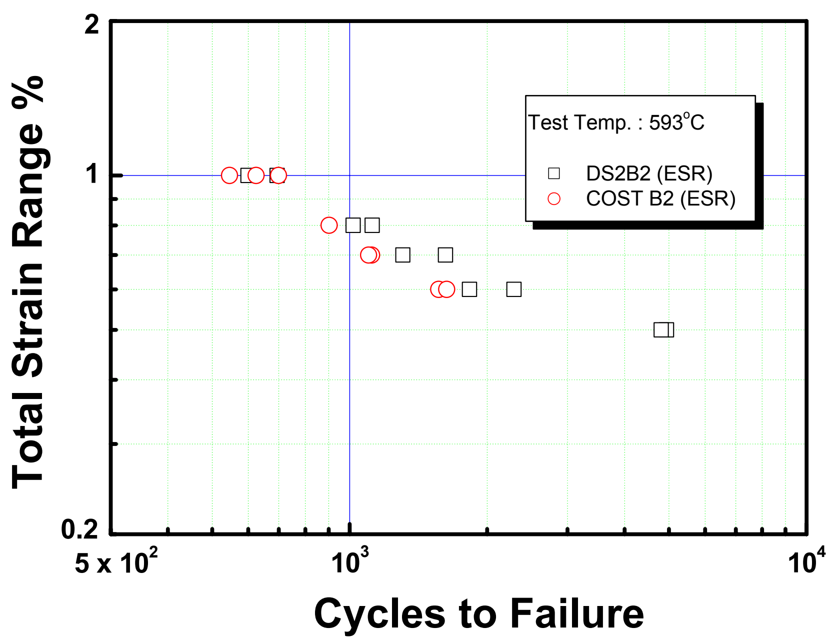
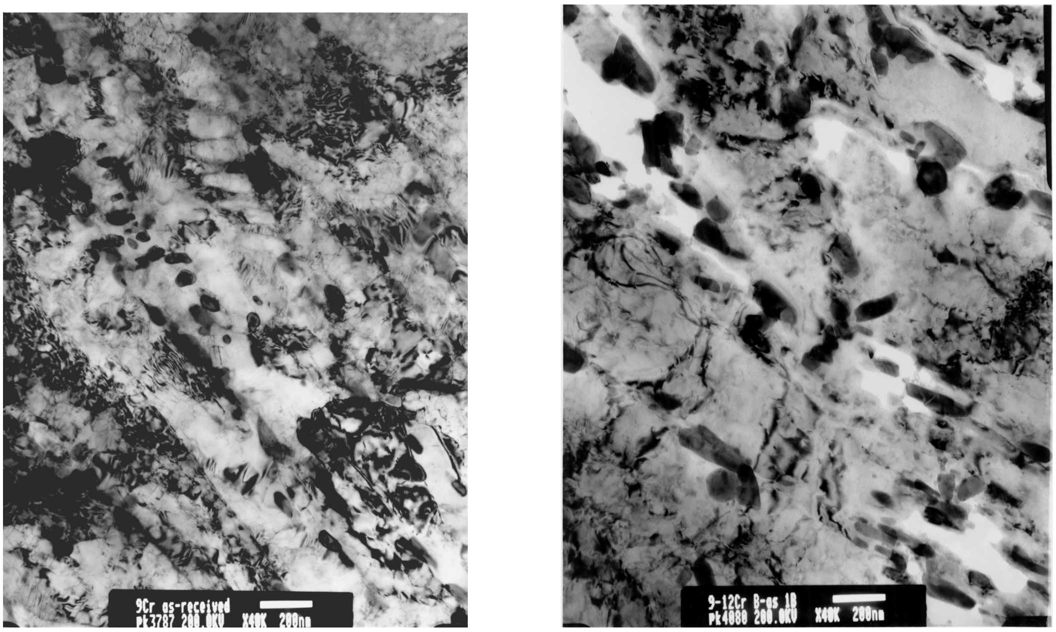


Fig. 3 Low cycle fatigue life of advanced steam turbine blade materials for ESR process at 593°C



(a) DS2B2　　　　(b) COST B2

Fig. 4 TEM micrographs as tempered state

Fig.4 illustrates TEM micrographs of tempered DS2B2 and COST B2 steels. Microstructures of the both materials showed a typical tempered martensitic structure having martensitic lath structure with high dislocation density. From the energy dispersive spectroscope (EDS) analysis results for the chemical composition of carbide, $M_{23}C_6$ carbides containing Cr, Mo and W for DS2B2 and $M_{23}C_6$ carbides containing Cr, Fe and Mo for COST B2 were distributed at prior-austenitic grain boundary and lath structure boundary. DS2B2 has smaller $M_{23}C_6$ carbides than ones of COST B2, it was due to the effect of carbide refinement by W. It is reported that the size of $M_{23}C_6$ precipitate decreased with the addition of W content for 9Cr steels[4]. In addition, it is known that coarse $M_{23}C_6$ carbide has a role of the fatigue crack initiation site[5]. In general, at a low strain amplitude, crack initiation period takes most of fatigue life at a high strain amplitude, crack growth period takes a great part of fatigue life. Therefore, at low strain amplitude, LCF life of DS2B2 with fine $M_{23}C_6$ carbide was longer than that of COST B2.

The strain-life relationship is given by the following equation proposed by Coffin-Manson and Basquin[6].

$$\frac{\Delta\varepsilon_t}{2} = \frac{\sigma_f'}{E}\left(2N_f\right)^b + \varepsilon_f'\left(2N_f\right)^c \quad (1)$$

where, $\Delta\varepsilon_t$ is the total strain range, $2N_f$ is the number of reversals to failure, E is the elastic modulus, σ_f' is the fatigue strength coefficient, ε_f' is the fatigue ductility coefficient, b is the fatigue strength exponent and c is the fatigue ductility exponent. The constants in Coffin-Manson

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and Basquin relationships, cyclic stress-strain relationship at room and elevated temperatures for DS2B2 and COST B2 materials are summarized in Table 2. According to the test results, the fatigue ductility exponent *c* was measured as about -0.7 for both materials. The half life cyclic stress-strain curve could be represented by the power law relationship.

$$\frac{\Delta\sigma}{2} = K'\left(\frac{\Delta\varepsilon_P}{2}\right)^{n'} \qquad (2)$$

where, $\Delta\varepsilon_P$, K' and n' are the plastic strain range, cyclic strain hardening coefficient and the cyclic strain hardening exponent, respectively. The value of cyclic strain hardening exponent n' is less than 0.1. Also, the values of n' at 593°C are less than those at room temperature.

Table 2 Constants in Coffin-Manson, Basquin relationships, cyclic stress-strain relationship of materials at room and elevated temperatures.

Temp. °C	Material		ε_f'	c	σ_f / E	b	K' MPa	n'
25	DS2B2	ESR	78.98	-0.728	0.624	-0.047	955.74	0.0646
		VIM	90.57	-0.708	0.563	-0.062	770.39	0.0838
	COST B2	ESR	29.27	-0.617	1.052	-0.120	1009.49	0.1222
		VIM	126.15	-0.800	0.698	-0.081	836.22	0.0838
593	DS2B2	ESR	19.04	-0.563	0.177	-0.029	305.43	0.0422
	COST B2	VIM	95.95	-0.784	0.185	-0.047	281.42	0.0452

Fig.5(a) and (b) show the SEM micrographs at the region of 0.5mm away from crack initiation site on fatigue fractured surface taken from ESR materials for the test condition of 0.8% total strain range and room temperature. For both fractographes, striations produced by cyclic loading were observed. The average widths of striation were 2.81μm and 4.40μm for DS2B2 and COST B2, respectively. It is reported that the longer fatigue life, the smaller striation width [7,8]. In case of applying the total strain range of 0.8% at room temperature for ESR material of COST B2, the fatigue life and the striation width were 8,220 cycles and 2.75μm, respectively (Fig.5(c)). For the total strain range of 1,0%, the fatigue life and the striation width were 2,696 cycles and 4.40μm, respectively as shown in Fig. 5(b). Small striation width indicates that crack propagation length per cyclic loading after crack initiation is small. Therefore, it is known that the material with excellent resistance for crack initiation has a good resistance for crack propagation.

As shown in Fig. 6, for the SEM micrographs of high temperature fatigue fractured surface taken from DS2B2 treated by ESR process, oxides were observed at the surface. It seems that the oxide

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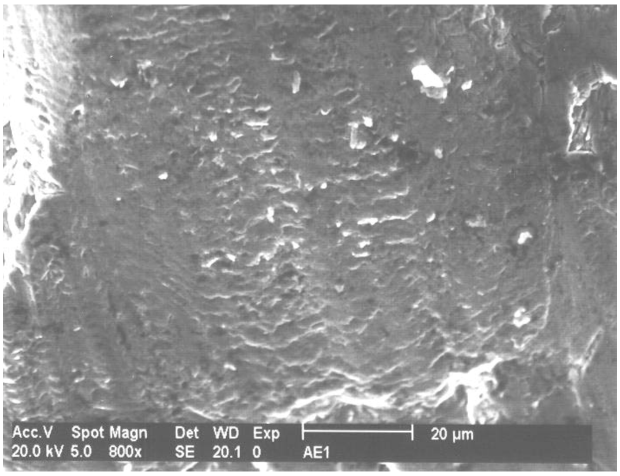
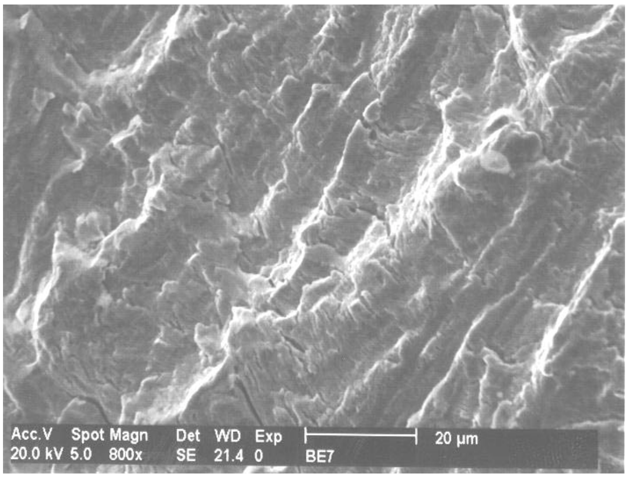
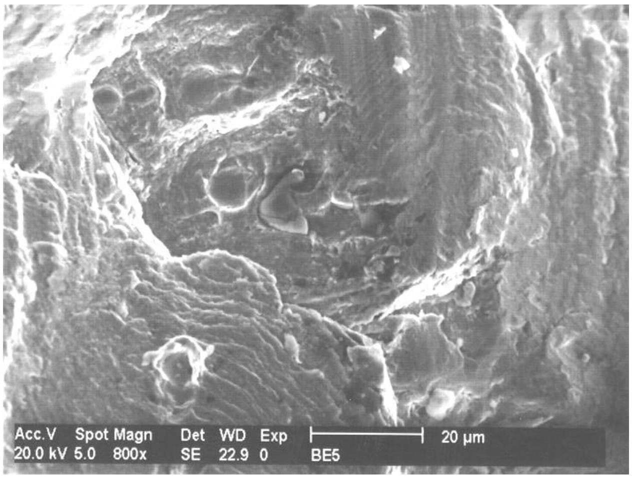
played a role of crack initiation site. J.C.Earthman[9] suggested that oxidation attack at the surface grain boundaries is a dominant corrosive process which can reduce the life of ferritic steels under high temperature LCF conditions. Therefore, it is known that the high temperature LCF life could be reduced due to the oxidation.



(a) ESR, DS2B2, $\Delta\varepsilon_t = 1.0\%$



(b) ESR, COST B2, $\Delta\varepsilon_t = 1.0\%$



(c) ESR, COST B2, $\Delta\varepsilon_t = 0.8\%$

Fig. 5 SEM micrograph of fatigue fractured surface

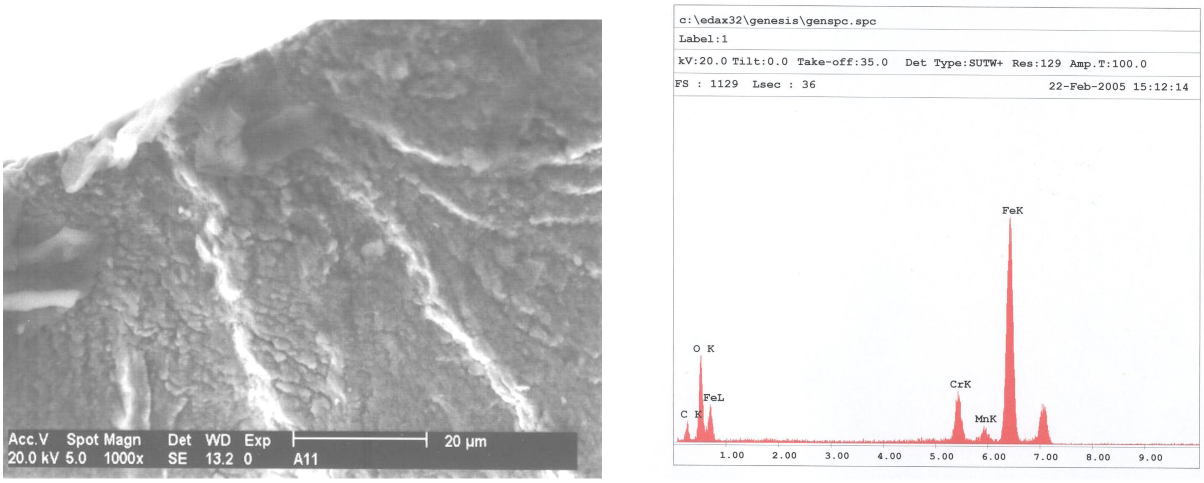


Fig. 6 Optical micrograph showing oxide layer at crack initiate site after fatigue test at 593^{o}C

2.2 HIGH CYCLE FATIGUE CHARACTERISTICS

Fig. 7 and 8 show HCF results for DS2B2 and COST B2 materials at room and elevated temperatures, respectively. HCF characteristic of DS2B2 was superior to that of COST B2. However, the HCF lives of both steels were almost same regardless of refining processes as shown in Fig. 7. In general, the higher strength, the superior HCF characteristics. The reason of the more excellent HCF characteristics of DS2B2 was the higher tensile strength than that of COST B2. It seems that the higher strength of DS2B2 was caused from the hardening induced by fine precipitates in high W steels as well as precipitation hardening by Cr.

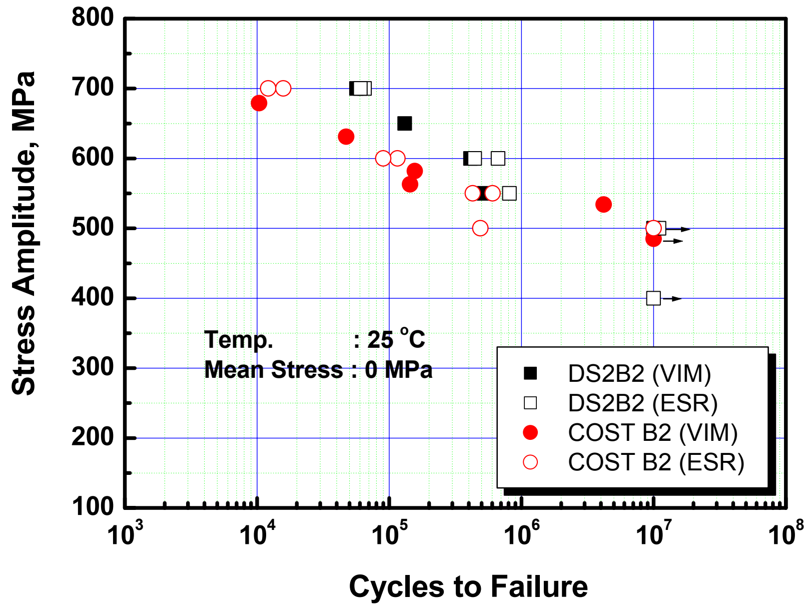


Fig. 7 High cycle fatigue life of advanced steam turbine blade materials at room temperature

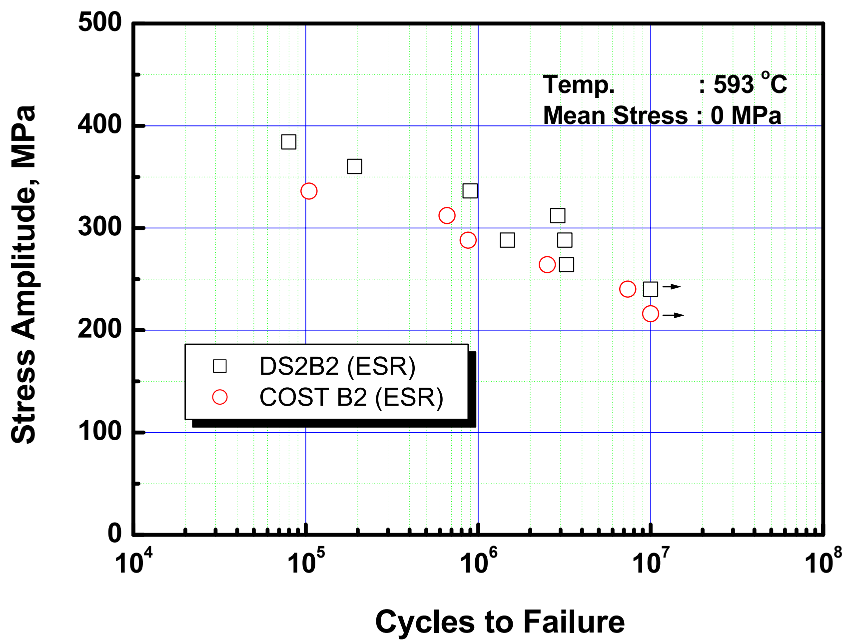


Fig. 8 High cycle fatigue life of advanced steam turbine blade materials for ESR process at 593°C

3. CONCULSIONS

(1) For LCF characteristics, DS2B2 was superior to COST B2 at a low strain amplitude, whereas two steels were similar at a high strain amplitude in fatigue life. It seems that DS2B2 has smaller $M_{23}C_6$ carbides than COST B2.

(2) LCF characteristics of the materials treated by VIM and ESR were better than those treated by VIM only. These results were due to the reduction of harmful elements such as sulfur and nonmetallic inclusions and small grain size enabled by the application of ESR.

(3) HCF characteristic of DS2B2 was superior to that of COST B2 since the higher strength of DS2B2 was caused from the hardening induced by fine precipitates in high W steels as well as precipitation hardening by Cr.

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