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Evaluation of fatigue resistance of a gradient CrN_x coating applied to turbine blades

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ABSTRACT

In order to protect metallic materials from solid particle erosion, the gradient CrN_x ceramic coatings with thickness ranging from 32 to 40 μm were deposited on the 10%Cr heat-resistant steel using a hybrid deposition system. The fatigue tests were conducted under three-point bending at a stress ratio of 0.1. The *S–N* curves of the substrate and coated CrN_x specimens were obtained. SEM observations on the fracture surfaces of the fatigue specimens were carried out. The results have indicated that the gradient CrN_x coating increased the fatigue life of the substrate at low stresses and increased the fatigue limit by 9.1% due to the strengthening effect of coating. Whereas at high stresses, it decreased the fatigue life of the substrate and widened the scatter bands of fatigue life compared to the substrate because of the relatively high notch sensitivity (droplets on the coating). The fracture analysis for the coated specimens has shown that the fatigue cracks nucleated on the surface and propagated towards the substrate.

1. Introduction

Solid particle erosion (S.P.E.) of the inner walls of steam pipelines is a major concern for the steam turbines. This is mainly because the solid particles (an oxide of iron) from the inner walls of furnace tubes and main steam pipes after long time operation are pushed into the steam turbines along with the steams and thus erode the internal valves, nozzles and rotor blades. What is mentioned above has led to a serious reduction of steam efficiency and cumulative fatigue damages of in-service components. Many research papers have proposed that a valid method for addressing the degradation is to adopt erosion-resistant coating such as boronizing, thermal spraying WC–Co/Ni, NiCr and NiCr–CrC coatings, etc. [1–5]. However, it is extremely difficult to boronize the complicated steam turbine blades, and sprayed coatings have numerous defects such as microcracks, porosity, etc. Thus, ceramic coating materials are expected to have high erosion and heat resistance.

CrN coatings, which exhibit high hardness, superior wear resistance, excellent corrosion resistance and good oxidation resistance, have been extensively used as protective coatings on various tools and dies [6]. Considerable research reports have been carried out to investigate the wear and corrosion resistance of CrN coatings [7–10]. However, the study of influence of CrN coatings on fatigue property of the substrate is by far very limited.

Gelfia et al. [11] have deposited a CrN coating with a thickness of 5 μm on H 11 tool steel by PVD technique and examined the compressive stress distribution in the coating and the substrate. In a subsequent fatigue investigation, it showed the fatigue cracks nucleated at the inclusions remained in the substrate. The nucleation sites were considerably associated with the distribution of residual stress and far away from the high compressive stress zone.

Baragetti et al. [12,13] have studied the fatigue resistance of a CrN coating deposited by PVD on a 2205 duplex stainless steel substrate by means of four-point bending tests. The effect of substrate preparation (rolling, polishing and shot peening plus polishing) was also evaluated in terms of both surface residual stress data and fatigue behavior. The fatigue tests revealed that the fatigue resistance of steel substrate was improved by the application of CrN coating. It was concluded that the most important parameter, affecting the enhancement of the fatigue resistance of coated specimens, was the compressive surface residual stress field induced by PVD coatings. Such high values of surface residual stress, even in the presence of surface defects (large droplets), prevented any surface microcrack from propagating.

Lecis et al. [14] have studied the effect of a Cr (C, N) PVD coating on the fatigue behavior of quenched and tempered 42CrMo4 steel, and the results indicated that a distribution of a compressive residual stress near the surface increased the fatigue life of the steel. The nucleation site of the fatigue cracks was strongly dependent on the residual stress profile.

Oka et al. [15] have investigated a ceramic coating of ion plated CrN with a sublayer of plasma nitride on a martensitic stainless steel. Fatigue tests of the CrN coating were conducted at room

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Table 1
Chemical composition of 2Cr10MoVNbN heat-resistant steel.

Element	C	Cr	Ni	Mo	V	Nb	N	Si	Mn	Fe
wt.%	0.19	10.8	0.4	1.0	0.17	0.41	0.06	0.55	0.58	Balance

Table 2
Mechanical properties of 2Cr10MoVNbN heat-resistant steel.

Yield strength ($\sigma_{0.2}$)	Ultimate tensile strength (σ_b)	Elongation (δ)	Reduction of area (ψ)	Toughness (A_{KV})	Hardness (HB)
810 MPa	965 MPa	18%	52.5%	48.3 J	293

temperature and 723 K, respectively. The results indicated that the fatigue resistance of the martensitic stainless steel was definitely improved by the application of a CrN coating material. The initiation and propagation of a crack did not necessarily occur from the notches, and solid particle impact or erosion limited within the thickness of the CrN coating did not decrease fatigue life.

The experimental results discussed above come to a conclusion that the residual stress in a deposited coating may play a significant role in affecting the fatigue life of substrate materials and the nucleation sites of cracks, whereas the morphology and defects in a deposited coating surface have a relatively slight effect. In addition, the thickness of the CrN coatings investigated is less than 10 μm.

The present investigation has been conducted in order to study the effect of a gradient CrN_x coating deposited by ion plating technique on fatigue properties of the 10%Cr heat-resistant steel. The thickness of the CrN_x coatings is approximately 32–40 μm. The work is first done by the analysis of the coated microstructure, mechanical characterization and residual stress distribution. The *S–N* curves for the coated and uncoated specimens are plotted and compared. In addition, the nucleation and propagation mechanism of fatigue cracks are also interpreted for the gradient CrN_x coating.

2. Experimental techniques

The base material used in this study was 10%Cr heat-resistant steel. This material was used in steam turbine blades that would be subjected to solid particle erosion. The steel was forged after the electroslag remelting process. It was oil quenched at 1100 °C and tempered at 660 °C for 2 h in air. The chemical composition and mechanical properties were respectively listed in Tables 1 and 2. The CrN_x coating was deposited using a hybrid deposition system [16]. Prior to deposition, the substrate was degreased in acetone ultrasonically and dried out. To deposit CrN_x coating on the substrate steel with the equipment, they were placed in a vacuum chamber which was evacuated to pressure of 6×10^{-3} Pa. Subsequently it was cleaned by chromium ion sputtering with a bias voltage of approximate −1000 V for 10 min. Finally, a gradient CrN_x coating was deposited with a varied nitrogen partial pressure of 6×10^{-2} to 2×10^{-1} Pa and the bias voltage of approximate −200 V. The detail information of the equipment and the deposition method were described in the literature [16].

The gradient CrN_x coating with two transition-layers was deposited. The rich chromium transition layer accommodated the PVD CrN_x internal stresses and allowed thicker composite coatings to be produced with significant improvements in toughness, adhesion, impact resistance and corrosion resistance; however, the presence of a relatively thick Cr buffer layer often involved a significant reduction in strength and hardness of the PVD coating. To overcome these limitations, the rich nitrogen layer with a harder and stiffer feature was deposited, providing a better distribution of stresses and avoiding the inner nucleation of fatigue cracks in the CrN_x coating.

The phases variation along the cross-section of CrN_x coating was analyzed with low-angle X-ray diffraction (XRD, Panalytical X'pert PRO diffractometer) using Cu Kα radiation, as reported in Ref. [17]. The compositional profile of CrN_x coating was measured by using electron probe microanalysis (EPMA, Shimadzu, EPMA 1610). The microstructural evaluation of CrN_x coating was conducted by using SEM technique (SEM, CamScan MX 2600). The surface roughness of CrN_x coating was measured by using a TR-200 surface roughness tester. The residual stress distribution along the transverse section was determined by using an X-ray stress tester (X-350A) with Cr Kα radiation, and the registration of {2 1 1} diffraction lines in a 2θ range of 146–158°. The accuracy of the stress measurement was $\Delta\sigma = \pm 25$ MPa. In order to obtain the stress distribution by depth, the layers of specimens were removed by electrolytic polishing with a nonacid solution. Microhardness across the transverse section of coated specimens was measured through using a Nano-Indenter XP Tester with a Berkovich indenter at a load resolution of ±75 nN and displacement resolution of ±0.04 nm. The adhesion of coating with substrate was measured with the scratch method using a WS-92 apparatus (Make: China), equipped with diamond indenter type C Rockwell with radius of 0.2 mm at a loading rate of 100 N/min from 0 to 100 N. Parallel scratches (5 mm long for each specimen) were carried out by moving indenter at the speed of 5 mm/min.

Fatigue testing was done with reference to GB3075-82 (China standard). It was carried out under three-point bending condition (R = 0.1, loading frequency = 85 Hz, room temperature = 25 °C)

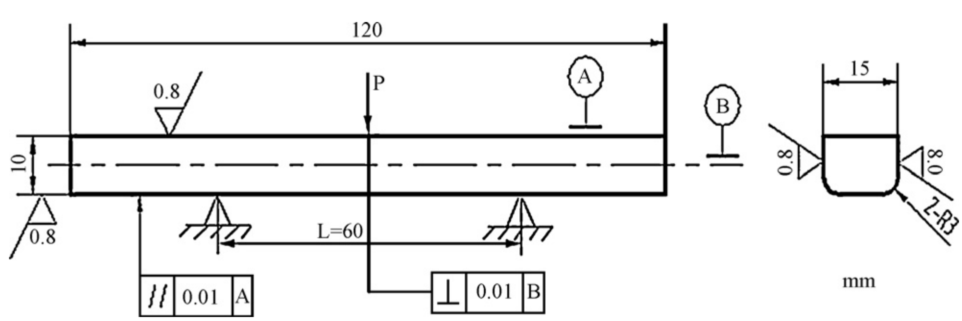

Fig. 1. A sketch with geometric dimensions under three-point bending conditions, where *F* represented the load applied on the specimens in N, *L* represented spacing of supports in mm.