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Study on the erosion characteristics of boride coatings by finite element analysis

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ABSTRACT

In this paper, tensile stress distribution in the surface of high-parameter steam turbine blade anti-erosion boride coatings under single particle impact was investigated using a nonlinear finite element software ABAQUS/explicit based on the actual erosion environment in power units. The results showed that the single Fe_2B phase coating hardly had stable anti-erosion capability when the coating thickness was less than 20 μm under the continuous impacts. For the bilayer boride coating composed of top phase FeB and bottom phase Fe_2B, the whole coating began to show the stable anti-erosion performance with top FeB phase coating thickness of 120 μm from the standpoint of maximum surface tensile stress reduction. Anti-erosion performance of single Fe_2B phase boride coating was 23.15% higher than the bilayer boride coating. Besides, the optimum parameters configurations for boride coatings were studied.

1. Introduction

For high parameter coal-fired generating units, iron oxide particles exfoliated from the boiler and pipeline system will flow into the turbine with steam and produce severe erosion damage to the cascade surface of these two stages, leading to lower unit efficiency and increasing maintenance costs [1–3]. Besides, under the comprehensive action of centrifugal force and high temperature, particles entering the turbine flow path would accumulate and stack on the inner surface of the blade shroud, which will not only change the through-flow characteristics of the unit, but also damage unit shaft balance, leading to serious accident. Therefore, how to effectively reduce or eliminate solid particle erosion damage of blades has been a core issue of turbomachinery.

In many cases, application of protective coatings on blades surface seems to be the most cost effective method to improve the erosion resistance for solving the SPE problem. The subject of erosion resistance coating has been extensively researched both theoretically and experimentally since at least the 1970s [1,3–13]. Lots of literature suggests that chromium carbide thermal spray coatings [3,10] and boride coatings [14,15] are effectively able to resist the erosion damage of blade profile for normal size of the iron oxide particles. Based on the systematic experimental studies on the erosion performance of various coatings in simulated steam turbine environments, Tabakoff [9,10,13] and Walsh [6,11] found the chromium carbide coating with high hardness demonstrated excellent erosion resistance at low impingement angles (smaller than 35°) in the tests, which was a good candidate for the strengthening of the turbine blade surface. B. S. Mann [14,15], J. Qureshi [4] and H. Kawagishi [5] considered that the boride coating was more recommended as a thermal diffusion coating with dense structure. Cai et al., [16] systematically investigated erosion characteristics of several typical anti-erosion coatings used in high parameter steam turbine cascade in the temperature range of 500–600 °C based on the high-temperature and high-speed accelerated erosion test system. Results showed that erosion resistance of several boride coatings were not identical. But the erosion rate was substantially less than supersonic chromium carbide coatings. Because of much larger surface hardness and dense degree, boride coatings were more appropriate than chromium carbide HVOF coatings as the protective coatings of turbine cascades. Therefore, as a widely used protective coating for turbine cascades, Investigation on the erosion mechanism and optimization of boride coatings is of great significance for guiding engineering application, which urgently needs further research. Due to the complexity of the erosion process, most researchers have analyzed the coating erosion mechanism only from the comparative test results and characteristics of the coating process, and the corresponding conclusions were not universal, and thus could not be the criterion to judge the merits of erosion

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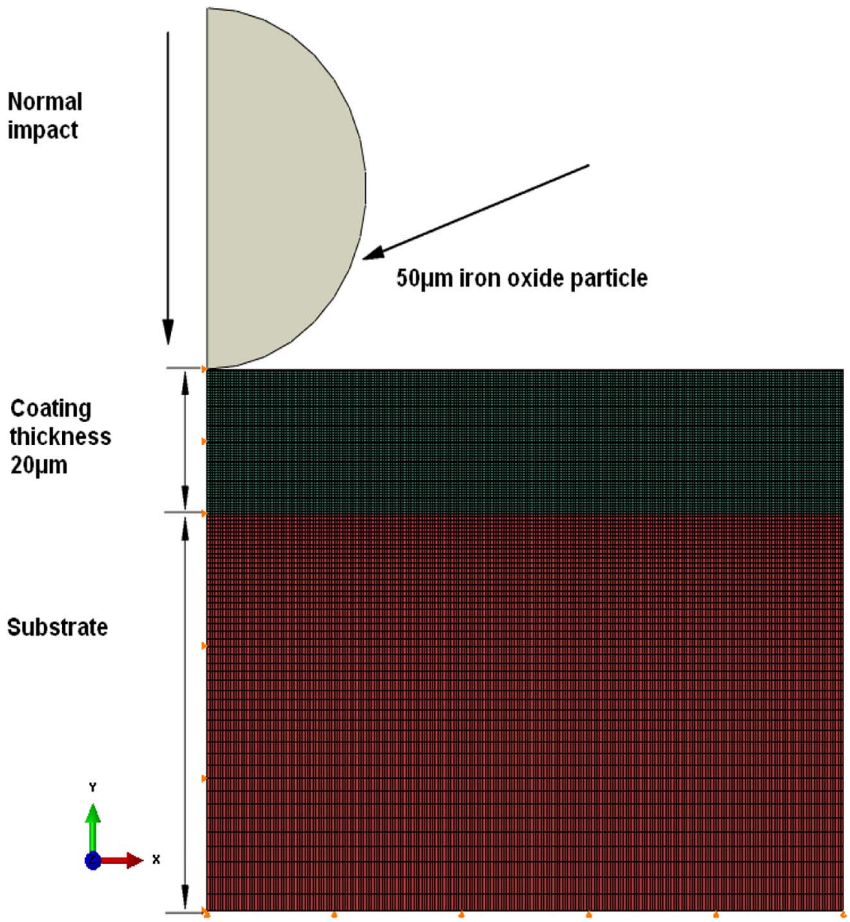

Fig. 1. Typical 2D axisymmetric FE model with fine mesh and boundary conditions used to investigate solid particle erosion of coated systems.

resistance [16]. In addition, the trial-and-error experiments are time consuming and costly.

Numerical simulation can well overcome the shortcomings and deficiencies of test methods, which has great advantages in terms of prevailing damage and failure mechanism research in the erosion process. Bielawski and Beres [17] investigated tensile stresses in the surface of single and multilayer TiN coatings under single particle impact by FE method. The results showed that the stress of the coating surface increased with decreasing coating thickness. Hassani [18] carried out a detailed erosion simulation for TiN coating used in gas turbine and aviation engines under the impact of 50 µm alumina particles with the velocity of 84 m/s by ABAQUS/explicit. The H^3/E^2 ratios showed to be suitable for ranking coatings in terms of erosion performance.

However, these studies did not consider the actual operating parameters of its real erosion conditions, such as the actual temperature and velocity corresponding to actual industrial erosion conditions. And, more important, due to the different forming mechanism and coating process of TiN coating (belonging to PVD or CVD coating) and boride coating (belonging to thermal diffusion coating), the mechanical parameters of boride coatings differ greatly from that of TiN coatings. What's more, TiN coating is generally deposited on a steel substrate using surface physical or chemical vapour deposition technologies (PVD or CVD). Such technologies determine that the thickness of the coatings is generally thin and hard. The thickness is usually in the range of several to dozens of microns. In most cases the thickness of TiN coating rarely exceeds 20 µm while the thickness of boride coating is relatively larger, general within the scope of dozens to hundreds of microns. Besides, according to different heat treatment process, boride coating is distinguished into single phase and duplex phases. The microstructure analysis indicates that single-phase boride coating is Fe_2B phase, and two-phase boride coating consists of top layer FeB coating and the bottom layer Fe_2B coating. The anti-erosion characteristics of the two materials are significantly different due to the different process parameters and mechanical properties. Therefore, the conclusions of TiN coating anti-erosion optimization cannot be directly applied to the boride coatings.

In this paper, the tensile stress distribution in the surface of high-parameter steam turbine blade erosion resistant boride coatings was investigated under single particle impact using a nonlinear finite element code ABAQUS/explicit based on the actual erosion environment in cascade. Combined with the existing test results, a detailed study was conducted to investigate the erosion characteristics and the optimum parameters for boride coating showing a stable anti-erosion performance. It is expected that the results may contribute to providing the theory basis for better understanding the erosion mechanism and will lay a foundation for optimizing the anti-erosion performance of boride coatings.

2. Modelling approach

The principal erosion mechanism for hard coatings is brittle fracture. Hard coatings have high compressive and relatively low tensile strengths. They can withstand relatively large compressive impact stresses, but are susceptible to failure at much lower amplitude of tensile stress due to the initiation and propagation of cracks [17]. The stresses that are produced by the impact are compressive in the vicinity of the coating-substrate interface and tensile at the top surface of the coating [19]. The cracking in the coating surface can be closely related to magnitude of the surface tensile stresses. Thus, coating response to a collision can be quantified by the magnitude of the tensile peak in the coating surface [17]. In the present model, the boride coating architecture was optimized from the viewpoint of minimizing the tensile