Measurement of Strain Distribution in Thermal Barrier Coating using Hard X-rays

The thermal efficiency of gas turbine engines increases with combustion temperature. Recently, the combustion temperature of gas turbine engines has become much higher than the melting point of their metallic parts, and their thermal efficiency has risen above 50%. A thermal barrier coating (TBC) enables such high-temperature combustion. Commonly, TBCs consist of a top coating and a bond coating as shown in Fig. 1. For the bond coating, NiCoCrAlY powders are plasma-sprayed on the substrate of a Ni-based superalloy. The top coating is made of plasma-sprayed zirconia, this ceramic top coating protects the components of the gas turbine engine from high-temperature damage. The molten zirconia collides with the substrate, flattens and solidifies suddenly, so that the top coating contains many pores and microcracks. The residual stress in the TBC is generated by many factors, such as the mismatch of thermal expansions between the top and bond coatings, thermally grown oxide (TGO) and interface roughness. Many types of residual stress promote the spallation of TBCs, and the spallation of the top coating results in the melt-down of the gas turbine engine. Therefore, the measurement of the spalling stress is very important for the improvement of coating technology.

A distribution of the residual stress in the TBC has been analyzed using computer simulations because there is no method of measuring the internal stress nondestructively. The residual stress can be measured with conventional X-rays. The energy of the X-rays, however, is low and its penetration depth is very shallow, for example the penetration depth of Cr-Kα is 3 μm for zirconia. Only the in-plane stress, σ_1, is measured with low-energy X-rays. A $2\theta-\sin^2\psi$ method is used for measuring the in-plane stress [1]. ψ is the angle between the normal direction to the surface of a specimen and the diffraction plane. The shift in the diffraction angle, 2θ, is proportional to the stress, therefore, the in-plane stress, σ_1, can be calculated from the gradient of the $2\theta-\sin^2\psi$ diagram.

On the other hand, high-energy synchrotron X-rays have a large penetration depth, so that diffractions with high-energy X-rays contain the diffraction from a deep position. Therefore, the residual stress near the interface between the top and the bond coating can be measured with high energy X-rays. In particular, it is noted that the out-of-plane stress, $\sigma_1-\sigma_3$, can be measured by the $\sin^2\psi$ method with high energy X-rays. Low-energy X-rays are used for the measurement of the in-plane stress, σ_1, and also high-energy X-rays are used for the measurement of the out-of-plane stress, $\sigma_1-\sigma_3$. From the results measured with low and high-energy X-rays, the spalling stress, σ_3, can be estimated. This method is called the hybrid method.

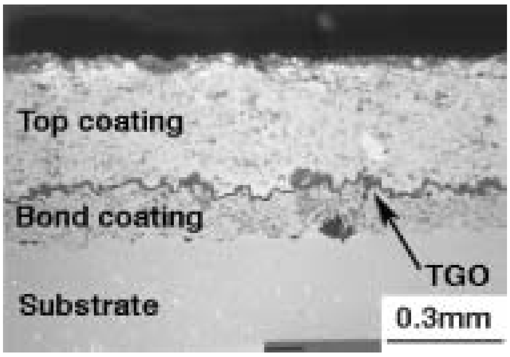

Fig. 1. Cross section of TBC with exposure at 1373 K for 1000 h. TGO is thermally grown oxide and promotes the spallation of the top coating.

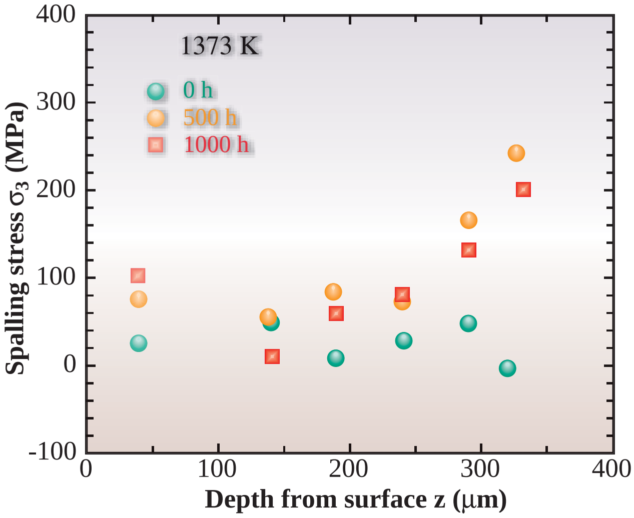

Fig. 2. Distribution of spalling stress evaluated by hybrid method. Specimens were exposed in atmosphere at 1373 K for 0, 500 and 1000 h. Thickness of top coating is approximately 350 μm.

Figure 2 shows the distribution of the spalling stress using the hybrid method. The spalling stress in the top coating with exposure time 0 h is small from the surface to the interface between the top and bond coatings. The spalling stress with oxidization is small beneath the surface but increases steeply near the interface. Actually, a spalling crack is initiated near the interface. The distribution of the spalling stress estimated by the hybrid method corresponds to the phenomenon of the spallation of the oxidized TBCs. Comparing the spalling stress oxidized TBC with non-oxidized TBC, the TGO promotes the spallation of the top coating. The convex part of the bond coating was more oxidized as shown in Fig. 1. The roughness of the bond coating creates the adhesion effect of the top coating but promotes the spalling stress and the non-uniform growth of the TGO. It is very important to control the TGO and the interface roughness. The TGO does not grow uniformly and the undulation of the interface between the top and the bond coating complicates the stress state. The measurement of the spalling stress is very important to evaluate the spallation.

The hybrid method is very useful for measuring the spalling stress of the TBC. However, a long experimental time is required because many specimens with surface removal have to be prepared and measured by the $\sin^2\psi$ method. Since the experimental shift in the synchrotron radiation facility is limited, it is necessary to reduce the experimental time. Therefore, a strain scanning method is expected as a method of speeding up the experiment.

Figure 3 illustrates the optics of the strain scanning method. As shown in the figure, a gauge volume is determined by the divergent and receiving slits. The position of the gauge volume is scanned by moving the sample stage. The distribution of the strain is evaluated by the shift in diffraction angle.

In our previous experiment by the strain scanning method, the measured peak angle shifted with the increase in the depth of the gauge volume. This was caused by interfering with the gauge volume with the surface of the TBC. In order to solve this problem, strict collimation is made by attaching an analyzer in front of the counter, and the correct strain can be obtained. LiF (200), Ge (111) and Cu (111) analyzers were examined for the strain scanning method. As a result, the LiF analyzer is the most suitable for the strain scanning method. The Ge analyzer showed a strict collimation but reduced the diffraction intensity. The Cu analyzer did not have a good collimation and the peak shift appeared. The LiF analyzer, however, had a deep penetration depth for high-energy X-ray, so that it was difficult to adjust the LiF analyzer. The strain scanning method will be established by improving the mount of the LiF analyzer. The out-of-plane strain can be measured by a reflection configuration as shown in Fig. 3, and also a transmission configuration is needed for measuring the in-plane strain, therefore, very high brightness is an advantage, i.e., an undulator.

Recently, large-penetration-depth and high-brightness hard synchrotron radiation X-rays have been highlighted and an international workshop on hard synchrotron X-rays for texture and strain analysis was held [2]. It is useful to apply high-energy synchrotron X-rays to strain analysis. To make a standard for measuring the stress with high-energy synchrotron X-rays, a new project was started by VAMAS-TWA20 [3]. Japan has been requested to cooperate in this project as a member.

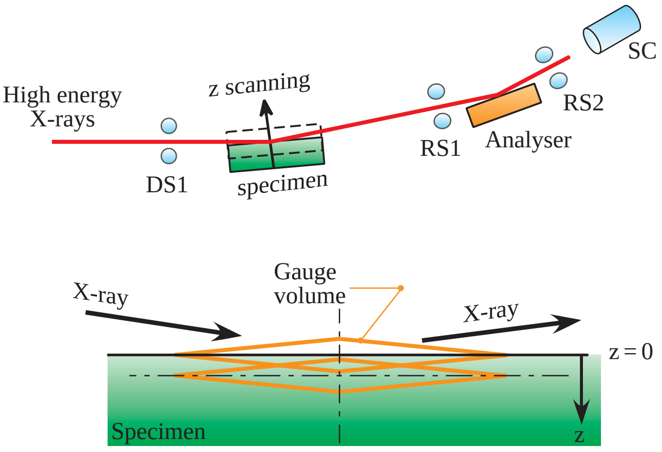

Fig. 3. Optics for strain scanning method and gauge volume. Strain distribution can be measured by scanning the sample stage.

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[3] http://www.vamas.org/