Damage Detection of Thermal Barrier Coating by Ultrasonic Guided Wave

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Abstract. Nondestructive testing (NDT) of damage in thermal barrier coating (TBC) has received a wide attention for the inspection of aeronautic blade. Use of the ceramic material on top-coat which contains high temperature resistance, corrosion resistance and low thermal conductivity improve the ability to resist high temperature and corrosion of the metallic substrate. The bonding layer, however, is a source of weakness while has the beneficial effect of protecting the base. In this work, various forms of damage in bonding layer between nickel base and ceramic coating are investigated. Different shapes, sizes, positions and quantities of flaws are studied with the simulation of different detrimental reaction occurred in bonding layer. The dispersive characteristics of guided wave propagation in TBC is analyzed using finite element modeling (FEM) to simulate its propagation and scattering. Both time and frequency domain are conducted to study the change in different occasions. The aim is to verify if NDT can detect the damage in TBC with different sensitivity of various acoustic parameters to different types of flaws. Selections of appropriate acoustic parameters for quantitatively nondestructive test and evaluation, as well as location of thermal barrier coating defects are discussed.

1. Introduction
It is a direct method to increase the thrust-weight ratio in the modern aero engines in order to improve the flight speed of aircraft, which means the turbine inlet temperature will be further increased. Some researches show the temperature of the turbine inlet would increase to 1773 K when the thrust-weight ratio reach 10[1]. However, the most advanced material used in the production of turbine blades is nickel based alloys, and its maximum operating temperature is only around 1473 K[2], which is far from the working temperature. The thermal barrier coating is a quick and efficient method to protect turbine blades both from high temperature and strongly oxidizing environment and enables blades operate at higher temperature [3]. The use of TBC not only can prolong the service life of blade, but also can reduce fuel consumption, so as to improve the efficiency of the turbine engine [4]. At the same time, turbine blades are subjected to thousands of alternating hot and cold cycles due to the special and poor working condition. TBC is composed of layers of different materials of which the physical properties are variant and this would result to cracks and pore space. The TBC would desquamate with the growth of cracks, which is a serious threat to the safe use of the blades [5]. However, it is difficult to find the cracks inside the TBC.
Consequently, there is a demand to develop nondestructive testing method to test the TBC of turbine blades to identify the defects caused by oxidation or fatigue in advance. L Lin [6] have proposed high-intensity pulsed ion beam (HIPIB) irradiation to evaluate the velocity and other characteristic of ZrO2-7%Y2O3 coatings. Acoustic emission and thermography have been studied by D Nies [7] to detect damage in the coating. However, these methods are difficult to detect small or invisible damage. Therefore, Lamb wave is a promising technique due to its high sensitivity to defects [8].

The key problem associated with evaluation of characteristics of TBC by propagating Lamb wave is that the working environment of engine blades are uncontrolled and the shape of them are complicated. Finite element method (FEM) is regarded as an ideal efficient method for Lamb wave evaluation of TBCs [9].

In this paper, ultrasonic Lamb wave has been used to test defects inside the TBC. Firstly, the finite element model has been established firstly to simulate the TBC on a turbine blade. Then appropriate modes of Lamb waves have been selected. Thirdly, the signal of Lamb wave propagating in TBC has been collected. The attenuation, velocity and frequency characteristic which is analyzed by fast Fourier transfer (FFT) method have been researched.

2. Model establishment of thermal barrier coating

Thermal barrier coatings have three major forms, double, multi-layers and gradient [1]. However, only the simplest form of a double TBC structure gained practical application at current situation. The two-layer TBC structures are consisted of ceramic insulation on the top and the metal bonding layers, under which is the protected nickel base alloy matrix, as shown in Figure 1.

![Figure 1. Two-layer thermal barrier coating structure](image)

The thickness of TBC is generally 200 to 300μm and its main function is heat insulation, corrosion, erosion and erosion protection. The metal bonding layer is 100μm, the function of which is to prevent the base from oxidization and corrosion and improve the quality of bonding by creating a rough surface between the ceramic coating and the base. The bonding layer may also be added to provide a cushioning effect due to the large gap between the thermal expansion coefficients of the substrate and the ceramic coating at the same time. Physical properties of TBC layers and metal substrate are listed in Table 1 [10].

| Material                         | E(kg/mm²) | µ     | ρ(kg/mm³) | σ       |
|----------------------------------|-----------|-------|-----------|---------|
| Ceramics (ZrO₂ + 8%Y₂O₃)        | 2.8 × 10⁴ | 0.25  | 5.61 × 10⁻⁶ | 5.56 × 10⁻⁶ |
| Bonding layer (Cr-Ni-Al-Zr)      | 1.4 × 10⁴ | 0.25  | 6.91 × 10⁻⁶ | 8.41 × 10⁻⁶ |
| Nickel base alloy matrix         | 1.79 × 10⁴ | 0.25  | 7.73 × 10⁻⁶ | 7.73 × 10⁻⁶ |
In summary, the 2-D model of two-layer plate structure is established to simulate TBC sectional by ABAQUS as shown in Figure 2. In this specimen, the substrate is a 3mm high temperature nickel-based alloys, the ceramic top-coat is 0.2mm and the bond-coat is 0.1mm. The total length of the specimen is 600mm.

![Figure 2. Schematic model of a two-dimensional of two–layer structure of TBC](image)

Under actual conditions, forms of defects of TBC are various, and it is difficult to exhaustive list situation to simulate. In this work, Different shapes and the changing nature of bonding layer are discussed in simulation. different shapes of defects are shown in Figure 3. The central of defects are at -50mm from origin. The changing nature of bonding layer is achieved by reducing the elastic modulus, which is -10% -20% -30% and -40%, respectively.

![Figure 3. Different shapes and width of defects](image)

3. Mode selection
According to physical properties of TBC, phase velocity dispersion curves of TBC are calculated as shown in Figure 4. Considering that A0 mode Lamb waves propagate mainly on surface in plate structure, which make it more sensitive to defects in the surface of specimen. Defects of thermal barrier coating are mainly in the metal bonding layer, only 0.2mm from the surface, so the A0 mode which is more sensitive to surface defects is a feasible selection. In addition, in order to suppress the generation of other modes, the frequency should be as small as possible, but as the frequency decreases, the wavelength increases, which will reduce the detection accuracy. Taking into account the above factors, the A0 mode at 0.385MHz is selected as shown in Figure 4.

The excitation diagram of Lamb wave is shown in Figure 5. The starting point for guided wave excitation is set at -200mm. Five boundaries with a spacing of 6 mm are used to load stress from the starting point to excite the selected mode. Guided wave excitation signal in this way is mainly A0 mode Lamb waves, of which the wavelength is 6mm and the number of cycles is 10. Signals from the excitation region to the left and right sides of the spread at the same time as shown in Figure 6.

In Figure 7, this is the time-domain signal received at reception point at 0mm, which is the excited Lamb wave propagating in thermal barrier coating. It is shown that with increase of time of propagation
or displacement of propagation, the amplitude of Lamb wave signal has decreased and the wave packet widens, a characteristic parameter called attenuation coefficient $\alpha$ is introduced to quantitatively describe the attenuation characteristics. The attenuation coefficient is as follows:

$$\alpha = \ln \left( \frac{A_0}{A_1} \right) \frac{(x_1 - x_0)}{L}$$

Figure 4. Phase velocity of Lamb wave in TBC

Figure 5. Schematic of excitation of Lamb wave with finite element simulation software.

Figure 6. Excitation signal of Lamb wave with finite element simulation software.

Where $A_1$ and $A_2$ are the amplitude at $x_1$ and $x_2$. Attenuation coefficient was calculated using the amplitude peak of wave A and wave B in Figure 7, where $\alpha = 0.1807 m^{-1}$.

4. Results and discussion

4.1. Shape of defects

Attenuation coefficients of four different shapes of defects were calculated by formula (1), as shown in Figure 8. Attenuation coefficients of arc-shaped and expanded defects are 3 times when there is no
defect. The amplitude of crack and rectangle defect were almost the same with no defect one, while the arc-shaped and expanded significant reduced. Those two types of defects caused badly attenuation, which resulted in dispersion and loss of energy. The result indicates that the arc-shaped and expanded defects are sensitive to the selected Lamb wave mode while cracks and rectangular defect are almost no reaction.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure7.png}
\caption{Time-domain signal at the origin}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure8.png}
\caption{Attenuation coefficients of different shapes of defects in time domain}
\end{figure}

4.2. Changing nature of bonding layer
Figure 9 show that the group velocity of Lamb wave changed obviously to different Modulus of Elasticity, as can be seen, with the increase recession of Modulus of Elasticity, the group velocity of Lamb wave decreases linearly. In this case, the recession of Modulus of Elasticity can be calculated by current group velocity.

5. Conclusion
The objective of this investigation is to evaluate Lamb wave propagation through thermal barrier coating. The study simplified the turbine blades into thin plates since it complex shape to reduce the difficulty of simulation in ideal situation.
Lamb wave is most sensitive to the arc-shaped and expanded defects, which are half wavelength long. However, small flaws are difficult to detect. The group velocity of Lamb wave decreased linearly when modulus of elasticity decreased.

All these data were resulted from simulation, which are supposed to provide a reference to later experiments. Furthermore, the conclusion of this investigation is not only directed against TBC, but also for most thin film coated.

![Group velocity to different recession of Modulus of Elasticity.](image)

**Figure 9.** Group velocity to different recession of Modulus of Elasticity.

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