Experimental study of the vibration fatigue for beam with hard coating damping treatment

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ABSTRACT

The hard coating material, with its superior advantages to temperature and corrosion resistance, is an ideal material for controlling the vibration of structures duo to its high capacity to dissipate vibration energy. The hard coating material has been widely used in the aerospace field. In this paper, the vibration fatigue properties of beam with hard coating damping treatment are investigated further. An experiment is conducted to obtain the vibration fatigue mechanism of the hard coating beam, in which the vibration fatigue life of beam are measured under bending and local resonance condition. The vibration excitation is produced by the shaker driven by an amplified signal from vibration controller. Moreover, based on the finite element fatigue analysis software ANSYS nCode Designlife, the vibration fatigue simulation analysis is carried out, and the influence of the vibration frequency, amplitude and various damping properties for the vibration fatigue life are all considered and compared. The results indicate that an appropriate selection hard coating parameters can obtain desirable damping properties and can improve the vibration fatigue life.

***Keywords*:**beam, vibration fatigue, experiment, hard coating damping

1. INTRODUCTION

With the rapid development of modern industry, the equipment of machine is moving towards high speed, high temperature and high pressure. So, the factors causing the failure of engineering structures are increasing, and the fatigue failure caused by vibration is one of the important factors. In the using process, many structures may be subjected to various dynamic loads. For example, the dynamic load of aircraft structure includes, Vibration and noise excitation of aircraft power plant, a variety of nonstationary aerodynamic effects, landing, taxiing ,the vibration and impact effect caused by certain ground motions, etc. These dynamic excitation may cause some structural parts of aircraft to produce violent vibration and fatigue failure，and even endanger the safety and reliability of the aircraft structure seriously.

The theoretical basis of structural vibration fatigue is mainly based on vibration theory, damage mechanics and fracture mechanics and so on. At present, there is no breakthrough in the dynamic nature of structural vibration fatigue, and the mechanism of vibration fatigue needs further study. In 1963, Crandall and Mark[1] described vibration fatigue for the first time as an irreversible vibration intensity damage with damage accumulation under vibration load excitation. Yao Qihang [2]thinks that vibration fatigue is a fatigue failure phenomenon caused by the structure of the resonance, it's caused by the structure of the dynamic alternating load(such as vibration, shock, noise load and so on) frequency distribution and the structure of the natural frequency distribution with the intersection. Sun Wei [3]thinks, when the vibration frequency and structural modal frequency are equivalent, it can be regarded as vibration fatigue problems. Although the gived definitions are not completely the same, it is believed that the structural vibration fatigue is closely related to the frequency of the load, the natural frequency of the structure, the magnitude of the alternating stress and the dynamic response of the structure to the cyclic load. That means, the vibration fatigue mainly refers to the dynamic characteristics of the structure, which has a significant effect on the load response and fatigue damage.

Hard coating is coating material made of a metal matrix and a ceramic substrate. It has high hardness, simultaneously, it can withstand high temperature, corrosion, vibration. It can be found from recent studies that hard coating has damping effect[4, 5], especially, it's suitable for power equipment in the thin shell structure(such as blades, cylindrical shells). A hard coat damping material is sprayed on the surface of the structural member, the method can significantly increase the component of the damping performance, improve the dynamic characteristics of component, raise the fatigue life of components. Hard coating material used in the research direction of damping vibration is emerging. Compared with the traditional viscoelastic coating, although the damping effect is inferior to viscoelastic coating material, the affected by the temperature is small. Related studies show that when the temperature is at least 400℃, the damping performance does not change. Therefore, it has been widely used in aviation, aerospace and other fields.

At present, the hard coating damping material mentioned in the relevant literature mainly includes Sn-Cr-MgO[4], $MgO+Al_2O_3$[6] , NiCrAlY[8], nano-ZrO_2[9] ,etc. There are many factors that affect the fatigue life, such as damping, loading frequency, working environment, material essence, etc.At present, the influence of various factors on the fatigue life is studied, however, there is little research on the effect of vibration fatigue life, especially, the influence of damping and other dynamic characteristics on the vibration fatigue life has not been studied. Because the failure rate of the typical thin-walled structures such as aeroengine compressor blades that is caused by vibration fatigue is high, it is of great significance to improve the vibration fatigue life of thin walled components by damping coating. In this paper, the beam coated with NiCrAlY hard coating on single face is taken as the research object, the vibration fatigue test was carried out by using the basic vibration excitation method, the vibration fatigue life of cantilever beam was calculated and compared, this paper analyzes the vibration fatigue characteristics of hard coating damping beam, the vibration fatigue mechanism of hard coated damping plate is studied.

2. DAMPING MECHANISM AND FAILURE MECHANISM OF THE HARD COATING

2.1. Damping mechanism of hard coating

Differences from the soft organic polymer coating, hard coating usually refers to the metal-based and ceramic-based coating, which are mainly used in the mechanical structure of the high temperature resistance (thermal barrier coating), friction resistance, erosion resistance, resistance to vibration (damping coating) etc. In recent years, the using of hard coating to improve the damping ability of components, to improve the dynamic characteristics of structures are effective, so that was paid great attention to. Using hard coating (especially damping coating) can effectively avoid the key structure early fatigue caused by vibration, as well as to improve the surface quality, and effective resistance caused by foreign object impact, wear and erosion, etc. Hard coating has damping vibration reduction effect are found from the experimental phenomena. For a long time. For hard coating principle experiment, the researchers conducted a large number of experimental studies for a long time, and from the before and after the coating structure of the inherent frequency and modal vibration mode, damping coefficient, strain, stress, vibration fatigue life on the parameters, such as research, found the hard coating has some unique mechanics phenomenon. Hard coating has played a unique role in many important occasions, and it is currently the focus of the international research about materials and engineering disciplines, and mechanics, mechanical and other fields.

The damping mechanism of hard coating is derived from the internal friction between the coating particles. Researchers at the university of Sheffield and Rolls-Royce verified by experimental test the correctness of the vibration reduction mechanism of hard coating.Through the experiment, found that magnesium aluminate spinel coating energy dissipation from the friction between the powder particles. Through a lot of analysis and theoretical calculation on the damping behavior of different types of materials research, the damping mechanism of metal matrix composites can be roughly divided into the following kinds: point defect damping, dislocation damping, grain boundary (or phase boundary) damping, etc., which is the main source of damping metal base material[10]. Crystal point defect refers to a certain atom displacement or vacancy, crystal lost the integrity of the original and symmetry of the crystal. Point defect caused a contributed to the need for redistribution is material damping[11]. Dislocation damping is the main source of damping of most metal materials and metal matrix composites. Dislocation damping mechanism is due to the dislocation by other defects existing in the crystal, lead to dislocation motion lag the applied stress[12]. Most of the metal crystal grain boundary usually into irregular arrangement, With a viscosity under a certain temperature, and the viscosity of grain boundary sliding converting mechanical energy which affect by the internal force from external loading into heat energy, Damping friction which caused by the relative displacement of the face of the grain boundary combination will cause energy loss and contribution to damping[13] .In the production of composite materials, the ideal damping material can be got. The application of coating damping can change the damping characteristics of the material by using the above three ways. Thus changing the damping properties of the material.

2.2. The failure mechanism of hard coating

The factors causing the failure of the coating is very much. During the working life, it was integrated impact by mechanical, thermal, chemical and other aspects, that eventually leading to the failure of the coating peel. The factors that affect the failure of the coating can be summed up as geometric factors, material factors, load and environmental factors, time factors and other four aspects. The types of common coating failure are three types [14],such as surface wear, peeling layered failure. Under low stress, there is a large number of microscopic peeling and pitting phenomenon, in which the contact area of the surface of the coating. known as the coating surface wear failure. The surface of the coating has a certain degree of roughness, when the coating surface and its contact with the contact and interaction, the coating surface due to local deformation or contact area micro-slip and wear debris into the contact area caused by wear. Coating flaking is one of the typical failure modes of coating failure due to contact fatigue. The flaking area is elliptical or nearly circular. The failure of the coating peel may be related to the surface wear behavior and the microstructure of the coating,Peeling failure starts at the surface or sub-surface of the coating, pitting, surface micropores, wear marks and so on, Above all may cause the coating to peel off. etc. It may be the main factor leading to the formation of peeling pits. Such as microscopic defects within the coating, and interfacial cracks, etc. There are two forms of coating stratification failure, internal stratification failure and interface stratification failure. The coating often undergoes internal stratification failure at lower loads. Under the action of shear stress, the coating will crack and expand, and when the crack extends to a certain extent, the coating will be stratified and the shear stress plays a major role. The stratified failure zone depth is deeper than that of the exfoliation pits. Under the action of higher load, the interfacial shear stress and the microscopic defect interaction of the interface lead to the interface stratification failure. The residual stress of the coating and the binding force with the matrix are the important factors leading to the delamination of the interface, in which the binding force of the film is the most pivotal factor.

3. SIMULATION ANALYSIS OF CANTILEVER BEAM ABOUT VIBRATION FATIGUE

3.1. Simulation of vibration fatigue

In this section, the vibration fatigue simulation of cantilever beam is carried out based on the frequency spectrum analysis method of power spectrum density(PSD). Using ANSYS finite element analysis software, firstly, the finite element modal analysis is carried out to obtain the natural frequency of the cantilever beam element, then the frequency response function (FRF) of the cantilever beam is obtained based on the Workbench, and then the finite element analysis results are introduced into nCode Designlife to simulate the vibration fatigue of the cantilever beam.

Vibration fatigue analysis module of nCode Designlife can only use standard S-N analysis engine, the type of vibration load is PSD acceleration load in this paper, which can be superimposed on the static finite element load condition. After the PSD load and the finite element frequency response function (FRF) are synthesized, we can obtain the cyclic count of the stress response spectrum directly. The analysis process of vibration fatigue by nCode Designlife is shown in figure 1.

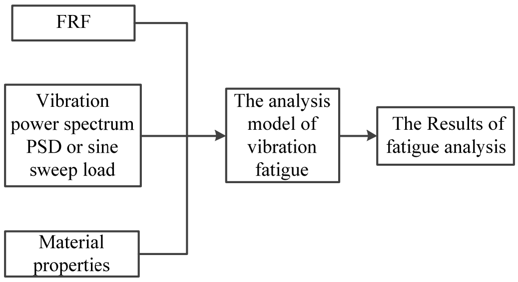
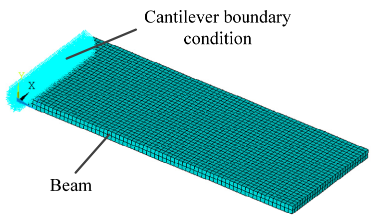


Figure 1 The analysis process of vibration fatigue by nCode Designlife

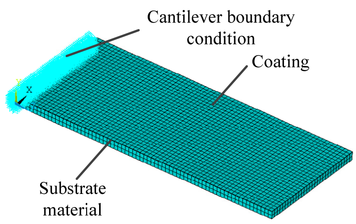
Before the analysis of vibration fatigue,the 3D model of beam and coated beam were established by SolidWorks, and the material properties of beam and coated beam were defined in ANSYS. The material of beam is 304 stainless steel,and the material of coating is NiCrAlY, the material properties are shown in Table 1. Then the model of the beam and the coated beam is divided into the mesh and the constraint condition is defined, as shown in Figure 2. The first five natural frequencies of the beam and the coated beam are obtained by the modal analysis, as shown in Table 2.

Table 1 Material properties of stainless steel and NiCrAlY coating

Material	Elastic modulus (GPa)	Density (Kg/m3)	Poisson ratio	Tensile strength (MPa)
304 stainless steel	204	7930	0.285	520
NiCrAlY	56.9	2840.7	0.3	43.5



(a) Beam



(b) Coated Beam

Figure 2 Model and mesh quality of beam and coated beam

Table 2 The first five natural frequencies of beam and coated beam

Order	Natural frequency of beam (Hz)	Natural frequency of coated beam (Hz)
1	340.95	357.92
2	1653.0	1732.9
3	2120.7	2225.4
4	4460.5	4460.5
5	5279.6	5533.0

Then, based on the ANSYS Workbench, the harmonic response of the beam and the coated beam is analyzed,which is used to determine the frequency response function of a cantilever beam under sinusoidal load of 1g acceleration. The analysis diagram is shown in Figure 3.

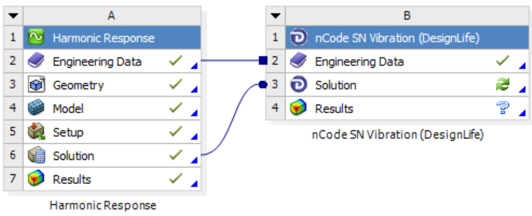


Figure 3 The diagram of harmonic response analysis

The results of harmonic response analysis obtained from the ANSYS Workbench and the material properties were introduced into nCode Designlife for random vibration fatigue analysis, the analysis diagram is shown in Figure 4. The acceleration power spectrum curve of the random vibration input is shown in figure 5, the flat spectrum bandwidth range contains the natural frequency of the first cantilever beam, the flat spectrum frequency range includes the basic natural frequency of cantilever beam. Random vibration time is set to 8 hours,the vibration fatigue damage nephogram of beam and coated beam is obtained, as shown in figure 6.

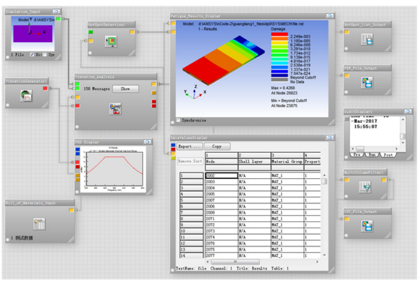


Figure 4 Analysis diagram of nCode Designlife

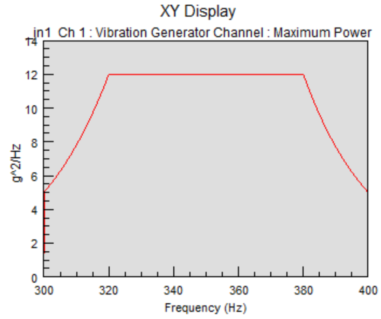
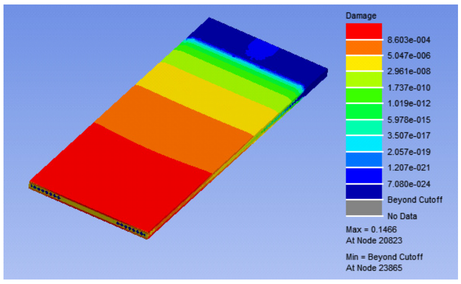
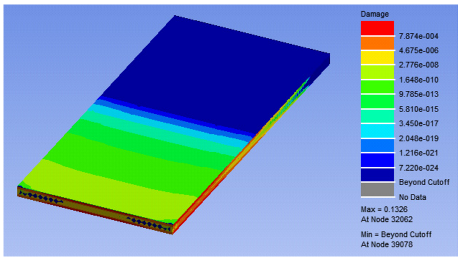


Figure 5 Acceleration power spectrum



(a) Beam



(b) Coated beam

Figure 6 Damage nephogram of beam and coated beam

Reduce the frequency range of PSD curve flat spectrum, as shown in figure 7. Random vibration time is set to 8 hours,the vibration fatigue damage nephogram of beam and coated beam is obtained, as shown in figure 8.

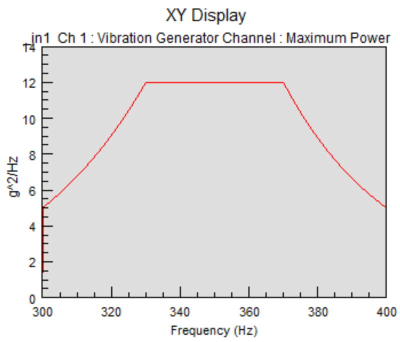
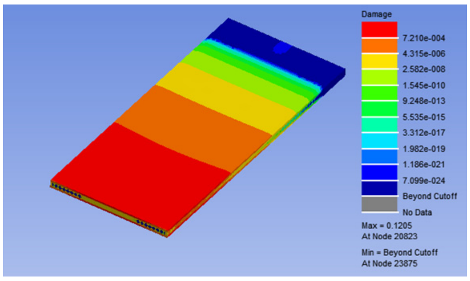
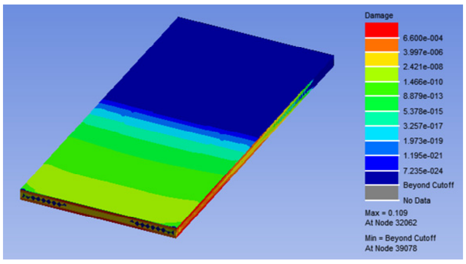


Figure 7 Acceleration power spectrum



(a) Beam



(b) Coated beam

Figure 8 Damage nephogram of beam and coated beam

Increase the frequency range of PSD curve flat spectrum, as shown in figure 9.Random vibration time is set to 8 hours,the vibration fatigue damage nephogram of beam and coated beam is obtained, as shown in figure 10.

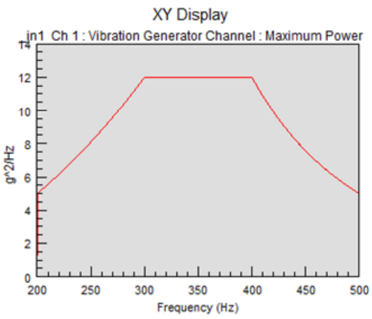
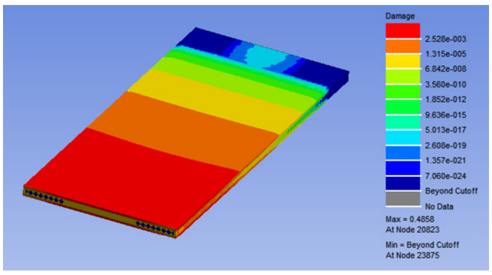
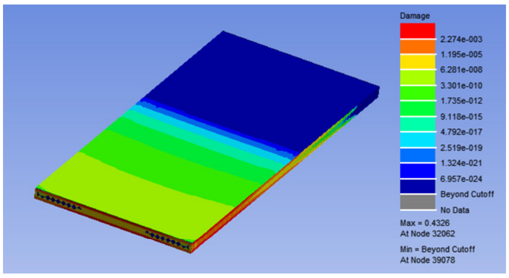


Figure 9 Acceleration power spectrum



(a) Beam



(b) Coated beam

Figure 10 Damage nephogram of beam and coated beam

According to the damage nephogram, it can be seen that the maximum damage of the beam and the coated beam is shown in Table 3 in the range of the above three different spectral frequencies

Table 3 Maximum damage of the beam and the coated beam

Frequency bandwidth (Hz)	Maximum damage of beam	Node number	Maximum damage of coated beam	Node number
60	0.1466	20823	0.1326	32062
40	0.1205	20823	0.109	32062
100	0.4858	20823	0.4326	32062

3.2. Result analysis

Through the simulation of the vibration fatigue of the uncoated beam and the coated beam, the damage cloud diagram can draw the following conclusions:

(1)Compared with the uncoated beams, the maximum damage of beam coated with NiCrAlY is reduced and the anti-vibration fatigue performance of it is increased because the coating increases the damping performance of the cantilever beam and improves the vibration fatigue life of the cantilever beam.

(2)It can be seen from the damage cloud diagram that the maximum damage appears in the middle of the cantilever beam, where the fatigue crack is prone to occur during the vibration of the cantilever beam. The maximum damage of the coated beam appears on the cantilever beam root where coating and beam joint surface. It can be predicted that the damage of the coated beam during the vibration process may be that the coating material is separated from the base material.

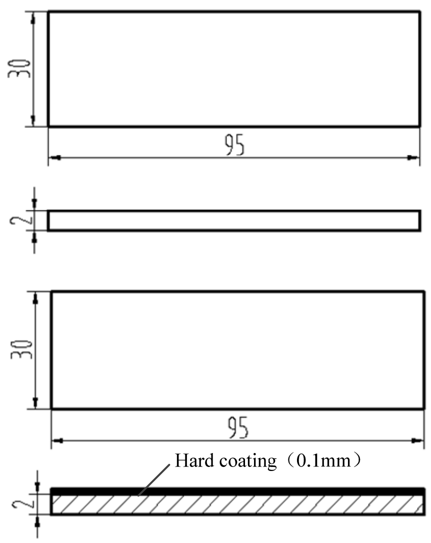
(3)Compared with the maximum damage of uncoated beam and coated beam under different frequency range, it can be seen that reducing the frequency range, the vibration fatigue damage of the cantilever beam will be reduce, and increasing the frequency range, the vibration fatigue damage of the cantilever beam will be increase. In the process of vibration, when the vibration frequency is close to the natural frequency of the cantilever beam, the cantilever beam will be damaged, and the natural frequency of the cantilever will decrease. When the random vibration frequency range does not contain the natural frequency of the cantilever, the damage of the cantilever beam will be reduced, which is the reason why the damage of cantilever beam is reduced when the random vibration frequency range is reduced.

The vibration fatigue simulation analysis provides a reference for the vibration fatigue test of the cantilever beam, and predicts the failure mode of the coating beam coating material, which is of great significance to the later vibration fatigue test.

4、Experimental study on vibration fatigue

4.1 specimen design and material

The experiments were carried out with light beam and single coated beam, the shape and size of the sample are shown in Figure 11. In order to shorten the test time, the sample has higher fundamental frequency, and the specimen is optimized by using the finite element software ANSYS. At the same time, in order to reduce the randomness and increase the reliability of the test data, 8 beams and 8 hard coated beams were designed. One end of the test piece is fixed on the clamp through a bolt, and the other end is free to form a cantilever beam with one end fixed. The clamping length of the specimen is 25mm, and the length of the cantilever is 70mm. Fixture can be installed at the same time 8 pieces of test, a number of life data will be acquired in a test, and the test time will be reduced effectively, clamping mode and installation of the specimen as shown in figure 12.



（a）physical dimension of beam

（b）physical dimension of coated beam

Figure 11 The geometry and dimensions of specimen

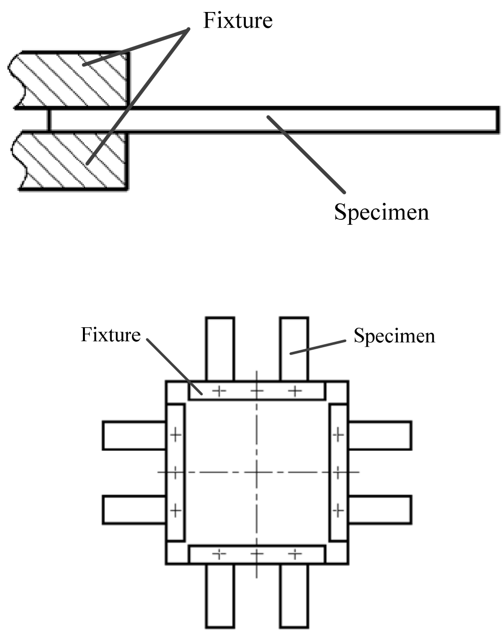


Figure 12 Clamping method of specimen

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