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ARTICLE

Vibration Damping Properties of NiCrAlY Coating Deposited by Arc Ion Plating

Du Guangyu[1], Tan Zhen[1,2], Ba Dechun[1], Liu Kun[1], Han Qingkai[1]

[1] Northeastern University, Shenyang 110819, China; [2] Shenyang Radio and TV University, Shenyang 110004 , China

Abstract: NiCrAlY coating was deposited on 3Cr13 stainless steel substrates by an arc ion plating technique. This paper is to explore the feasibility of NiCrAlY coating for the damping application and to characterize the method that may be used in defining the vibration features of the coatings. The phases of the NiCrAlY coating were determined by X-ray diffraction (XRD) technique. The surface morphology and chemical composition of the NiCrAlY coating were analyzed by scanning electron microscope (SEM) and energy dispersive spectrometer (EDS), respectively. The damping properties were characterized by dynamic mechanical analyzer (DMA) and sine sweeps. Results show that the damping properties of the substrate are considerably improved by the NiCrAlY coating.

Key words: arc ion plating; NiCrAlY coating; damping; dynamic mechanical analyzer; sine sweeps

It has been shown that a leading cause of failure within an aircraft engine is related to high cycle fatigue (HCF) [1,2]. And in the study of high cycle fatigue in turbomachinery, the vibration at resonance frequencies becomes a major issue in aircraft engine reliability. The aircraft engine community is investigating several approaches to solve this problem, one of which is the application of a coating to act as a damping material for the affected component. Some traditional viscoelastic polymer coatings have outstanding damping potential, but they have temperature limitation and are easy to be damaged[3]. Now some references have been published and imply that hard coatings can be used as damping treatments when applied on the surface of a component[4-10]. However, hard damping coatings used as damping treatments are still in the experimental stage. So far, no practical applications are reported. And for most materials, including hard coatings, their damping properties are usually characterized by damping capacity (Q^{-1}) obtained by dynamic mechanical thermal analyzer (DMTA). This method is based on three-point bending beam. But in aircraft engine community damping characteristics of components are usually characterized by sine sweeps or dynamic ping tests. In order to represent the basic damping properties of a coating, appropriate methods are critical.

As the main component of thermal barrier coatings, NiCrAlY coating is drawing more and more attention. Its anti-oxidation properties at high temperatures have been widely studied[11-14]. However, very limited work has been performed on its damping properties. The purpose of the present paper is to explore the feasibility of NiCrAlY coating for the damping application and to characterize the method that may be used to determine the vibration features of the coatings.

1 Experiment

NiCrAlY coating was deposited on 3Cr13 stainless steel substrates by arc ion plating. Prior to the introduction of the pure Ar gas (99.99%), a pressure of 1×10^{-3} Pa was obtained in the sputtering chamber using a turbo molecular pump. The Ar gas was then introduced. The working pressure was 1 Pa. The target was prepared with 60Ni-33.7Cr-4.5Al-1.8Y (wt%) alloy. The distance between the substrates and the target was 10 cm. The arc current was 60 A and the substrate biases were 50, 100, 200, 300 V. The deposition time was 2 h. The deposition thicknesses of the samples under different biases were close about 10 μm. The elemental composition was determined using

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Corresponding author: Du Guangyu, Ph. D., Associate Professor, School of Mechanical Engineering and Automation, Northeastern University, Shenyang 110819, P. R. China, Tel: 0086-24-83676945, Fax: 0086-24-83691216, E-mail: gydu@mail.neu.edu.cn

energy dispersive spectrograph analysis (EDS). Structural study was carried out by X-ray diffraction with Cu Kα (λ=0.154 06 nm) radiation in the 2θ range from 20° to 100°. The surface morphology of the films was observed using scanning electron microscope (SEM).

Test specimens were 3Cr13 stainless steel beam. Two beams with different size were tested. They were 60 mm×10 mm×2 mm and 200 mm×10 mm×2 mm. The short beams damping capacity (Q^{-1}) was tested by dynamic mechanical analyzer (DMA) according to the three-point bending method (Fig.1). The difference between this method and sine sweeps or dynamic ping tests is that three-point bending method is pure deformation mode and there are no fixture effects. The tests were carried out in strain-scanning mode. The strain range was set from 10^{-5} to 10^{-4} at room temperature. The long beams damping was tested by sine sweeps method. Sine sweeps were conducted using the Bruel & Kjaer (B&K) system, with the PULSE LabShop software. The function generator was set for sine sweep, with the frequency range of 390~410 Hz, time of 120 s and voltage of 5 V peak-to-peak. Schematic diagram of damping performance testing experiment was shown in Fig.2.

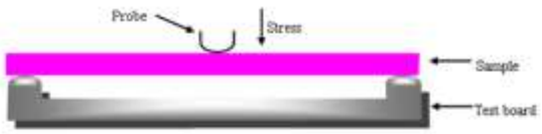

Fig.1 Schematic diagram of dynamic mechanical analyzer

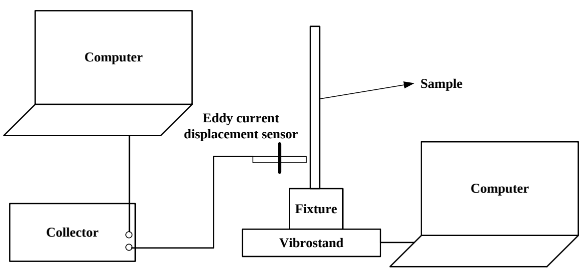

Fig.2 Schematic diagram of sine sweeps testing

2 Results and Discussion

2.1 Compositional study

Fig.3 shows a representative EDS result of NiCrAlY coating deposited by arc ion plating with 100 V bias. Strong peaks for Ni, Cr and Al are found in the spectrum. The mass fraction (wt%) of Ni, Cr, Al and Y in NiCrAlY coating are 56.73, 36.85, 5.12 and 1.29 respectively. And there is no significant influence of bias on the chemical constitution. The deviation of chemical constitution between coating and target is caused by the selectivity of different elements during the deposition process. Another reason is the inevitable measurement error. But generally the chemical constitution of NiCrAlY coating deposited by arc ion plating is similar to that of the target. So the result proves that there is no significant influence of arc ion plating at this processing point on chemical constitution.

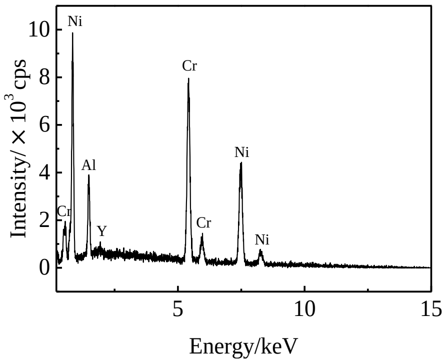

Fig.3 EDS spectrum of NiCrAlY coating

2.2 Surface morphology

Fig.4 shows the surface and cross-sectional microstructure of NiCrAlY coating deposited at 100 V bias. SEM test results for other samples are similar. The surface morphology of NiCrAlY coating is homogeneous, and exhibits the typical characteristics of most coating systems prepared by arc ion plating. The coating has the typical structure of metal “droplets” and “island”. Some pores and cracks are formed among these structures. Usually, the damping mechanism of hard coatings is attributed to the internal friction occurring at interfaces. In coating and substrate composite structure, interfaces include the macro-interface between the coating layer and substrate, lamellar interface in the coating layer, grain boundary and porosity, etc.[15]. Some researchers think that the interface under vibration load could improve the structure's damping capability[16].

2.3 Phase composition analysis

The structure of NiCrAlY coating was determined by the

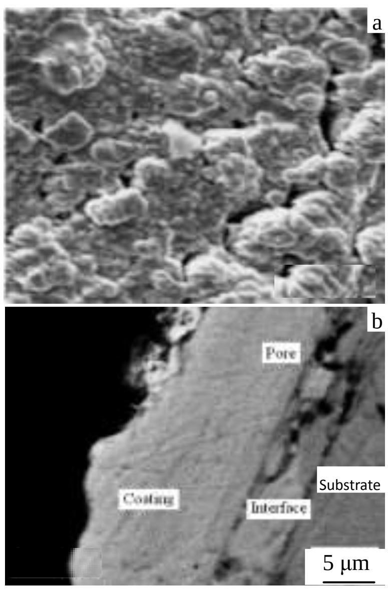

Fig.4 SEM morphologies of NiCrAlY coating surface (a) and cross-sectional (b)

X-ray diffraction technique. And the XRD patterns of the NiCrAlY coatings are shown in Fig. 5. It is shown that the coating is crystalline and consists of γ-Ni, γ'-Ni_3Al, β-NiAl, and α-Cr phases. The intensity of α-Cr diffraction peak is higher than that of other phases. β-NiAl diffraction peak can be found in 50 V bias sample and the diffraction peak decreases at 100 V bias, which may result from the solid state reaction: γ-Ni(Cr) + β-NiAl $\rightarrow$ γ'-Ni3Al + α-Cr during the bias increase process[17].

2.4 Damping properties

The damping capacities (Q^{-1}) of the samples with and without NiCrAlY coating were tested by a dynamic mechanical analyzer (DMA). The dynamic storage modulus (E') and loss modulus (E'') can be simultaneously measured by DMTA, and Q^{-1} can be expressed as: $Q^{-1}= E''/E$. Fig.6 shows the variation of the damping performance with strain amplitude of the samples with and without NiCrAlY coating at room temperature. As is seen, Q^{-1} of the coated sample is higher than that of the sample without coating. And the results of samples with different biases are similar. When the deposition bias changes, only the phases of the coatings change, deposition thickness, surface and cross-sectional microstructure and chemical constitution have no obvious changes. It can be concluded that the phases of the coatings have no obvious impact on the damping capacity of samples.

The coating's damping capacity increases as the strain amplitude. This relation can be explained by interface slip

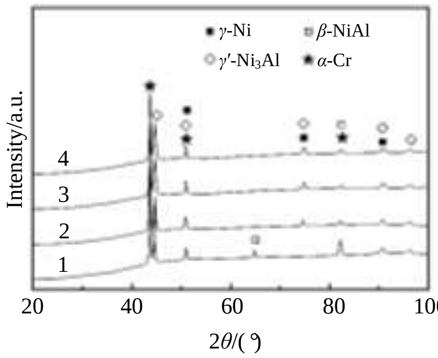

Fig.5 XRD patterns of NiCrAlY coating (1-sample with 50 V bias, 2-sample with 100 V bias, 3-sample with 200 V bias, 4-sample with 300 V bias)

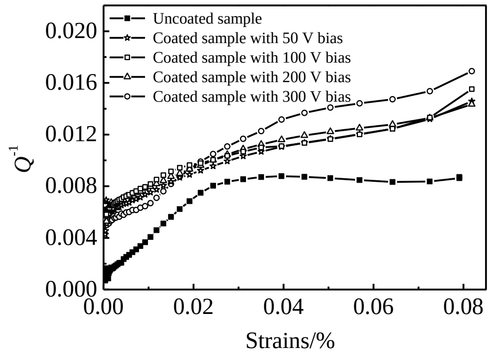

Fig. 6 Variation of the samples damping capacity (Q^{-1}) with the strains tested by DMA

model [18,19]. Some research shows that when the strain amplitude increases, the number and the intensity of the interface slip would become more, and correspondingly, the energy loss would increase [20]. It can be concluded that the arc ion plating NiCrAlY coating is able to improve the damping capacity of the substrate notably.

In aircraft engine community, the damping characteristics of components are usually characterized by laser vibrometry, sine sweeps or dynamic ping tests. Dynamic ping tests are usually conducted on components to determine their resonance frequencies. Laser vibrometry is used to determine the mode at each resonance frequency. And the damping ratios are determined through the use of sine sweeps. It is important to determine the damping characteristics precisely. So in the present paper, the sine sweeps were used to compare with dynamic mechanical analyzer.

The damping parameter output by the PULSE software is the damping ratio (ζ). The parameter most commonly used in damping investigations is the quality factor (Q). The quality factor was developed by electrical engineers as a measure of the clarity of a signal. The quality factor is inversely proportional to the damping ratio. They are related by:

$$Q = 1/ 2\zeta \tag{1}$$

As damping increases, ζ increases, and Q decreases.

The test results of uncoated samples and the coated sample with 100 V bias are shown in Table 1 and Table 2, respectively.

Table 1 Sine sweeps results of the uncoated sample

Excitation acceleration, *g*	0.5	0.7	1.09	1.5	1.8	2.0	2.5	2.7	3.0
Frequency/Hz	397	396.9	396.8	396.7	396.6	396.4	396.4	396.4	396.4
Damping ratio/%	0.103	0.118	0.125	0.136	0.16	0.172	0.188	0.197	0.244
Response/mm	0.337	0.475	0.521	0.56	0.763	0.779	0.82	0.875	0.904

Table 2 Sine sweeps results of the coated sample

Excitation acceleration, *g*	0.5	0.7	1.09	1.5	1.8	2.0	2.5	2.7	3.0
Frequency/Hz	398.7	398.6	398.4	398.1	398	397.6	397.5	397.4	397.2
Damping ratio/%	0.155	0.178	0.188	0.224	0.234	0.256	0.27	0.285	0.326
Response/mm	0.496	0.554	0.613	0.841	0.886	0.957	1.074	1.083	1.171

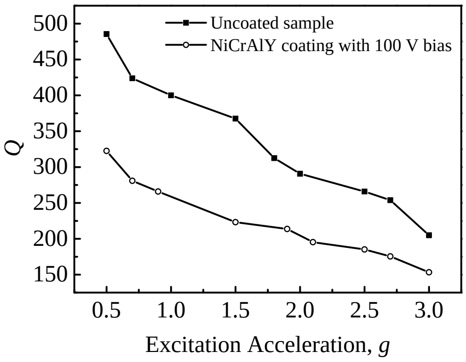

Fig.7 Variation of samples quality factor (Q) with excitation force (g) tested by sine sweeps

And the variation of sample quality factor with excitation force is shown in Fig.7. The nature frequency of coated samples shows tiny excursion, and damping ratio of coated sample is larger than that of uncoated sample. And as response displacement increases, ζ increases. This variation of the damping is the same as DMA results. So these results indicate that sample's damping is increased by NiCrAlY coating. And the test results of damping characterized by sine sweeps and DMA are similar. These results provide a feasibility of NiCrAlY coating for the damping application.

3 Conclusions

1) Crystalline NiCrAlY coating can be deposited on 3Cr13 stainless steel substrate by an arc ion plating technique, and the coating consists of γ-Ni, γ'-Ni3Al, β-NiAl, and α-Cr phases.

2) Damping capacities (Q^{-1}) are obtained by DMA, which damping ratio (ζ) and quality factor (Q) are obtained by sine sweeps.

3) The test results of the two methods are similar. These usual methods can be used in defining the vibration features of hard coating. It has been observed that NiCrAlY coating is able to improve the damping performance of the substrate.

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电弧离子镀沉积 NiCrAlY 涂层的阻尼性能

杜广煜[1]，谭　祯[1,2]，巴德纯[1]，刘　坤[1]，韩清凯[1]

(1. 东北大学，辽宁 沈阳 110819)

(2. 沈阳广播电视大学，辽宁 沈阳 110004)

摘　要：采用电弧离子镀沉积 NiCrAlY 涂层，探讨 NiCrAlY 涂层作为阻尼涂层的可行性并研究涂层的阻尼测试方法和阻尼特性。采用 X 射线衍射和扫描电镜等手段分别对涂层的物相结构、表面形貌以及化学成分进行了测试表征。而涂层阻尼的测试则采用动态机械分析仪和正弦扫频的方法进行，实验结果表明 NiCrAlY 涂层能明显提高样品的阻尼性能。

关键词：电弧离子镀；NiCrAlY 涂层；阻尼；动态机械分析；正弦扫频

作者简介：杜广煜，男，1980 年生，博士，副教授，东北大学机械工程自动化学院，辽宁 沈阳 110819，电话：024-83676945，E-mail: gydu@mail.neu.edu.cn