Engineering Notes

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Potential of Graded Coatings in Vibration Damping

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Introduction

DURING a development program for turbine blade and vane coatings, serendipity revealed a vibrational damping property of these coatings in simulated engine operation.

These low conductivity coatings were pursued as a means to cope with the trend to more severe thermal conditions in gas turbine engines. An experimental program was undertaken to evaluate candidate materials under conditions approximating an engine. The principal test used was a thermal shock test.[1] Some of the more promising materials were graded plasma coatings. These coatings were applied as multi-layered, plasma-sprayed coatings, with the composition varying from 100% metal at the base to 100% ceramic at the outermost layer. The graded composition was chosen in an effort to minimize thermal expansion discontinuities, and thus make the coatings more resistant to thermal shock trauma. The results of thermal shock and foreign object damage testing were reported earlier.[2]

During operation of gas turbine engine, rotor blades are subjected to relatively high steady-state stresses resulting from the high rotational speed of the rotors and from the gas loads due to the airflow through the engine. In addition, blade vibratory loads are introduced when the blades pass through wakes generated by stator vanes, combustors, bearing support struts, etc. Since the root is fixed in the rotor, the blade vibrates as a cantilever. The vibration mode can be fairly complicated consisting of torsional, bend, and combined modes. When the rotor speed is such that the wake-passage frequencies are synchronized with the blade vibrational frequencies, resonances will occur. This may lead to fatigue failure.

It was this likelihood of fatigue failure that led to a vibration endurance subprogram to insure that the graded arc-plasma sprayed coatings would survive on a vibrating blade. During this portion of the thermal barrier program, some unusual vibration damping characteristics of these graded coatings were found. We shall describe some of these interesting results.

Materials and Preparation

In practice, the graded plasma coating has been applied as a three to six layer coating, arc-plasma sprayed on a metal substrate. The composition starts with a metal or alloy layer sprayed onto the metal substrate and grades to 100% ceramic in the outer layer. These coatings have been applied in total thickness up to 0.082 in. Typical procedures for applying a graded coating are described elsewhere.[2]

Throughout the course of this paper, we shall use the terms, "arc-plasma spray," "plasma spray," and "flame spray" synonymously. They all refer to a spraying process using a hot gas, typically produced by plasma discharge or by combustion. Since "flame spray" is more commonly used, we shall use it as the generic term.

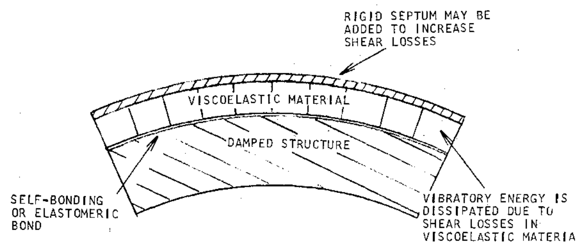

Fig. 1 Viscoelastic damping.

Test Procedure

The initial test used conventional compressor blades. The blades were mounted as a cantilever, and the stress was monitored by a strain gage ¼ in. from the mounting on one side. Excitation of the specimens was by an air siren equipped with a solenoid operated plunger to close the siren discharge and chop the excitation. The strain gage output was displayed on an oscilloscope and the stress vs cycle number and % logarithmic decrement of damping was calculated from the die-away traces.

Subsequently, a more sophisticated apparatus was used. In this test, rectangular plates (6½ in. × 1 in. × 0.063 in.) were supported at the center and mounted on a shaker table. "Die-Away" damping data was monitored by strain gages as the driving frequency was abruptly increased one decade. The logarithmic decrement was obtained from stored data on an oscilloscope.

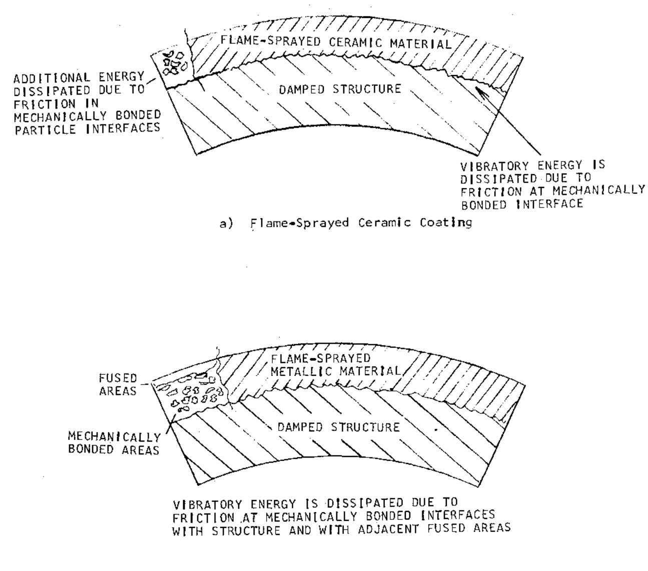

Fig. 2 Flame-spray damping.

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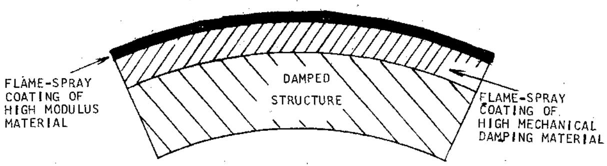

Fig. 3 Method of increasing material mechanical damping.

The first test compared the damping characteristics on aluminum compressor blades. The blades were mounted in an MB Model C11 shaker table with a strain gage placed on the pressure face near the trailing edge. One blade was uncoated and used as a control. Another was flame sprayed with a 0.010 in. thick coating of magnesium aluminate ($MgO \cdot Al_2O_3$). The third test blade was sprayed with a 0.010 in. thick coating graded from molybdenum to $MgO \cdot Al_2O_3$.

The second test used Hastelloy-X¶ rectangular plates (described above). Again one plate was left uncoated as a control. In this test, however, a second control was used consisting of a 0.011 in. thick coating of flame sprayed Hastelloy-X. Two graded coatings were evaluated: Hastelloy-X graded to zirconia (ZrO_2) in three layers and Hastelloy-X graded to $MgO \cdot Al_2O_3$ in 4 layers.

Results and Discussion

Tables I and II show the results. Referring to Table I, and particularly to the aluminum blades, it may be seen that the % logarithmic decrement of damping (% log dec) for the uncoated blade was 0.7. The single-layer coating had a % log dec considerably higher—5.7; and the graded coating's value higher yet—7.1. This trend was shown for all vibrational modes at virtually every cycle, as shown in Table II. Table II also suggests an amplitude-dependent damping mode.

Table 1 Vibration damping data

Specimen	Coating	% log dec.[a]
Aluminum blade	Uncoated control	0.66
Aluminum blade	0.010 in $MgO \cdot Al_2O_3$[b]	5.66
Aluminum blade	0.003 in molybdenum[c]	
	0.002 in 65 w/o moly + 35 w/o $MgO \cdot Al_2O_3$	7.12
	0.002 in 35 w/o moly + 65 w/o $MgO \cdot Al_2O_3$	
	0.003 in $MgO \cdot Al_2O_3$ (outer coat)	
Hastelloy X plate	Uncoated control	0.40
Hastelloy X plate	0.011 in Hastelloy X[d]	1.15
Hastelloy X plate	0.003 in Hastelloy X	
	0.002 in 65 w/o Hastelloy + 35 w/o $MgO \cdot Al_2O_3$	
	0.0025 in 35 w/o Hastelloy + 65 w/o $MgO \cdot Al_2O_3$	1.80
	0.0035 in $MgO \cdot Al_2O_3$ (outer coat)	
Hastelloy X plate	0.0035 in Hastelloy X	
	0.0045 in 50 w/o Hastelloy + 50 w/o ZrO_2[e]	1.47
	0.003 in ZrO_2 (outer coat)	

[a]Average of first fifteen cycles.
[b]METCO Powder No. 63-NS.
[c]METCO Powder No. XP-1134.
[d]Stellite Div. Cabot Corp. Powder.
[e]Plasmadyne Powder No. 327-M.

Table 2 Damping data for aluminum compressor blades

Vibration mode	Cycle no.	Uncoated blade Stress (± psi)	Uncoated blade % Log-dec	0.010 in. $MgO \cdot Al_2O_3$ coating Stress (± psi)	0.010 in. $MgO \cdot Al_2O_3$ coating % Log-dec	4 Layer graded coating of Mo and $MgO \cdot Al_2O_3$ Stress (± psi)	4 Layer graded coating of Mo and $MgO \cdot Al_2O_3$ % Log-dec
Fundamental	1	8908	0.656	7185	6.18	6193	7.78
	15	8118	0.669	3255	5.13	2285	6.46
	30	7335	0.683	1640	4.00	965	5.03
	45	6614	0.696	979	2.87	504	3.61
	60	5952	0.709	692	1.75	326	2.19
2nd Bend	1	3882	0.169	4158	1.008	3920	3.31
	15	3787	0.186	3461	1.608	2439	3.47
	30	3678	0.204	2592	2.25	1430	3.65
	45	3562	0.221	1762	2.89	817	3.82
	56	3482	0.233	1291	3.32	554	3.94
1st Torsion	1	1877	0.306	2377	1.09	2232	1.76
	20	1783	0.231	1882	1.37	1578	1.88
	40	1717	0.151	1390	1.66	1069	2.01
	60	1679	0.072	969	1.95	705	2.14
	80	1668	0.000	651	2.23	464	2.26
3rd Bend	1	2257	0.032	2692	−.485	1085	−.41
	15	2232	0.129	2745	.204	1019	1.31
	30	2172	0.233	2520	.942	730	3.15
	45	2081	0.337	2070	1.68	396	4.99
	55	2005	0.406	1707	2.17	226	6.22

Figure 1 shows the commonly accepted explanation of damping provided by viscoelastic coatings. The damping effectiveness is related to the vibratory energy losses developed in the coating material as a result of shear stresses produced by deflection of the damped structure. Kahawa and Krokstad[3] derived an expression for this type of damping effectiveness, β.

$$\beta_{\mathrm{BEND}} = 3g_E r_E r_h(1 + 2r_h + 4/3r_h^2) \qquad (1)$$

where g_E is the loss factor of viscoelastic material, r_E is the ratio of coating bending modulus to that of structure (includes consideration of Poisson's ratios), and r_h is the ratio of coating thickness to thickness of structure.

This equation shows damping to be proportional to the loss factor peculiar to the particular viscoelastic material, the ratio of the coating modulus to the modulus of the structure, and the ratio of the coating thickness to the thickness of the structure. As indicated in Fig. 1, the damping effectivity is frequently enhanced by the addition of a rigid septum over the outer surface of the coating which then forces additional shear losses in the viscoelastic material.

Figure 2a shows the mechanism by which we have accounted for the unexpected damping properties of flame-sprayed *ceramic* materials. The ceramic category includes the refractory materials, such as magnesium zirconate, ROKIDE,** alumina, and zirconia. When sprayed, these materials leave the gun in a molten state, but do not fuse to the surface on which they are sprayed. The bonding process is a mechanical one in which the ceramic flows around the macroscopic surface irregularities with no metallurgical interactions. The bonding of individual ceramic particles to each other is a combination of fusion and mechanical bonding, since some of the particles have cooled to the solid state prior to impact on the surface. Ceramic materials have no viscoelastic properties; their damping stems from an entirely different phenomenological source. The dissipation of vibratory energy is, perhaps, derived from the friction forces generated at the mechanically bonded interfaces between the coating and the damped structure, as well as at interfaces with adjacent coating fused areas.

As shown in Fig. 2b, the damping mechanism for flame-sprayed *metallic* materials, such as molybdenum and copper-nickel, is very similar. However, in the case of these materials, some fusion with the surface material does occur, and the bond mechanism is partly fusion and partly mechanical. Figure 3 shows a means for increasing the damping effectiveness of flame-sprayed coatings. The principle is the same as that used to increase the damping of viscoelastic materials, but in this case we are developing greater friction losses in the mechanically bonded interfaces.

To date we have seen no explanation in the literature for the damping provided by flame-sprayed materials and no recognition of the existence of such damping properties. While Lull's patent[4] (which covers a damping coating treatment consisting of a low modulus plating overlaid with a high modulus plating) may seem to bear some similarity, the basic principles involved are entirely different. Lull[4] attempted to develop a viscoelastic-like loss through enhanced shear stresses in the lower modulus coating. Neither that treatment nor the conventional viscoelastic treatments introduces the opportunity for the internal mechanical friction losses believed to be the damping source in this application of flame-sprayed materials.

†Trademark, Stellite Div., Cabot Corp.
**Trademark Norton Co.

Conclusions

1) A new damping mechanism is believed to be revealed which involves mechanical friction within flame-spray coating materials, probably unique to the method of application and associated bonding mechanism represented by the flame-spray technique.

2) The use of layered coatings of different rigidity (modulus) appears to enhance this internal friction damping phenomena.

References

[1]Spicer, W. C., Ross, P. T., and Newman, R. L., "A Well-Defined Thermal Shock Transient Test Burner," *Review of Scientific Instruments*, Vol. 43., No. 2, Feb. 1972, pp. 236–244.

[2]Cavanagh, J. R., Cross, K. R., Newman, R. L., and Spicer, W. C., "The Graded Thermal Barrier–A New Approach for Turbine Engine Cooling," *Journal of Aircraft*, Vol. 9, No. 11, Nov. 1972, pp. 795–797.

[3]Kahawa, Y. and Krokstad, A., "On the Damping of Cylindrical Shells Coated with Viscoelastic Materials," ASME Paper 69-VIBR-9, Philadelphia, Pa. (1969).

[4]Lull, W. R., "Damped Blade," U.S. Patent No. 3,301,530 (1967). Assigned to General Motors Corp.

Structure of Betz Vortex Cores

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THIS Note is concerned with the radial distribution of the tangential speed v_T in a rolled-up vortex behind a lifting wing. We are specifically concerned with the situation when roll-up is just completed; the flow has become essentially two-dimensional (the presence of the wing is no longer felt acutely), but vortex decay has not yet set in measurably. A key question is: to what extent is the vortex structure at this stage defined by the roll-up process as a potential flow mechanism, and how important, by contrast, is the role of viscosity (of turbulent shear)? Assuming different answers to this question, a variety of vortex models have been proposed. Recent observations (e.g., trailing vortices may persist for long times; the viscous core is much smaller than had been predicted) seem to indicate that the potential flow mechanism is of overriding importance. Indeed, as was pointed out first by Donaldson,[1] a "forgotten" early model that disregards viscosity entirely seems to fit experiments much better than any one of the later models. This has been well confirmed by the later experiments of Mason and Marchman[2] and of Brown.[3]

The "forgotten" model is that of Betz[4] (1932). Let us denote by "core" that part of the vortex where it differs from a Rankine vortex (i.e., where not $v_T \sim 1/r$). This core consists of a small inner core where the flow is so dominated by viscosity that, roughly, $v_T \sim r$, and a much larger outer core. The Betz argument is concerned only with the outer core; it shows that, by accounting for the laws of conservation of momentum in potential flow, one

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