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Residual Stresses as a Factor in the Selection of Tungsten Carbide Coatings for a Jet Engine Application

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Tungsten carbide thermal spray coatings are important to the aerospace industry for the mitigation of midspan damper wear on jet engine fan and compressor blades. However, in some cases the coating can fail due to spallation and cracking, and in other situations the fatigue life of a fan or compressor blade is reduced when a coating is applied. Coating failures can result in decreased engine performance and costly maintenance time. A comprehensive experimental research program was conducted to evaluate coating crack resistance in bending, low-cycle fatigue properties of the coating and substrate, coating performance in jet engine tests, and microstructures for a wide range of coating compositions and application processes. Coating residual stress distributions also were evaluated. Eleven coatings were ranked according to their performance relative to the other coatings in each evaluation category. Results from the bend and low-cycle fatigue evaluations were compared to the experimentally evaluated residual stresses. Comparisons of rankings indicate a strong correlation between performance and the residual stresses in the coatings. Results from the program were used to select a suitable coating system for final in-service use based on two important criteria: (1) the coating must not fail while in service, and (2) the coating must not induce crack propagation into the substrate of the midspan damper.

1. Introduction

VIBRATION of fan and compressor blades in jet engines can be controlled by the use of midspan dampers. A midspan damper provides a contact surface between blades to constrain lateral and torsional motion that could result in flutter (damaging blade vibration). Figure 1 is a photograph of midspan dampers on fan blades. Tungsten carbide (WC) thermal spray coatings are often applied to the contact surfaces of such dampers to reduce wear. Although coatings have controlled the wear of midspan dampers, coating failures have been observed due to cracking and spallation caused by cyclic fatigue and impact. The result is a loss of coating performance or a continued crack propagation through the midspan damper, resulting in damper separation and in some cases complete engine failure.

Residual stresses have been a contributing factor or a suspect in many cases of shortened service life for thermal spray coatings (Ref 1, 2). Residual stresses in thermal spray coatings have been linked to bending strength, fatigue life, bond strength and microstructure (Ref 3-5). The magnitude of the residual stress and whether it is tensile or compressive can significantly influence coating performance. It has been established that a compressive residual stress zone near the surface of a material impedes surface crack initiation and propagation (Ref 2, 6).

Fatigue behavior of thermally sprayed parts can be considered as a combination of coating and substrate performance (Ref 7). The fatigue characteristics of a thermally sprayed part can in some situations be linked to the residual stresses in the coating and substrate. In some cases, a coating can have a high degree of crack resistance due to compressive residual stresses in the coating. When the coating is in compression, the substrate will likely have a tensile residual stress at the coating/substrate interface, which could result in accelerated substrate cracking once a crack has propagated through the coating.

Keywords: cracking resistance in bending, fatigue life, mid-span dampers, residual stresses, tungsten carbide coating

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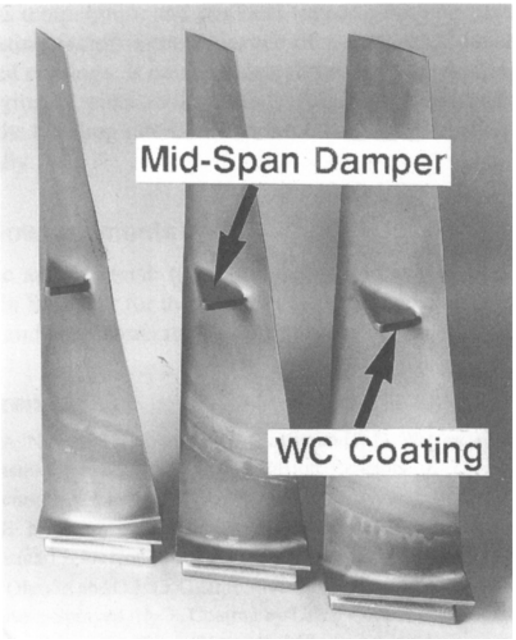

Fig. 1 Midspan dampers on fan blades

Table 1 Tungsten carbide coating system designations

Coating Composition	Application process HVOF A	 B	 C	 D	 E	 F	 G	 Plasma H
1 (WC-Co)	x	x	x	x	x	x	x	x
2 (WC-Ni)	x			x			,	
3 (WC-Co/Cr)					x		,	

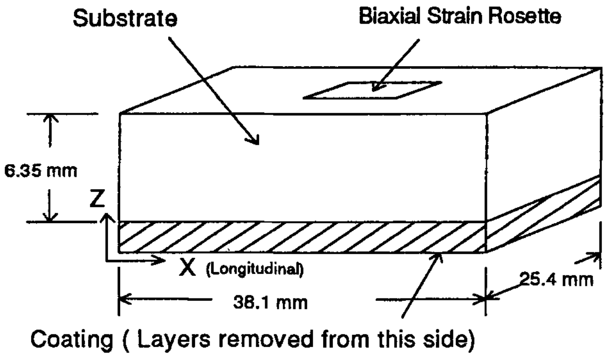

Fig. 2 Typical residual stress specimen for layer removal

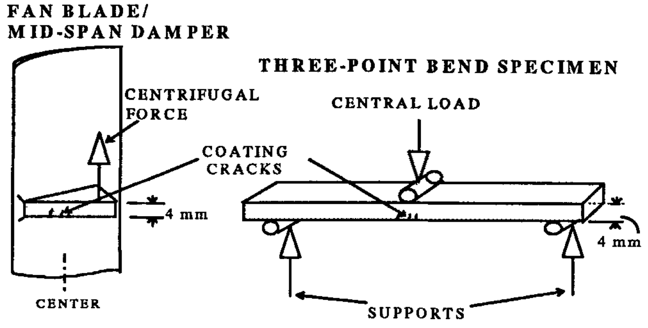

Fig. 3 Three-point bend test

Possible mechanisms for cracks initiating in the substrate have been reported in Ref 8 and 9. Hwang et al. (Ref 8) contend that cracks do not propagate from the coating into the substrate, but that substrate cracks instead initiate at nonspecific locations. They then conclude that the fatigue life of a part should be based on the substrate properties if cracking of the coating is acceptable. Rakitsky et al. (Ref 9) suggest that voids and impurities are initiation locations for coating cracks.

Based on these results, it is reasonable to consider residual stresses as a significant factor in coating failures of midspan dampers. An experimental program was established to consider many factors, including residual stresses.

2. Experimental Program

The research program consisted of coating evaluations that included the following tests and property evaluations: low-cycle fatigue, bending crack resistance, residual stresses, jet engine performance, impact and abrasive wear, bond strength, porosity, hardness, and microstructure. Wear resistance was found to be acceptable for all but the most porous coatings. However, results from the fatigue, bending, and residual stress evaluations varied significantly among the coatings. This paper concentrates on the residual stress, crack resistance in bending, and low-cycle fatigue evaluations; the characteristics represented by these evaluations support a linkage with in-service observations and jet engine performance evaluations.

The coating materials selected for this study were tungsten carbide thermal spray coatings with cobalt, nickel, or cobalt/chromium binders. The coating compositions and application processes are proprietary. The general coating compositions and application processes are listed in Table 1. The high-velocity oxyfuel (HVOF) processes are labeled A to G, and the plasma spray process is labeled H. Each HVOF application process is represented by a different thermal spray equipment manufacturer. Spray parameters for the application processes are approximately those recommended by each manufacturer. A coating system designation of "A-1" indicates the application process is HVOF process "A" with a coating composition of WC-Co. The substrate for all evaluations was Ti-6Al-4V.

2.1 *Methods to Evaluate Residual Stresses*

The modified layer-removal method (Ref 10) for thermal spray coatings and substrates was used to determine the through-thickness residual stress distribution in specimens prepared for each coating system. Figure 2 illustrates a typical specimen used for the modified layer-removal method. In this method, layers are removed from the coating side of the specimens, and the changes in strain on the substrate are monitored with a resistance type biaxial strain rosette. Strain change data and thickness information are inputs to a computer program for calculating residual stresses.

2.2 *Bend Tests*

Figure 3 illustrates the three-point bend test used for determining coating crack resistance under a bending load. The test simulated the bending strain configuration that a midspan damper experiences due to centrifugal forces. The coating is applied to one edge of a test specimen having the same width as a midspan damper. A central load is applied to the noncoated top surface, and coating cracks are observed on the coated edge.

2.3 *Low-Cycle Fatigue*

A typical low-cycle fatigue specimen is shown in Fig. 4. Specimens were designed according to ASTM E 466-82 (Ref 11). All fatigue tests were run in a zero-to-tension load condition

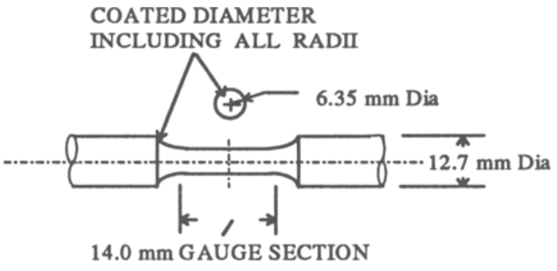

Fig. 4 Fatigue specimen

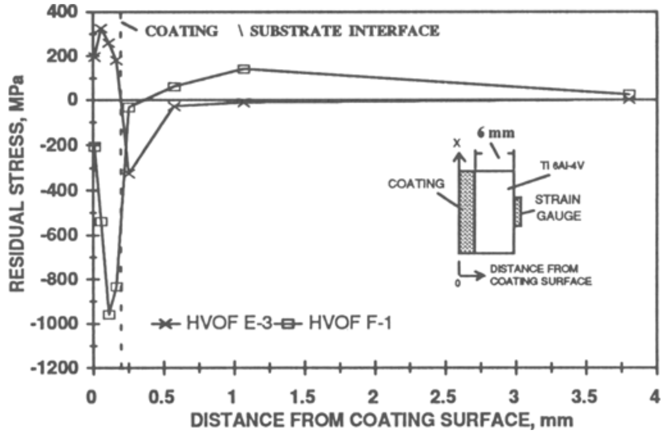

Fig. 5 Typical through-thickness residual stress distributions for coatings E-3 and F-1

($R = 0$). Specimens were initially loaded by applying incremental load steps corresponding to an increase of 0.1% strain for each step, with 1000 cycles between load steps until a crack was initiated in the coating. A fluorescent penetrant was used before any applied loading and after each 1000 cycles to inspect for crack initiation. The purpose of cracking the coating was to investigate the substrate fatigue life after a crack had occurred in the coating. After coating crack initiation, the load was increased directly to a stress of 700 MPa for 100,000 cycles or until failure of the substrate.

2.4 *Microstructures*

As-sprayed, nontested specimens of each coating type were mounted and sectioned for microstructure evaluations. Additional microstructural evaluations on fracture surfaces in bending and fatigue were also performed.

3. Results

3.1 *Residual Stress Distributions*

Figure 5 shows the typical through-thickness residual stress distributions in the longitudinal direction, σ_x, for coating systems E-3 and F-1. The result for the E-3 coating system is tensile residual stresses in the coating and compressive residual stresses in the substrate near the interface. The result for the F-1 coating system is opposite to system E-3, showing compressive residual

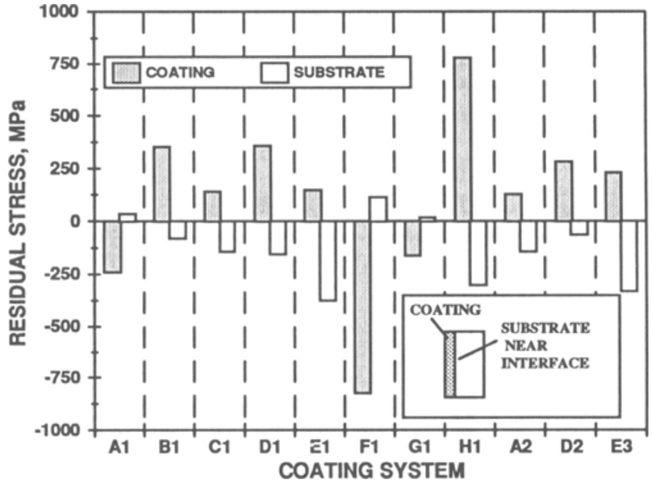

Fig. 6 Average residual stress results for the coating and substrate for all coating systems

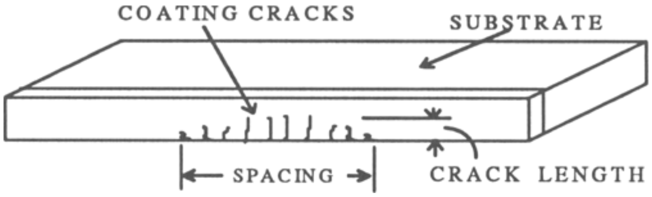

Fig. 7 Schematic of bending cracks from the three-point bend tests

stresses in the coating and tensile residual stresses in the substrate. It is interesting to note that coating systems E-3 and F-1 produce residual stress profiles that are opposite in sign although coating compositions and application processes are similar.

Figure 6 summarizes the average through-thickness residual stress results for the coating and substrate for all of the coating systems. The residual stress for the substrate applies to locations near the coating/substrate interface. The results in Fig. 6 are averages of two to four specimens for each coating system. The average residual stresses in Fig. 6 were calculated using the residual stress data to compute the cross-sectional force on the coating and substrate near the interface separately and then dividing the resulting forces by the cross-sectional areas.

3.2 *Crack Resistance Ranking for Bend Tests*

Figure 7 shows a schematic of typical coating cracks generated by the three-point bend evaluations. Each coating system was ranked based on the spacing and lengths of cracks; the coating with the least number of relatively short cracks received a ranking of 1. Table 2 lists the three-point bend rankings for all coating systems.

3.3 *Low-Cycle Fatigue Life*

Figure 8 shows strain levels for coating fatigue crack initiation. Cracks were discovered in the coating after being loaded at the strain level indicated in Fig. 8 for 1000 cycles. Coating systems A-2, D-1, and H-1 cracked prior to any loading and were directly evaluated under maximum fatigue stress.

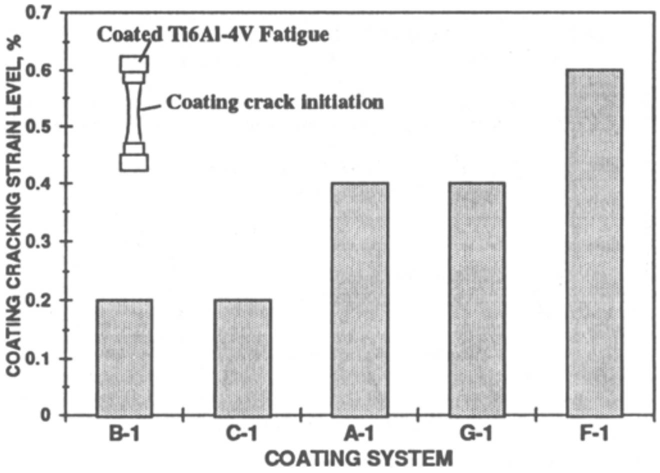

Fig. 8 Fatigue strain level at 1000 cycles for coating crack initiation

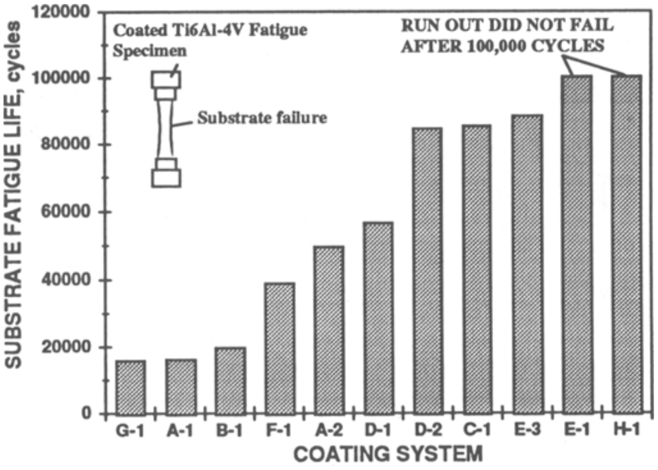

Fig. 9 Cycles to failure for titanium substrate after coating crack initiation

Figure 9 shows cycles to substrate failure after coating crack initiation. Each specimen was cycled under a maximum stress of 700 MPa for 100,000 cycles or until the substrate failed. The results in Fig. 9 are averages of two to four specimens for each coating system. Coating systems E-1 and H-1 did not fail after 100,000 cycles.

3.4 *Microstructures*

Figures 10 and 11 show micrographs taken by scanning electron microscopy (SEM) for cross sections of the HVOF coating A-1 and the plasma-sprayed coating H-1, respectively. Both coatings exhibit low porosity and a homogeneous tungsten carbide distribution. Although the micrographs of coatings A-1 and H-1 are similar, their performance properties as determined by mechanical testing were significantly different. These results indicate that in some cases microstructural analysis may provide insufficient information for differentiating coating performance.

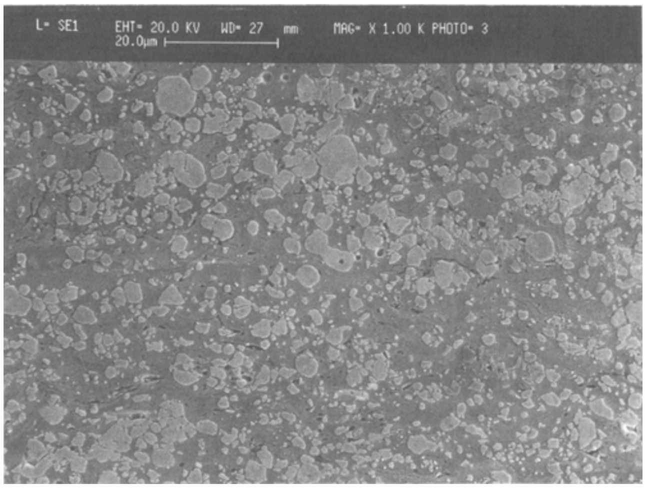

Fig. 10 SEM micrograph of HVOF coating A-1

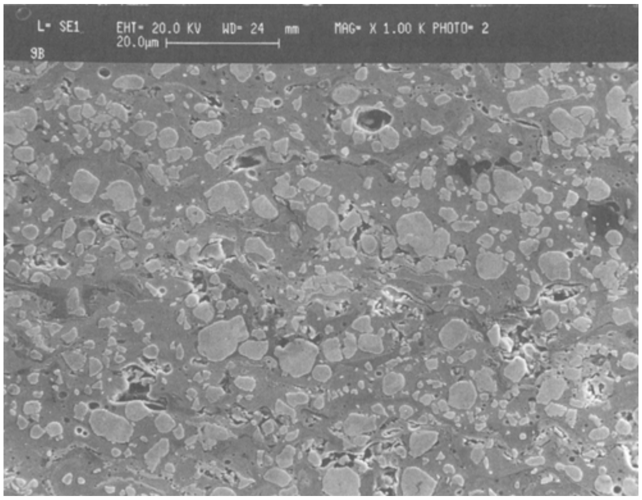

Fig. 11 SEM micrograph of plasma coating H-1

Table 2 Rankings for resistance to cracking in bending

Coating system	Bend rank	Coating system	Bend rank
F-1	1	D-1	7
A-1	2	D-2	8
G-1	3	H-1	9
C-1	4	E-3	10
B-1	5	E-1	11
A-2	6		

4. Discussion

4.1 *Correlations*

Certain observations can be made regarding the connection between residual stresses and coating system performance. A comparison between the average coating residual stresses and the bend rankings for each coating system is shown in Fig. 12.

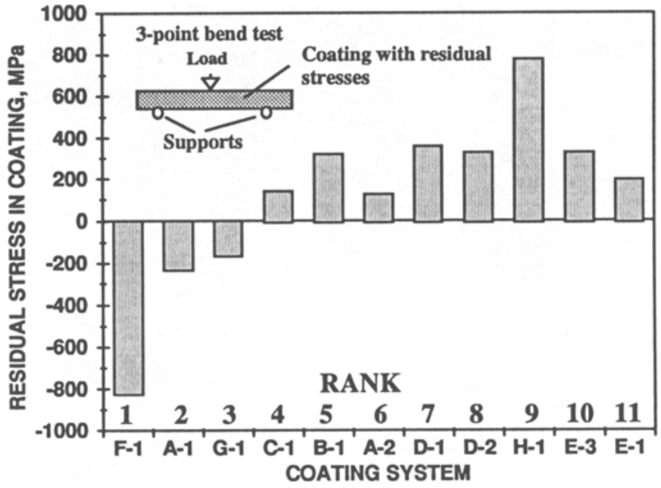

Fig. 12 Correlation of residual stresses in the coating to bend crack ranking

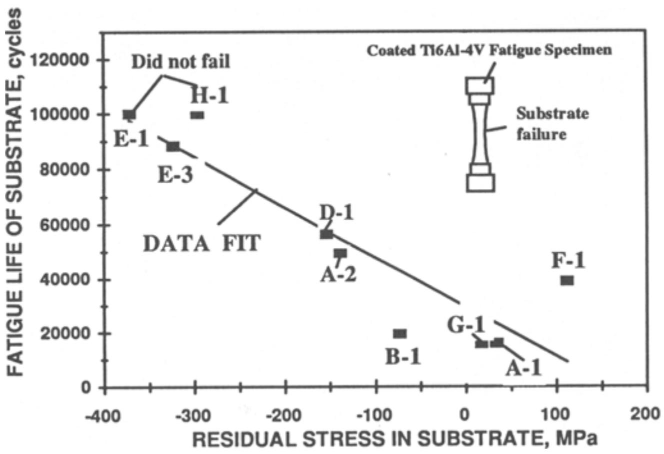

Fig. 13 Correlation of substrate fatigue life and substrate residual stress near the coating/substrate interface

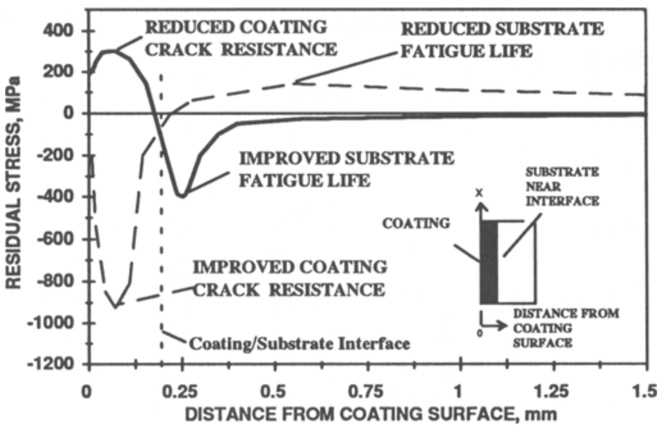

Fig. 14 Relation of through-thickness residual stresses to cracking resistance of the coating and fatigue properties of the substrate

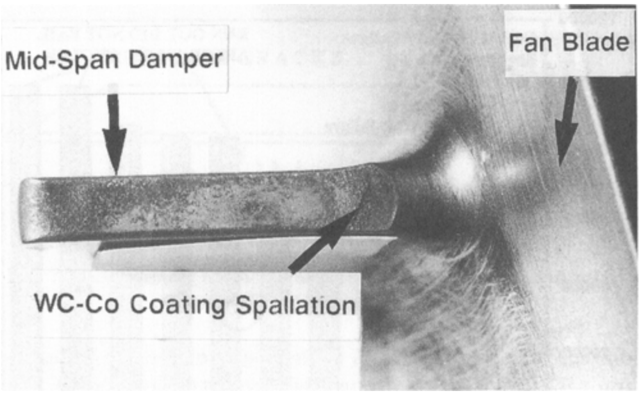

Fig. 15 Spallation failure of coating system F-1 during jet engine performance evaluations for midspan dampers

Those coatings with compressive residual stresses had the best bend rankings, whereas coatings with tensile residual stresses had reduced crack resistance. These results imply that compressive residual stresses in the coating will greatly enhance coating crack resistance in bending.

A correlation of substrate fatigue life and residual stresses in the substrate is presented in Fig. 13, which shows that substrates with compressive residual stresses can have a significantly improved fatigue life compared to substrates with tensile residual stresses. This is an interesting result, because coating systems with compressive residual stresses in the substrate will likely have tensile residual stresses in the coating, which results in reduced crack resistance for the coating.

Results for coating crack resistance in bending and for the fatigue life of the substrate suggest that a coating system selection can be based on the residual stresses in the coated part and the design criteria for the part. A coating system with a relatively high coating crack resistance due to compressive residual stresses in the coating could have a lowered substrate fatigue life due to tensile residual stresses in the substrate. This would be the coating system of choice if coating cracking is unacceptable and if substrate fatigue life can be improved through appropriate design of the component. A coating system with a relatively low coating crack resistance due to tensile residual stresses in the coating could have an increased substrate fatigue life due to compressive residual stresses. This would be the coating system of choice if coating cracking is acceptable and if substrate fatigue life is the most important design criterion. Figure 14 summarizes the relation of residual stresses to coating crack resistance and substrate fatigue life.

4.2 *Selection of a Coating System for Midspan Dampers*

Results for bend rankings, fatigue life of the substrate, and residual stresses for three coating systems are listed in Table 3. These coatings were selected because of their varied performance properties. Systems A-1 and F-1 have superior coating crack resistance, and system H-1 has superior substrate fatigue properties.

Each coating system listed in Table 3, as well as many of the other systems investigated here, were evaluated on fan blades

Table 3 Comparison of coating systems F-1, A-1, and H-1

Coating system	Coating residual stress, MPa	Bend rank	Substrate residual stress, MPa	Substrate fatigue life, cycles
F-1	–822	1	115	39,000
A-1	–234	2	45	16,000
H-1	770	9	–300	>100,000

with midspan dampers while in a stationary jet engine. The jet engine performance evaluations simulated actual in-service conditions. The performance evaluations were used as a validation for final coating selection, and residual stress, bend ranking, and fatigue life evaluations were used to gain an understanding of coating performance.

Results from the jet engine performance evaluations suggest that coating systems with compressive residual stresses in the coating have extended performance lives compared to coatings with tensile residual stresses. However, an interesting observation has been made regarding the coating system with the greatest magnitude of coating compressive residual stress (–822 MPa), F-1. Figure 15 shows a photograph of a midspan damper with the F-1 coating system that has a spallation failure after being tested in the jet engine performance evaluation. A possible explanation for the spallation failure of this coating is that the high level of compressive residual stress in the coating combined with in-service compressive stresses may be near the ultimate compressive strength of the thermal spray tungsten carbide material (Ref 12). Therefore, a coating with a lower magnitude of compressive residual stress (approximately –250 MPa) would be less susceptible to spallation, because the stress would likely be farther from the ultimate compressive stress limit. Other coatings with lower levels of compressive stress, such as A-1, had satisfactory jet engine performance evaluations. Coatings with tensile residual stresses, such as H-1, experienced coating cracking and spallation failures that rendered their performance unsatisfactory. This supports the contention that coating compressive stresses are essential for satisfactory midspan damper performance as long as the sum of the in-service stress and the residual stress is below the level that induces spallation.

Based on the bend, fatigue life, residual stress, and jet engine performance evaluations, A-1 was selected as the primary coating system for midspan damper production. This coating system has a level of compressive residual stress in the coating that does not induce spallation, and it exhibited the best jet engine performance. Although the substrate fatigue life of this coating system may be lower than that of other candidate coating systems, the level of coating compressive residual stress is sufficiently large to suppress coating crack initiation, which could lead to crack propagation into the substrate. The possibility of reduced substrate fatigue life has been considered for production midspan damper life evaluations.

5. Summary and Conclusions

An experimental research program was developed to evaluate tungsten carbide thermal spray coatings for midspan dampers. A strong link was found between residual stresses and coating performance. Coated specimens with high coating crack resistance showed compressive residual stresses in the thermal spray coating. Coated specimens with compressive residual stresses in the substrate had longer substrate fatigue life. However, the highest level of coating compressive residual stress resulted in coating spallation. These results suggest that an appropriate level of compressive residual stress in the coating is advantageous to thermal spray coating performance.

Results from this research project have been used to select a suitable coating system for production midspan dampers. The coating system selected has logged numerous hours of jet engine performance time without a failure. The compressive residual stress in the coating is at an appropriate level to improve coating crack resistance, without inducing coating spallation. Jet engine performance evaluations also confirm that the level of compressive stress in the coating is sufficient to avoid crack propagation into the substrate.

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