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HVOF Coatings for Heavy-Wear, High-Impact Applications

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The aircraft hookpoint used for an arrested landing is exposed to various forms of heavy wear and impact. Nowhere is this more true than training field landings, where the hookpoint is subjected to drag along a concrete runway for possibly thousands of feet while flying at high speeds and heavy downloads. After extensive screening, a series of materials were subjected to special impact tests and concrete wear tests. Ten coatings, applied by thermal spray, were selected for future arrestment testing on the basis of these results.

Keywords aircraft hookpoints, comparative properties tests, HVOF process, spray and fuse, wear-resistant coatings

1. Introduction

Hookpoints used on A-4 aircraft are subjected to considerable wear. During arrested landings at speeds greater than 100 mph (160 kph), the hookpoint is lowered 1000 ft (305 m) in front of the cable and then held under an 800 lb (365 kg) load while it scrapes across the concrete runway. The wear on the bottom of the hooks under these conditions limits their life to three to ten landings. The wear problem warranted attempts at improving the hookpoint life; the problem is further aggravated by the fact that the U.S. Navy has no qualified vendors at this point (in 1996).

It was suggested that a high-velocity oxyfuel (HVOF) coating applied to the bottom of the hooks after manufacture might improve wear life. In addition, development of an adequate coating could permit multiple reapplications to truly extend the hookpoint life. The wide variety of coating systems available, coupled with the severity of the application, suggested that laboratory screening tests might reduce the number of candidate systems needed for actual arrestment tests. The results of the screening tests are detailed in this article.

2. Coating Selection

The selected candidates would have to perform in situations beyond the realm of their usual recommended conditions. These coatings would have to withstand the heavy impact jolt to which the bottom of the hookpoints would be subjected, then withstand the heavy wear. In the past, a welded coating of Stellite 6 had significantly improved the life of the hookpoint, but several plasma-sprayed coatings had failed to withstand impact loads. In addition, an HVOF coating in an A-6 hook cable groove had spalled after one arrestment in 1981. A "D-gun" coating of 8Co-WC had also been used. Experience showed that sprayed and fused coatings of NiCrB work well in both the cable groove and the bottom of hookpoints, with the softer Metco 12C coating providing better wear life than Metco 16C (SulzerMetco, Westbury, NY). Also, cobalt-base Stellite coatings, when HVOF sprayed, were significantly harder than welded coatings—probably because these alloys work-harden very rapidly, and self-work-hardening occurs during spraying. Powder oxidation during spray may also aggravate or cause this problem.

It was believed that as any of the thermal-sprayed coatings were increased in thickness, residual tensile stresses in the coatings would tend to reduce impact strength, particularly for the hard carbide systems that had the ability to withstand heavy wear loads. In this screening test program, the thickness of harder coatings was limited to a maximum of 0.025 in. (0.64 mm), with many of the test samples sprayed at 0.010 in. (0.25 mm).

Since the cable groove coatings were fusable NiCrB coatings, HVOF versions were added to these hookpoint tests. Note that "spray-and-fuse" variations were not considered for actual hookpoints because the high fusing heat might generate a very coarse base metal structure as well as cause cracks in the steel alloy used for the A-4 hookpoint. A spray-and-fuse sample of Metco 12C was included as a control for comparison purposes.

Low friction coefficient systems (i.e., molybdenum) also were evaluated. Originally it was intended to evaluate only HVOF-sprayed materials since the usual plasma-sprayed coatings would not have the impact resistance to withstand the landing shock. However, twin wire arc coatings were evaluated as well, since a different quality coating (probably a higher oxide content with more lubricity) evolves that may exhibit a bond quality superior to plasma-sprayed coating systems. In addition, cobalt-molybdenum systems (Tribaloy alloys) were tested. Here, the Laves intermetallic phases enabled classification of these materials as "hard" systems, but the reported low friction coefficients were similar to those of molybdenum alloys. The Tribaloy systems were classified as molybdenum based, although this is not completely accurate.

Ferrochrome alloys with high boron contents, which had been shown to develop amorphous layers, especially after abrasion, also were selected. These materials had proved successful

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in the oil drilling industry, showing considerable wear resistance while drilling through rock. Finally, the possibility of using laser-welded coatings was investigated, with welds applied directly to the fully hardened hookpoints. A quick investigation indicated that the costs of such coatings would be prohibitive. However, laser-quality welds might be obtained with "mini" plasma transferred arc (PTA) welds at significantly lower costs. A test sample of a welded Stellite that produced a very small heat-affected layer was added to the test series.

The candidate materials selected for the test program, along with coating thicknesses, are listed in Table 1. The HVOF molybdenum samples were sprayed by two different vendors; therefore, coating qualities probably vary. However, the test results were very similar; thus indicating the reproducibility of coating procurement.

3. Test Program

The test programs used for evaluation were designed and executed by the Dayton T. Brown company.

3.1 *Types of Tests*

Two types of comparison tests—wear and impact—were used for the screening evaluation of coatings. The tests were designed to employ the same type and configuration of test samples for ease of sample preparation and uniformity. The impact test would be used to evaluate the ability of a coating to resist cracking and debonding under heavy impact conditions. The wear test would be used to evaluate resistance to wear and heat that result from rubbing against concrete under load. A baseline

Table 1 Coating selection

Identification (ID) no.	Coating system	Thickness, in. (mm)
Carbide systems		
1	8Co-WC	0.010 (0.25)
2	25NiCr-CrC	0 010 (0.25)
3		0.025 (0.6)
Fusible coatings		
4	Metco 15 (17Cr, 4Si, 4Fe, 3.5B, 1C, bal Ni)	0.025 (0.6)
5		0.050 (1.3)
6		0.100 (2.5)
7	Colmonoy 88 (15Cr, 4Si, 3.5Fe, 3B, 0.80C, 17 3W, bal Ni)	0.010 (0.25)
8		0.025 (0.6)
9	Metco 12C (10Cr, 2.5Si, 2.5Fe, 2.5B, 0.015C, bal Ni)	0.050 (1.3) (sprayed and fused)
Cobalt alloys		
10	Stellite 6 (28Cr, 1.1C, 1Si, 12W, bal Co)	0.050 (1.3)
11		0.125 (3.2) (Sermatech mini PTA weld)
12		0 125 (3.2) (Eutectic mini PTA weld)
13	Stellite 21 (27Cr, 0.25C, 5.5Mo, 2.8Ni, bal Co)	0.050 (1.3)
14	Stellite 25 (20Cr, 0.1C, 3Fe, 10Ni, 15W, 1.5Mn, bal Co)	0.050 (1.3)
15		0.100 (2.5)
Molybdenum (high-lubricity) based alloys		
16	Pure molybdenum	0.050 (1 3) (twin wire arc sprayed)
17		0.100 (2.5) (twin wire arc sprayed)
18		0.035 (0.9) (HVOF Metco DJ sprayed)(a)
19		0.050 (1.3) (HVOF Metco DJ sprayed)(a)
20	Tribaloy T-400 (62Co, 28Mo, 8Cr, 2Si)	0.010 (0.25)
21		0.025 (0.6)
22	Tribaloy T-800 (52Co, 28Mo, 17Cr, 3Si)	0.010 (0.25)
23		0.025 (0.6)
Amorphous ferrochromes		
24	Armacor M (28Cr, 1.6Si, 1.7Mn, 3 7B, bal Fe)	0.010 (0.25) (HVOF)
25		0.050 (1.3) (twin wire arc)
26		0.125 (3.2) (Eutectic mini PTA)
27	Duocor	0.050 (1.3) (twin wire arc)

(a) DJ, diamond jet

was established by using fused Metco 12C on one of the samples as a control for impact tests. Metco 12C is the coating presently used on all fleet hookpoints.

3.2 *Sample Preparation*

The test samples were made of 3340V alloy steel, the material used for hookpoint manufacture. Each sample was a 3 in. (75 mm) diam circular disk, 0.5 in. (13 mm) thick. The samples were ground flat and parallel to 0.002 in. (0.05 mm), with a 32 surface finish. The samples were heat treated to 46 to 49 HRC, the hardness of actual fleet parts, then cleaned and blasted to a 350 µin. (9 µm) rms finish in preparation for coating application. Coatings were applied to each disk by the appropriate process to a specific designed thickness.

3.3 *Impact Test Procedure*

The impact test machine consisted of an 8 ft (2.4 m) aluminum tower with a sliding arm mechanism to which the coated samples were attached. The sliding arm mechanism, supported by teflon bearings, could be raised to any height from 0 to 8 ft (0 to 2.4 m), held, and then released—with its drop being guided onto an impact surface. The weight of the sliding arm, including the test sample, was approximately 3 lb (1.4 kg), including the 0.5 lb (0.2 kg) test coupon. The impact surface was 1 in. (25 mm) diam stainless steel with a hardness of 57 to 61 HRC.

Single or repeated impacts could be obtained from specific tests. Samples were originally to be impacted in the center of the coating, then inspected. However, no cracking or debonding occurred in the first few samples dropped from the maximum height. No comparisons were possible unless some damage was found; therefore, to help induce failure, the impact samples were sectioned 1 in. (25 mm) from an edge to expose a straight section of coating on base metal. Multiple drops could be used from any height and the exposed interface inspected at the cut interface for coating cracks after every drop. The number of drops required to cause cracking was used as the measure for impact quality.

Initially, 3 ft (0.9 m) drops were used to screen the samples to a maximum of 50 drops. If no failures occurred, the drop height was increased to 6 ft (1.8 m). Only one sample did not fail using the 6 ft (1.8 m) drop, so no additional height adjustment was necessary.

Table 2 Cracking properties of alloy coatings

ID No.	Coating system	Nominal thickness mils	Nominal thickness µm	Conditions for observed cracking(a)
Carbide systems				
1	Co-WC	10	255	6 ft, 10 drops
2	25NiCr-CrC	10	255	6 ft, 10 drops
3	25NiCr-CrC	25	635	6 ft, 40 drops
Fusible coatings				
4	Metco 15	25	635	6 ft, 5 drops
5	Metco 15	50	1270	3 ft, 45 drops
6	Metco 15	100	2540	3 ft, 50 drops
7	Colmonoy 88	10	255	6 ft, 9 drops
8	Colmonoy 88	25	635	3 ft, 5 drops
9	Fused Metco 12C	50	1270	6 ft, 10 drops
Cobalt alloys				
10	Stellite 6	50	1270	3 ft, 44 drops
11	Stellite 6, Sermatech mini PTA	125	3175	Did not crack
12	Stellite 6, Eutectic mini PTA	125	3175	3 ft, 22 drops
13	Stellite 21	50	1270	3 ft, 19 drops
14	Stellite 25	50	1270	3 ft, 22 drops
15	Stellite 25	100	2540	6 ft, 20 drops
Molybdenum alloys				
16	Pure Mo, wire arc	50	1270	3 ft, 13 drops
17	Pure Mo, wire arc	100	2540	3 ft, 8 drops
18	Pure Mo, HVOF	35	890	3 ft, 48 drops
19	Pure Mo, HVOF	50	1270	3 ft, 5 drops
20	Tribaloy T-400	10	255	6 ft, 25 drops
21	Tribaloy T-400	25	635	6 ft, 37 drops
22	Tribaloy T-800	10	255	6 ft, 21 drops
23	Tribaloy T-800	25	635	6 ft, 43 drops
Amorphous ferrochromes				
24	Armacor M, HVOF	10	255	6 ft, 15 drops
25	Armacor M, wire arc	50	1270	3 ft, 37 drops
26	Armacor M, Eutectic PTA	125	3175	3 ft, 2 drops
27	Duocor, wire arc	50	1270	3 ft, 21 drops

(a) 3 ft = 0.9 m; 6 ft = 1.8 m

3.4 *Wear Test Procedure*

The wear test machine consisted of a steel structure housing a 150 hp motor connected through bearings and a shaft to a 2 ft (0.6 m) diam steel wheel. The wheel was filled with concrete reinforced with reinforcement bar and fiberglass to a depth of 18 in. (455 mm). The steel disk samples were attached to hydraulic rams that could apply load to the samples while the coated faces were in contact with the rotating wheel. The intent of the test was to simulate a hookpoint being dragged along a concrete runway during an arrestment and to obtain a comparative measure of the wear resistance of the coating.

After experimentation, the sample loading was chosen to be 100 lb (45 kg). A cooling spray on the wheel was necessary to avoid an unrealistic heat buildup. The heat buildup occurred as a result of the high speeds used for the test; the concrete wheel speed was 1,750 rev/min, and the disk contacted the wheel 19 in. (480 mm) from the center of the wheel. This produced a surface speed of 145 ft/s (45 m/s), equivalent to 100 mph (160 kph) aircraft speed. The heat buildup in the test was more severe than on the hookpoint because of the reduced heat sink of the test.

For each test, the wheel was run 1 min clockwise and then 1 min counterclockwise. This created an equivalent of approximately 0.060 in. (1.5 mm) loss on an uncoated steel disk, which is the estimate for metal loss of an actual hookpoint. Coating thickness was measured before and after each run to determine metal loss. The coatings were inspected for cracks or other abnormalities at the end of the test.

3.5 *Impact Tests*

The results of the impact test are shown in Table 2. The best system for withstanding impact was the welded Stellite 6 applied by the Sermatech mini PTA (no. 11) (Sermatech International Inc., Limerick, PA). This material did not fail in these tests. Although this result would have been expected from a weld overlay onto a softer steel, it was encouraging to find that welding onto alloy steel hardened to 50 HRC did not generate residual stresses or cracks from the welding process. The PTA welds with the Eutectic welder (Eutectic Corp., Flushing, NY) were not as successful. The impact results for the same material, Stellite 6 (no. 12), indicated that cracks developed from 3 ft (0.9 m) drops, and this welded sample did not fare as well as most of the HVOF systems. The ferrochrome Armacor alloy was cracked in the as-welded condition. The poor impact results exhibited by this material were as much a reflection of the weld quality as they were of the material capability.

In general, the hard particle systems did well in the impact tests. None of the carbide materials (no. 1 to 3) cracked from 3 ft (0.9 m) drops, nor did the Tribaloy materials (no. 20 to 23) or Colmonoy 88 (no. 7) (Wall Colmonoy Corp., Madison Heights,

Table 3 Hard carbide materials

ID No.	Coating material	Thickness		Bond strength		Hardness		Impact	Loss		Wear result
		mils	μm	psi	MPa	DPH	HR15N		mils	μm	
1	8Co-WC	10	255	>11,000	>75	...	...	6 ft, 10 drops	1	25	No cracks
									2	50	No cracks
2	25NiCr-CrC	10	255	>12,000	>80	1060	90 6	6 ft, 30 drops	3	75	Minute cracks
									3	75	Minute cracks
3	25NiCr-CrC	25	635	...	...	...	...	6 ft, 40 drops	4	100	Light cracks
									2	50	Light cracks

Table 4 Fusible materials

ID No.	Coating material	Thickness		Bond strength		Hardness		Impact	Loss		Wear result
		mils	μm	psi	MPa	DPH	HR15N		mils	μm	
4	Metco 15	25	635	8,489	58.5	785	89	6 ft, 5 drops	14	356	Severe cracking; some coating loss
									12	305	Severe cracking; some coating loss
5	Metco 15	50	1270	...	...	...	...	3 ft, 24 drops	11	279	Severe cracking; some coating loss
									15	380	Severe cracking; some coating loss
6	Metco 15	100	2540	...	...	...	...	3 ft, 50 drops	8	203	Severe cracking; major coating loss
									23	584	Severe cracking; major coating loss
7	Colmonoy 88	10	255	10,196	70.3	760	81 8	6 ft, 9 drops	8	203	Light cracks
									8	203	Light cracks
8	Colmonoy 88	25	635	...	...	...	...	3 ft, 5 drops	1	25	Severe cracks; major coating loss
									5	127	Severe cracks
9	Fused Metco 12C	50	1270		..	...	74	6 ft, 10 drops	19	483	Minute cracks
									11	279	No cracks

Table 5 Cobalt-base materials

ID No.	Coating material	Thickness		Bond strength		Hardness		Impact	Loss		Wear result
		mils	μm	psi	MPa	DPH	HR15N		mils	μm	
10	Stellite 6	50	1270	>12,000	>80	645	87 4	3 ft, 44 drops	N/A		Entire coating lost at start of test; one very severe crack
11	Stellite 6, Eutectic mini PTA	125	3175	N/A		...	91	3 ft, 22 drops	77	1956	No cracks
									86	2184	No cracks
12	Stellite 6, Sermatech mini PTA	125	3175	N/A		...	77	Could not get coating to crack	30	762	No cracks
									29	737	No cracks
13	Stellite 21	50	1270	7,907	54.5	605	85.9	3 ft, 19 drops	3	75	Severe cracking; major coating loss
									4	100	Severe cracking; major coating loss
14	Stellite 25	50	1270	7,816	53.9	430	84.8	3 ft, 22 drops	N/A		Severe cracking; major coating loss
									N/A		Severe cracking; major coating loss
15	Stellite 25	100	2540	...	...	...	...	3 ft, 50 drops	N/A		Severe cracking; major coating loss
									N/A		Entire coating lost; adhesion during test

Table 6 Molybdenum-base materials

ID No.	Coating material	Thickness		Bond strength		Hardness		Impact	Loss		Wear result
		mils	μm	psi	MPa	DPH	HR15N		mils	μm	
16	Mo, wire arc	50	1270	2757	19.0	345	65.4	3 ft, 13 drops	11	279	No cracks
									17	432	No cracks
17	Mo, wire arc	100	2540	...	...	...	...	3 ft, 8 drops	19	483	No cracks
									21	533	No cracks
18	Mo, HVOF	35	890	Not measured		...	...	3 ft, 48 drops	1	25	Severe cracking; major coating loss
									4	100	
19	Mo, HVOF	50	1270	2294	15.8	505	85.2	3 ft, 5 drops	4	100	Severe cracking; major coating loss
									4	100	
20	Tribaloy T-400	10	255	7413	51.1	645	88.8	6 ft, 25 drops	9	229	Light cracks; minor coating loss
									8	203	Moderate cracks; minor coating loss
21	Tribaloy T-400	25	635	...	...	...	...	6 ft, 37 drops	15	381	Moderate cracks
									13	330	Minor coating loss
22	Tribaloy T-800	10	255	7238	49.9	660	88.6	6 ft, 21 drops	2	50	Minor cracks
									3	75	Slight coating loss
23	Tribaloy T-800	25	635	...	...	...	...	6 ft, 43 drops	10	255	Moderate cracks
									9	229	Moderate cracks

Table 7 Amorphous ferrochromes

ID No.	Coating material	Thickness		Bond strength		Hardness, HR15N	Impact	Loss		Wear result
		mils	μm	psi	MPa			mils	μm	
24	Armacor M, HVOF	10	255	>10,000	>70	91	6 ft, 15 drops	8	203	Minute cracks
								5	127	Minute cracks
25	Armacor M, wire arc	50	1270	...	...	86	3 ft, 37 drops	12	305	Moderate cracks
								15	381	Moderate cracks
26	Armacor M, Eutectic PTA	125	3175	N/A		84	3 ft, 2 drops	3	75	Severe cracks
								3	75	Severe cracks
27	Duocor, wire arc	50	1270	...	...	85	3 ft, 21 drops	17	432	Light cracks
								16	406	Moderate cracks

MI). The latter materials also have very hard particles embedded in a softer matrix material. Surprisingly, some of these materials did better in these tests than the sprayed and fused coating of Metco 12C (no. 9). Since the fused material is softer and metallurgically bonded to the substrate, the fact that it was outperformed by some HVOF systems was unexpected.

None of the coatings applied by the twin wire arc system sustained drops of 6 ft (1.8 m). It is not known how this represents the material capability or the application technique. With pure molybdenum (no. 16 to 19), the results were about the same for both HVOF- and wire-arc-applied samples. Slightly thinner HVOF samples performed better under impact tests. On the other hand, the HVOF-applied amorphous material was one of the better samples in impact, and the twin-arc-applied samples were mediocre in performance.

Comparisons of wire-arc-applied versus HVOF-applied coatings should also take thickness into consideration. Except for the welded Stellite 6 and the fused Metco 12C, none of the samples applied to thicknesses of greater than 0.025 in. (0.6 mm) were able to sustain drops of 3 ft (0.9 m) without cracking. With direct comparisons of the same material, these tests frequently showed better results with heavier coatings (i.e., NiCr-CrC, Tribaloy, and Stellite 25). It is also possible that residual stresses become significant at some thickness value, at which point coating impact quality starts to deteriorate. The use of 0.050 in. (1.3 mm) thick material has been questioned for both the HVOF molybdenum and the amorphous metal. The only fusible materials to withstand drops of 3 ft (0.9 m) were the Colmonoy 88 and Metco 15 applied at thicknesses of 0.010 and 0.025 in. (0.25 and 0.6 mm), respectively.

3.6 *Wear Tests*

Wear test results for duplicate samples are shown in Tables 3 to 7, which also include data on the mechanical properties (bond strength, hardness, and impact resistance) of the coatings. A significant finding in the wear tests was the realization that for this application, in addition to wear and impact, the ability to withstand thermal stresses may become a significant factor. All of the Stellite and Metco 15 samples failed more from thermal stress cracks and metal loss rather than from wearing down. It is possible that since all these materials were applied at heavier thicknesses, they were more sensitive to thermal gradients. The welded Stellite samples, however, exhibited no thermal cracks, even though they were 0.125 in. (3.2 mm) thick. The presence of thin oxide layers on the powder splats apparently affect the thermal conductivity of the HVOF coatings.

The carbide materials did not develop severe thermal cracks, nor did Colmonoy 88 at 0.010 in. (0.25 mm) (but not at 0.025 in., or 0.6 mm), the wire arc samples, welded Stellite, and the amorphous material. The Tribaloy samples exhibited reasonable wear properties and did not develop serious thermal cracks, but did suffer small amounts of coating loss. The PTA welded Armacor developed additional cracks, but no spalling occurred.

4. Concluding Remarks

The purpose of these tests was to help select candidate materials for actual hookpoint tests. The materials recommended for evaluation are shown in Table 8; other candidate materials for hookpoints are listed in Table 9.

Table 8 Materials to be evaluated for hookpoints

ID No.	Material	Thickness in.	mm
1	8Co-WC	0.010	0.25
2, 3	25NiCr-CrC	0.010, 0.025	0.25, 0.6
11	Stellite 6, mini PTA	0.125	3.2
16	Mo, wire arc	0.050	1.3
22	Tribaloy T-800	0.010	0.25
24	Armacor M, HVOF	0.020-0.025	0.5-0.6
26	Armacor M, mini PTA	0.125	3.2

Table 9 Potential materials to test for hookpoint applications

ID No.	Material	Reason for testing
3	Co-WC (0.025 in.)	Can WC coatings be used for heavier applications?
7	Colmonoy 88 (0.010 in.)	Was one of the better noncarbide materials for wear resistance.
20, 21	Tribaloy T-400	If wear is adequate, this material might be better for thermal shock.
25	Armacor M, wire arc	Can be applied heavier than the HVOF version
N/A	Armacor X-16, welded	Vendor claims this material is less crack-prone than the alloy used for the screening tests.

The first three materials in Table 8 were selected due to their excellent impact and wear characteristics. The 0.025 in. (0.6 mm) 25NiCr-CrC sample should also help determine how well heavier coatings will compare to 0.010 in. (0.25 mm) thick samples. The Armacor coating will be applied slightly heavier than the test sample, as can be inferred from the wear test results. The coating will be ground after application to initiate amorphous layer transformation. The Tribaloy materials exhibited excellent impact and wear resistance, but some spalling did occur. The test sample will reveal whether this happens in actual use.

The wire-arc-sprayed molybdenum will be evaluated on the basis of its excellent thermal stress crack resistance. Impact values for this material were low, but it is felt that better bond strength, which could improve impact resistance, is achievable.

The two welded samples were included for different reasons. Welded Stellite had been shown to improve wear life in the past; therefore, this test will determine whether the material can be safely welded after heat treatment. The welded Armacor was included because of the potential for increased wear for a heavy coating despite its poor impact strength. Quality control of the welds such that no cracking evolves during the process indicates that the Sermatech PTA welds would be better than the sample used in the current tests. Some effort at welding to normalized metal may also be evaluated as a possibility that this material be applied before heat treating on hookpoints manufactured in the future. The material is amenable to buildup with HVOF spraying after the initial weld application.