Deposition of carbides by Activated Combustion HVAF spraying

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In Activated Combustion HVAF process, coatings are formed of powder particles, heated and accelerated by high-velocity jet of air and gaseous fuel combustion products. A distinguished feature of the process is that spray particles are heated below their melting point while accelerated to velocity well above 700 m/s. Such spray scheme appeared beneficial for deposition of cemented carbides, in particular, WC-based composites. Dense, practically non-oxidized neither heat-deteriorated coatings were formed. Spray rates from 1 to 25 kg/hr were achieved without decline of coating quality or deposition efficiency. Specific coating structure resulted in noticeably improved resistance to fatigue at high level of stresses.

1 Introduction

Activated Combustion HVAF spraying (AC-HVAF) is relatively new technology, designed for deposition of dense and non-oxidized metallic and metal-carbide coatings [1]. A distinguished feature of the process is that spray particles are heated but not fused during spraying. The particle surface temperature usually remains 100-200^{o}C below their melting point. Herewith, improved efficiency of the spray guns results in achieving rather high spray particle velocities, measured within 700-850 m/s. The AC-HVAF sprayed tungsten carbide-based coatings revealed outstanding crack resistance, improved density and specific structure providing ability for super-finishing them to optical mirror surface, low level of residual stresses allowing a buildup of thick, over 10 mm, layers, etc. Current paper presents information on technological aspects of AC-HVAF spraying of tungsten carbide coatings and describes recent results on their fatigue testing.

2. Process Description

For deposition of carbides, the SB9300 gun was used, recently modified version of SB250 (Intelli-Jet^{TM} spray system of UniqueCoat Technologies, Ashland VA, USA). The gun consisted of a mixing chamber, an activated combustion chamber, internal and external nozzles, and a powder injection assembly. Major part of the air-fuel mixture combusted in the combustion chamber. Secondary combustion was organized in the external nozzle, fed with additional fuel and air. The spray powder was injected axially into combustion chamber. Propelled through the chamber and both nozzles, the powder was gradually heated and accelerated to form a coating when impacting a substrate.

A specific feature of the AC-HVAF gun was the patented combustion chamber. The chamber included hot ceramic rear wall with high temperature catalyst continuously activating combustion after initial ignition by a spark plug. This way, the combustion remained stable at high gas velocity without a need of pilot flames and specific gases. Propane, propylene or MAPP-gas was used as the fuel gas. The gun was cooled by the part of air, subsequently used for secondary combustion in the external nozzle. Nitrogen was used as the spray powder carrier gas.

3. Materials and Experimental Procedure

Test coatings were sprayed onto AISI 1018 carbon steel coupons, 75 x 25 x 6 mm size, aimed for metallography, wear and microhardness testing, as well as onto 150 mm diameter and 300 mm length carbon steel tubes, wall thickness 6 mm, used for deposit efficiency measurements. Spray powders were agglomerated and sintered WC-10Co-4Cr, WC-12Co and WC-17Co (manufactured by WOKA GmbH, Germany). Several powder cuts were evaluated. Sintered and crushed powder of WC-17Co (manufactured by Praxair-Tafa Inc., USA) was used for coating structure comparison.

Optical metallography was performed on coating cross-sections. X-ray diffraction analysis was carried on for powder stock and sprayed coatings. Microhardness testing of coatings was performed per ASTM E384 at 300 g load. The coating abrasive wear tests were conducted according to ASTM G65 (dry sand/ rubber wheel), using quartz sand Grade 70.

Within General Service Administration Task Order 5TS5701D056-02 and 5TS5702D035L-02 [2], the metallurgical and fatigue testing was performed onto WC-17Co AC-HVAF coatings by a group of companies, general contractor Concurrent Technology Corporation, Johnstown PA, USA. Metallurgical testing was performed for the coatings sprayed onto 50 x 50 x 6 mm plates of AISI 4340 carbon steel in accordance with General Electric Aircraft Engine Specification F5OTF71. The fatigue testing was conducted per ASTM E-466 at various maximum stress levels σ between 160 and 220 ksi (1.10 and 1.52 kPa) and at stress ratios R of 0.1 and –1.0. The original test material substrate was AISI 4340 steel, heat treated to 50 HRC and shot pinned, gage section diameter 6.2 mm, gage length 19 mm. Before testing, the coatings were machined to final thickness 100 micron. The coating integrity was evaluated by pictorial results and ranking of delamination, flaking and cracking as related to the specimen fatigue life. The ranking index was a ratio of noted cycle at which the above event occurred to the total cycles when the steel specimen failed.

4. Results and Discussion

4.1. Technological Aspects of WC-10Co-4Cr Coating Deposition

AC-HVAF Gun. The SB9300 gun was specifically designed for spraying of tungsten carbide materials. Compared to basic model SB9500, the smaller nozzle diameter in the SB9300 and corresponding changes in combustion chamber aimed to increase the gas pressure and temperature at reduced total gas flow. The former improved deposit efficiency of carbides. The latter reduced total heat input into the spray workpiece, this way providing better control of residual stresses in the coating. The results of WC-10Co-4Cr spray particle velocity and surface temperature measurements for both guns are presented in **Table 1**. The powder cut was 5-30 micron at average particle size 19.5 micron. The data were taken at standoff distance 150 mm.

Table 1. Gun operating parameters and WC-10Co-4Cr spray particle velocity V_p and surface temperature T_p measurement results

	Gun type		
	SB9300	SB9300	SB9500
Fuel gas	Propylene	Propane	Propane
Inlet air pressure, bar	5.95	5.95	5.95
Inlet fuel pressure, bar	6.02	5.74	5.6
Inlet secondary fuel pressure, bar	4.20	4.13	3.36
Total gas flow, m^3/s	0.083	0.083	0.130
Powder rate, g/s	2.8	2.8	2.8
V_p, m/s	800-820	720-740	690-720
T_p, ^oC	1400	1410	1310

According to the obtained data, the SB9300 gun heated particle surface about 100^{o}C higher than the SB9500 gun. The increase in particle velocity was not large though. The use of propylene instead of propane increased particle velocity about 100 m/s, but particle temperature remained similar to one when spraying with propane. In all cases, the surface particle temperature remained below cobalt alloy melting point. The data suggested higher efficiency of the SB9300 gun for deposition of tungsten carbide coatings. This gun was used in the all presented below experiments.

Spray Power Size. Four cuts of WC-10Co-4Cr powder were used to determine the influence of powder particle size on deposition efficiency and coating quality: 1-20, 5-30, 10-30 and 11-45 micron. Propylene was the fuel gas. The coatings were sprayed at 15-kg/hr powder rate. Average data are presented in **Fig.1**.

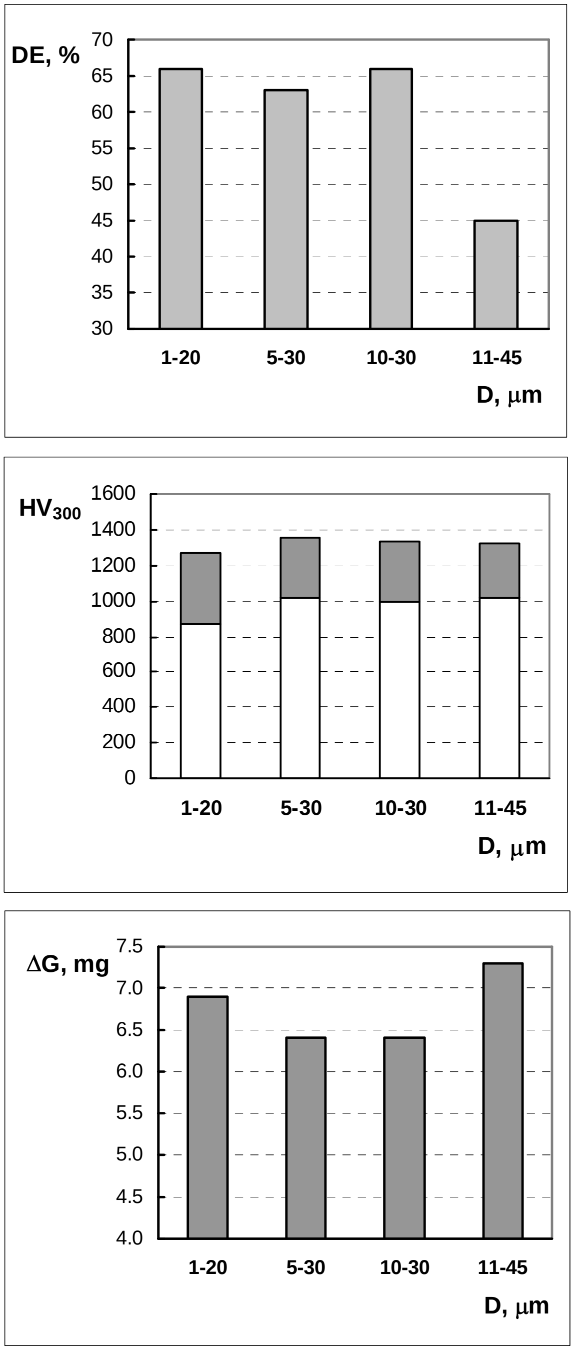

Fig. 1. Influence of WC-10Co-4Cr powder particle size D on the coating deposit efficiency DE, hardness HV_{300} and weight loss ΔG during abrasive wear test.

Appeared, that deposition efficiency of the first 3 powder cuts was rather similar, 63-66%. The data for 11-45 micron powder were noticeably lower, 45%. The coating hardness practically did not depend on the powder size sprayed. Wear resistance data were slightly better for the coating sprayed of 5-30 and 10-30 micron powder cuts.

Fuel Gas. Propane, propylene and MAPP-gas were used to spray WC-10C-4Cr powder of 5-30 micron cut to determine the influence of the gas type on coating deposition and quality. The coatings were sprayed at 15 kg/hr powder rate. Results are presented in **Fig.2**. It was found that the coating deposit efficiency was improved when using propylene instead of propane. However, little improvement over propylene was found when using MAPP-gas. The coating resistance to abrasive wear was rather similar when using different fuel gases, slightly worse for the coating sprayed with propane.

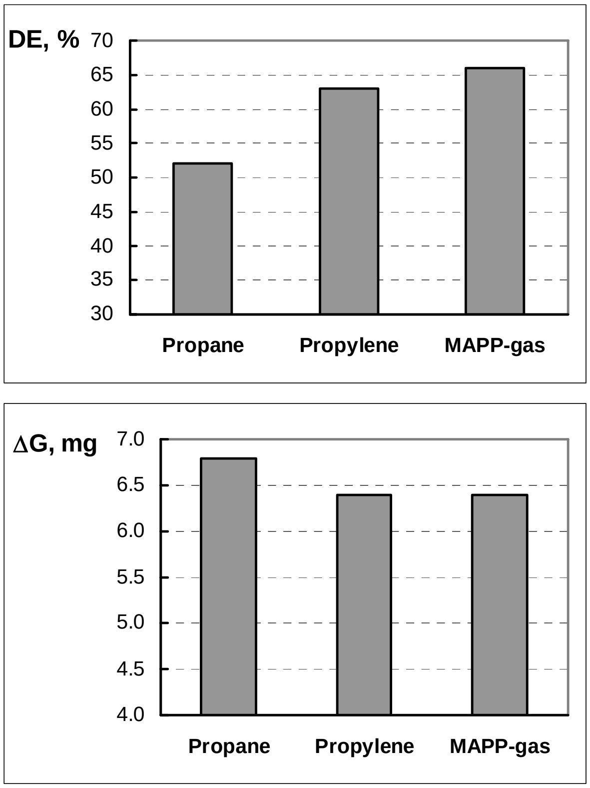

Fig. 2. Influence of fuel gas type on WC-10Co-4Cr coating deposit efficiency DE and weight loss ΔG during abrasive wear test.

Spray Rate. The increase of powder spray rate from 2 to 25 kg/hr had no negative effect on the WC-10Co-4Cr coating deposit efficiency. In fact, the lowest deposit efficiency (58-60%) was found when spraying at lower spray rates, such as 2 and 5 kg/hr. After spray rate exceeded 5 kg/hr, the deposit efficiency remained 63-65% up to spray rates of 25 kg/hr. The coating hardness remained unchanged, too. Utilized powder feeder did not allow further increase of the spray rates of WC-10Co-4Cr powder, 5-30 micron cut.

4.2. Coating Structure

The AC-HVAF method deposited very dense tungsten carbide- based coatings, **Fig.3**. Apparent metallographic porosity was well below 1.0% for all tested materials (WC-10Co-4Cr, WC-12Co, WC-17Co).

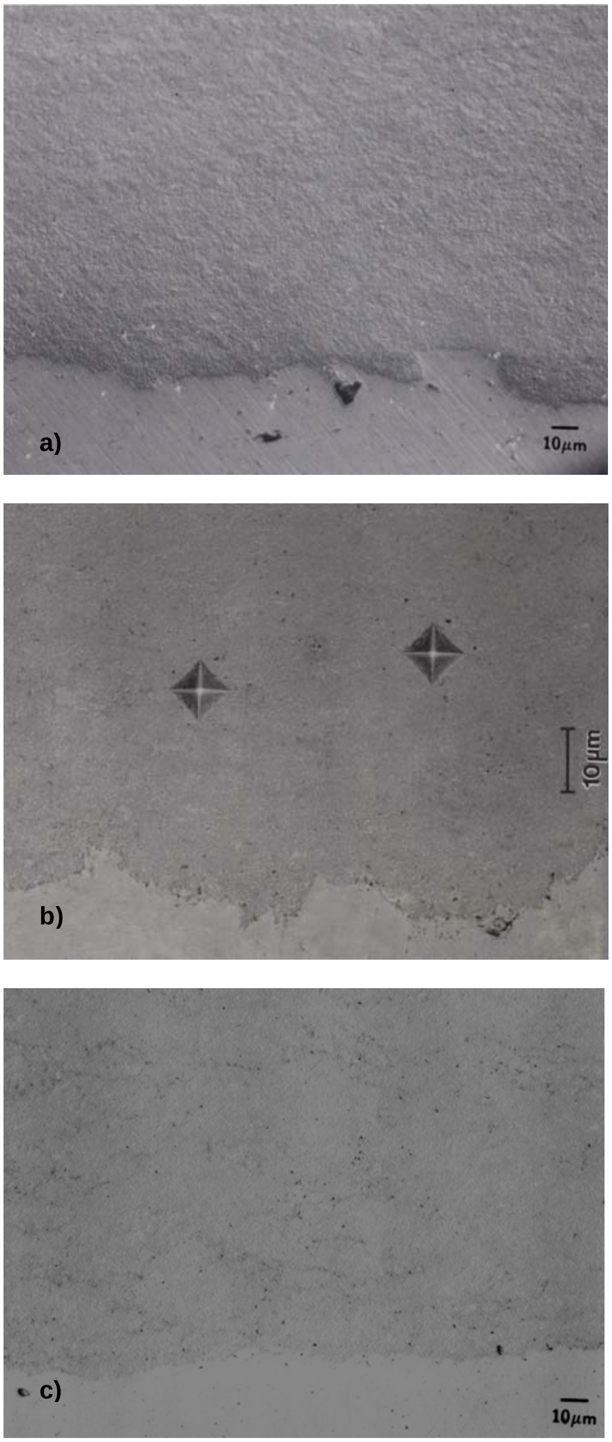

Fig. 3. Optical micrographs of WC-10Co-4Cr (a), WC-12Co (b) and WC-17Co (c) AC-HVAF coatings, x 500.

In optical micrographs, there was no significant difference found for coatings sprayed of agglomerated/ sintered or sintered/crushed powders. However, etching of mounts revealed that sintered/crushed powders were more deformed in the coating, while agglomerated/sintered powders remained essentially round in shape after deposition, **Fig.4**. The X-ray diffraction did not reveal changes in the coating structure compared to initial powder. Some decline in amount of W_2C traces was found in the coating compared to powder stock when spraying the WC-10Co-4Cr fine powder (1-20 micron).

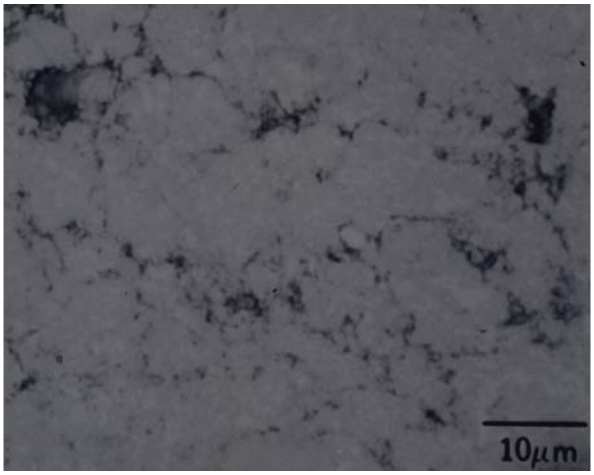

Fig. 4. Optical micrograph of WC-10Co-4Cr AC-HVAF coatings after etching, x 1000.

4.3. WC-17Co Coating Metallurgical and Fatigue Testing

The coatings were sprayed of agglomerated/sintered WC-17Co powder, particle size 10-30 micron, using SB9300 gun and propylene as the fuel gas. Metallurgical testing revealed that the coating met all requirements of GEAE F5OTF71 specification, which included analysis of transverse cracks, delamination, interface, voids, oxides, unmelts and other abnormalities. Measured by the two companies, the coating average microhardness was 979 and 965 HV_{300}, both data met minimal requirement of 950 HV_{300} set by GEAE F5OTF71CLA specification.

Specimen fatigue test results are presented in **Fig. 5**. The testing revealed that the coating remained intact practically to the moment of the steel specimen failure, **Table 2**, **Fig. 6**. After specimen failure, no coating delamination was found at maximum stress 1.28 kPa (R=01. and R=-1), and only minor coating delamination in failure zone at maximum stress 1.52 kPa (R=0.1). At the highest stress levels, some post-failure cracks and micro-flaking became evident in the coatings near the failure zone. Majority of those coating failures were caused by the substrate failure, and no surface flows were apparent prior to the failure.

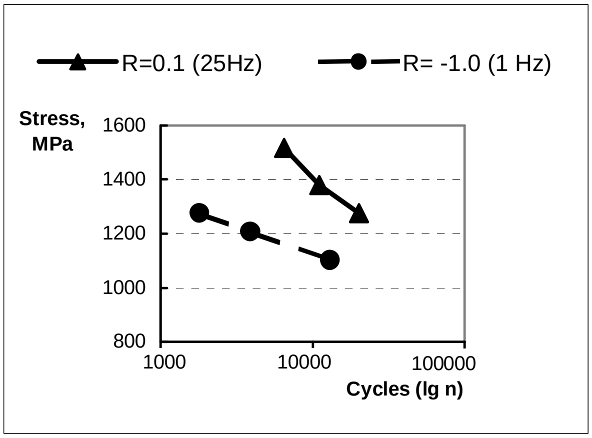

Fig. 5. Plot of fatigue life of 4340 (50 HRC) specimens with WC-17Co AC-HVAF coating

Table 2. Fatigue test data of AISI 4340 specimens with WC-17Co AC-HVAF coating and coating integrity evaluation per ASTM E-466

	Maximum stress σ, kPa		
	1.28 (R=0.1)	1.52 (R=0.1)	1.28 (R= -1.0)
Test frequency, Hz	25	25	1
Cycles to specimen failure	20,000	6,500	1,800
Coating integrity ranking index:			
Delamination	1.00	0.99	1.00
Flaking	None	0.99	None
Cracking	None	0.95	0.98

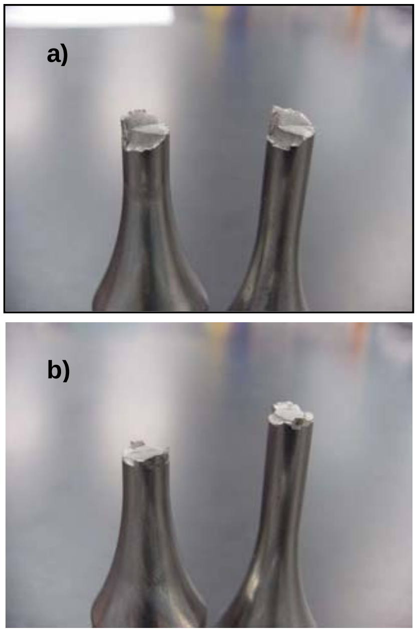

Fig. 6. Appearance of WC-17Co AC-HVAF coating after failure of AISI 4340 fatigue specimens. Test

conditions: a – σ=1.28 kPa, R= -1.0, 1Hz; b – σ=1.52 kPa, R=0.1, 25 Hz.
Retrieved data were compared to corresponding data for hard chrome and HVOF coatings [2, 3]. It was concluded that under current test conditions the WC-17Co AC-HVAF coating outperformed both counterparts. Thus, the AC-HVAF coating was considered as a promising alternative to hard chrome at high stress level applications.

5. Conclusions

Tungsten carbide based coatings were deposited by the Activated Combustion HVAF process (AC-HVAF), where spray particles were heated below melting point and accelerated to velocity well above 700 m/s. The deposition process with propane, propylene and MAPP-gas was investigated. The coating deposit efficiency was better when using propylene or MAPP-gas, however the coating structure, hardness and wear resistance remained similar when spraying with either gas. When spraying the WC-10Co-4Cr powders of different size, the best results were achieved for 5-30 and 10-30 micron cuts. The increase of spray rates from 1 to 25 kg/hr did not affect deposit efficiency or coating quality. Optical metallography and X-ray diffraction revealed that the coatings of WC-10Co-4Cr, WC-12Co and WC-17Co powders were of high density, without detectable oxidation or phase transformation as compared to initial powder stock. Metallurgical analysis and fatigue testing was performed on the AISI 4340 specimens with the 100 micron thick WC-17Co AC-HVAF coatings according to accepted by aircraft industry standards and specifications. The coating integrity during testing was a particular subject of the investigation. It was found that the coating structure and microhardness met the standard requirements. During fatigue testing at maximum stress level from 160 to 220 ksi (from 1.10 to 1.52 kPa) the coating remained intact practically to the moment of the steel specimens failure. Some coating cracking, minor delamination and micro-flaking in the specimen failure zone were found after the testing at the highest stress levels. Those surface flows were considered been caused by the substrate failure. It was concluded that the WC-17Co AC-HVAF coating outperformed the HVOF counterparts and hard chrome in similar test conditions, becoming a promising alternative to hard chrome at high stress level applications.

Acknowledgements

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Literature

[1] Verstak, A. and Baranovski, V.: Activated Combustion HVAF Coatings for Protection against Wear and High-Temperature Corrosion. Proceedings of the International Thermal Spray Conference 2003 “Thermal Spray 2003: Advancing the Science and Applying the Technology”, 2003, Vol.1. – ASM Publication.
[2] AFRL/MLSC/WPAFB Report: Alternative Technology Identification and Evaluation Screening. General Service Administration Task Order 5TS5701D056-02 and 5TS5702D035L-02, Subtask 56-02 Cold Spray Technology, March 31, 2003.
[3] AFRL/MLSC Report Number 02-069: Characterization of High Velocity Oxygen-Fuel (HVOF) Coatings for Aircraft Components. August 20, 2002.