

AC-HVAF Sprayed Tungsten Carbide: Properties and Applications

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Abstract

Activated Combustion HVAF (AC-HVAF) spraying provides efficient deposition of metallic and carbide coatings using solid particle spray technology. Oxidation and thermal deterioration of sprayed materials is significantly reduced, resulting in improved quality of coatings. Resistance of different WC-Co and WC-Co-Cr AC-HVAF coatings to abrasive wear was investigated using ASTM G-65 test. It was found that the AC-HVAF hardware setup, type of fuel gas and spray parameters affected deposition efficiency but not wear resistance of coatings. Herewith, the method of powder manufacturing revealed significant influence on coating wear resistance. The AC-HVAF sprayed coatings were compared to HVOF-sprayed counterparts, as well as to hard surfacing and chrome plating. The AC-HVAF sprayed coatings were efficient in competing with modern surfacing technologies in many industrial applications.

Introduction

Activated Combustion High-Velocity Air-Fuel spraying (AC-HVAF) is an emerging method for deposition of high quality coatings of cemented carbides and metallic alloys [1, 2]. Spray powder particles are heated and accelerated by products of internal combustion of air and gaseous fuel. Fuel is propane, propylene, MAPP-gas or natural gas. For tungsten carbide based powders, particle velocity exceeds 700 m/s, while particle surface temperature remains about 100°C below melting point of metallic binder, allowing AC-HVAF to operate in a "solid-particle" spray mode. The latter is possible due to relatively low combustion temperature of air-gaseous fuel mixtures at 3.5-4.5 Bar chamber pressure (maximal 1850°C for propane, 1900°C for MAPP-gas). The result is a formation of coatings with extremely low oxygen content as well as little, if any, thermal deterioration of carbides. Improved toughness, cohesion and low residual stresses in the AC-HVAF sprayed layers permit routine deposition of thick carbide coatings, superfinishing of coatings to optical mirror,

as well as result in noticeable improvement of fatigue resistance of the coatings. According to the US Air Force Research Lab data [3, 4], the WC-17Co AC-HVAF coatings outperformed HVOF counterparts in fatigue testing at increased loads and specifically when thicker layers applied, their integrity ranking similar or better than electroplated hard chrome coatings.

The total amount of working gases in the AC-HVAF guns is about 5 times larger than in HVOF, boosting spray rates of cemented carbides to over 30 kg/hr. Considering the lowered residual stresses in the coatings due to solid particle impact, thicker carbide layers are possible to apply per pass. This expands "high-productivity" mode of the AC-HVAF to a vast range of spray parts, not only to large surfaces. High spray rates, absence of oxygen and little consumption of spare parts make the cost of the AC-HVAF sprayed carbides very competitive to other hardface technologies, including casting, hard chrome electroplating, braze cladding and weld overlay.

In spite of dozens of tons of metallic and carbide coatings are sprayed with the AC-HVAF equipment annually, there is an evident lack of understanding of critical factors of this technology, partially because of its novelty. Such knowledge is important for further improvement of the AC-HVAF equipment, too. The paper attempts to analyze critical parameters of the AC-HVAF process for deposition of high quality wear resistant tungsten-carbide coatings.

Description of Equipment

Schematic of typical AC-HVAF gun is presented in Fig. 1. The back wall of its combustion chamber is made of perforated catalytic ceramic. After initial ignition of air-fuel mixture with a sparkplug, the ceramic is heated above the mixture auto-ignition temperature. The wall continuously ignites flowing through it mixture, activating combustion and making it stable within a wide range of gas flow parameters. This way activated combustion does not require large volume

chamber. It is short, allowing feeding of the spray powder axially through it.

The chamber ends up with an accelerating nozzle, where spray material is accelerated and further heated. In the SB9300 gun, a secondary nozzle of larger diameter is set after the primary (internal) nozzle. Air, cooling the gun, is fed into the secondary nozzle with additional amount of fuel, forming cascade combustion. Such design increases the gun efficiency and allows the precise control of spray particles temperature and velocity. The TSR3000H gun is made with a single nozzle, while longer than primary nozzle of the SB9300 gun.

Pictures of both operating guns are presented in Fig. 2. Note extremely narrow powder jets, typically less than 5-6 mm in diameter – a feature very different from HVOF process.

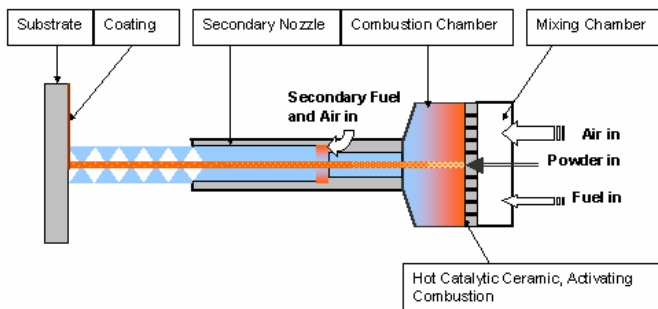


Figure 1: Schematic of the SB9300 gun of the AC-HVAF spray system.



Figure 2: Spraying carbides with SB9300 (a) and TSR3000H (b) guns.

Materials and Experimental Procedures

Spray Powders

The nominal chemical composition (wt.%) of spray powders was WC-10Co-4Cr. Three types of powders were chosen for analysis: agglomerated/sintered (WOKA 3632, Sulzer-Metco), sintered/crushed (Amdry 5843, Sulzer-Metco), fused/crushed (Amperit 553.065, H.C. Starck). Powders were supplied with 5-30 micron particle size. Amdry 5843 powder was screened through 400-mesh screen, resulting in 10-38 micron particle size distribution. Cross-sectional micrographs of the powders are presented in Fig. 3.

Agglomerated/sintered powder particles were of spherical shape and revealed the largest initial porosity. According to X-ray diffraction analysis, decomposition of WC was negligible ($I_{WC}/I_{W_2C} = 40-50$). Total carbon content was 5.3 wt.%. Sintered/crushed powder particles were of more irregular shape and denser. Initial decomposition of WC was also negligible ($I_{WC}/I_{W_2C} = 60-70$) and total carbon content was similar – 5.3 wt.%. Finally, fused/crushed powder particles were of irregular shape, initially very dense and with high degree of WC decomposition (about 10% of W_2C). Carbon content was about 4.0 wt.%.

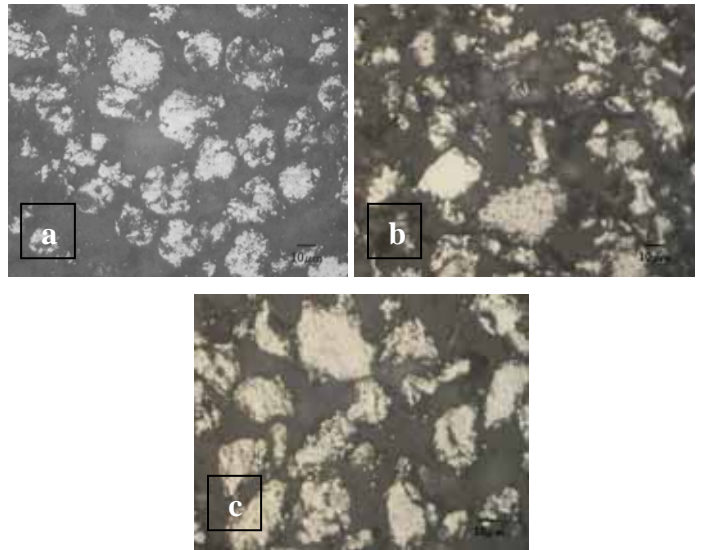


Figure 3: Cross-sectional micrographs of WC-10Co-4Cr powders (x 500): agglomerated/sintered (a), sintered/crushed (b) and fused/crushed (c).

Coatings

The WC-10Co-4Cr AC-HVAF coatings were sprayed with the SB9300 and TSR3000H guns using propane, propylene or MAPP-gas as a fuel gas and typical hardware setup for carbides spraying. For comparison, the WC-17Co and WC-12Co (wt.%) coatings were also applied of agglomerated/sintered powders. Wear resistance of the AC-HVAF sprayed

coatings was compared with typical HVOF sprayed counterparts: JP5000 (oxy-kerosene) and DJ2600 (oxy-hydrogen), supplied by GE Global Research (Niskayuna, New York). The HVOF coatings were sprayed of the same powders, but with particle size specific to each method (15-53 micron for JP5000 and 15-45 micron for DJ2600). Other surfacing technologies were represented by spray-fused Colmonoy 63 coating (Ni-15Cr-3.2B-4.8Si-4Fe alloy, applied by Mark 9 Colmonoy Fusewelder Torch, hardness 57-58 HRC after fusion) and Hard Chrome Electroplating (0.5 mm thick Hard Chrome coatings were supplied by Hard Chrome Co., Evansville, Indiana). All coatings were applied onto 75 x 25 x 6 mm carbon steel substrates.

Testing Procedures

Deposit Efficiency: The deposit efficiency (DE) of powders was measured by spraying onto 150 mm diameter rolls during 30 seconds and comparing the weight increase of the roll with the weight of powder spent.

Abrasive Wear Resistance: The coatings onto 75 x 25 x 6 mm coupons were tested according to ASTM G-65 wear test (dry sand- rubber wheel), Procedure A, using 50-70 mesh quartz sand, load 30 pounds, duration 10 minutes. Each coating was tested 2 times on the same wear pattern, and only second round data were used for analysis. Wear data were presented as coating volume loss per test. Standard deviation was estimated as 0.3 mm³. Several tests were also performed with coarser quartz sand (40-70 mesh) to compare the coatings performance under more severe wear conditions.

Structure: Coating structure was analyzed with optical metallography and X-ray Diffraction methods. Microhardness tests were performed at 300 g load.

Deposit Efficiency

Powder Type

Manufacturing method of spray powder affected the deposit efficiency of the AC-HVAF coatings strongly, exhibiting the lowest data for fused/crushed material, while similar ones for the other two types of powder (Table 1). The increase of content of fine particle below 5 micron in the powder resulted in slight drop of the deposit efficiency.

Structure of the coatings applied of agglomerated/sintered and sintered/crushed powders was similar, while the coatings of fused/crushed material revealed somewhat coarser carbides (Fig.4). The hardness appeared much higher for the coatings of fused/crushed powder (Table 1). It was similar for the other two materials. More low-hardness individual readings were obtained for the coatings of agglomerated/sintered powder with increased content of fines. The X-ray diffraction analysis revealed no increase of W₂C phase in the coatings compared to initial powders. Evidently, higher hardness of the coatings

applied of fused/crushed powder was attributed to the presence of hard phases in initial powder (products of WC decomposition and reaction with the metal binder).

Table 1: Typical deposit efficiency (DE) and micro-hardness data for WC-10Co-4Cr coatings, applied with SB9300 gun at 3.0 g/s (10.8 kg/hr) spray rate, MAPP as a fuel gas.

WC-10Co-4Cr powder type and particle size	DE, %	Hardness, HV ₃₀₀
Agglomerated/sintered, -30+5 micron	62	1050
Agglomerated/sintered, -30+10 micron	64	1100
Sintered/crushed, -38+10 micron	60	1120
Fused/crushed, -30+10 micron	43	1320

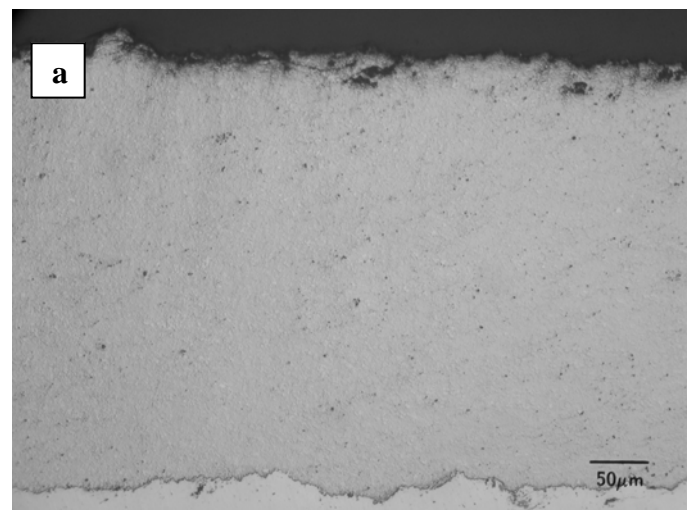


Figure 4: Micrographs of WC-10Co-4Cr coatings applied of agglomerated/sintered (a) and fused/crushed (b) powders; x 200.

Spray Rate

The AC-HVAF method allows substantial increase of spray rates of carbides compared to other thermal spray techniques. According to data in Fig. 5, the increase of spray rate up to 8.0 g/s (28.8 kg/hr) did not affect deposit efficiency of tungsten carbide powders sprayed with either fuel gas. Further increase of spray rate, up to 9.1 g/s (32.76 kg/hr), reduced deposit efficiency, but less than 1/10 of initial value.

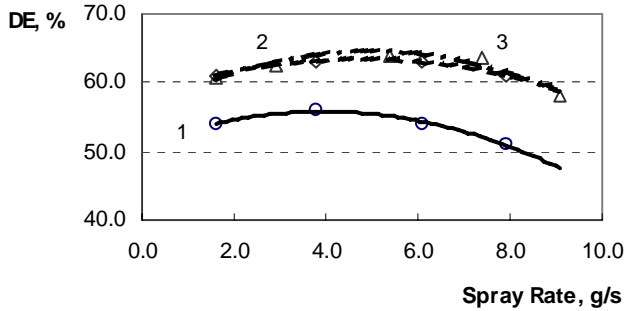


Figure 5: Influence of spray rate of WC-10Co-4Cr powder on deposit efficiency (DE) of AC-HVAF coatings applied with propane (1), propylene (2) and MAPP (3) fuel gas.

Nitrogen Flow Rate

Nitrogen was used as a powder carrier gas. It appeared that the increase of its flow rate greatly reduced the deposit efficiency of WC-powders (Fig.6). This finding resulted in certain design improvements in the AC-HVAF guns hardware, allowing minimization of the nitrogen flow. It also initiated further development of the AC-HVAF technology by changing the chemistry of the carrier gas, in particular, using hydrogen injections in it.

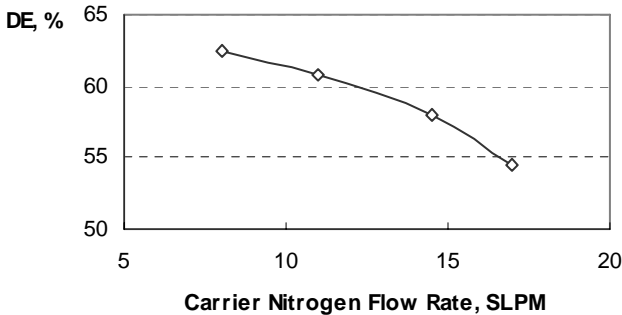


Figure 6: Influence of flow rate of nitrogen as a carrier gas on deposit efficiency (DE) of WC-10Co-4Cr AC-HVAF coatings, SB9300 gun.

Hydrogen

Injection of hydrogen into powder injector of the AC-HVAF gun dramatically improved heat transfer from hot gases of combustion chamber to the spray particles. Additional heat

and turbulence due to combustion of hydrogen and air evidently improved heating of the spray material, too.

The influence of the injected hydrogen on the coating deposit efficiency appeared very strong, boosting DE over 70% when spraying with one-nozzle TSR3000H gun using propane (Fig. 7), and up to 80% when spraying with SB9300 using MAPP as a fuel gas. The flow rate of hydrogen with positive effect on deposit efficiency was limited by 20-25 SLPM at the total gas consumption of about 5,000 SLPM. Further increase of hydrogen flow lowered the powder deposition efficiency. Injections of hydrogen did not change micro-hardness of the coatings.

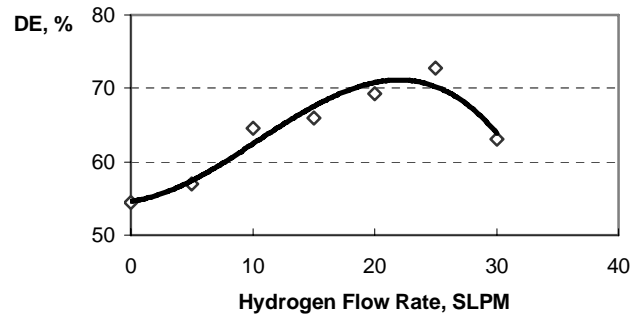


Figure 7: Influence of injected hydrogen flow rate on deposit efficiency (DE) of WC-10Co-4Cr coatings applied by TSR3000H AC-HVAF gun using propane as a fuel gas

Wear Resistance

The abrasive wear test data for the WC-10Co-4Cr AC-HVAF coatings appeared very consistent and practically non-dependent on type of fuel gas used, spray rate and carrier nitrogen flow rate. Only type of spray powder and hydrogen injections affected test results noticeably.

Spray Powder

Volume loss during standard wear test was similar for the coatings of all three types of powder tested, while somewhat better results were found for the coatings of agglomerated/sintered material (Table 2). However, in more severe conditions of the test with the coarse quartz sand, the coatings of fused/crushed material revealed noticeably better resistance than other counterparts (Table 3). Higher hardness of the first might be a contributing factor in such performance.

Influence of Hydrogen

Hydrogen injections in spray powder revealed profound improvement in wear resistance of all AC-HVAF coatings under both tests conditions (Table 1, 2). The coatings of agglomerated/sintered powder were clearly better performing in standard test conditions, while the coatings of fused/crushed powder outperformed when testing with the coarse sand.

Table 2: The WC-10Co-4Cr coatings volume loss during ASTM G-65 wear test, quartz sand 50-70 mesh.

No	Coating method	Volume loss, mm ³		
		Agglom./sintered powder	Sintered/crushed powder	Fused/crushed powder
1	AC-HVAF, Air-MAPP	1.21	1.36	1.29
2	AC-HVAF, Air-MAPP, H ₂ injection	0.79	-	1.21
3	JP5000, Oxy-kerosene	5.00	2.71	-
4	DJ2600, Oxy-hydrogen	7.57	1.79	-

Table 3: The WC-10Co-4Cr coatings volume loss during modified ASTM G-65 wear test, quartz sand 40-70 mesh.

No	Coating method	Volume loss, mm ³		
		Agglom./sintered powder	Sintered/crushed powder	Fused/crushed powder
1	AC-HVAF, Air-MAPP	7.43	7.71	4.86
2	AC-HVAF, Air-MAPP, H ₂ injection	6.68	-	3.43

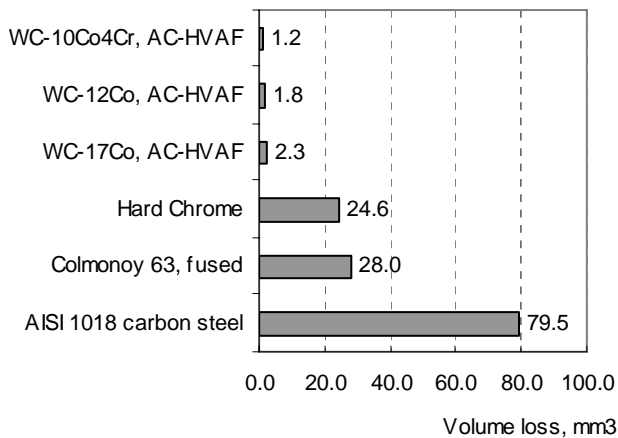


Figure 8: Materials volume loss during ASTM G-65 wear test, quartz sand 50-70 mesh.

Comparison with HVOF Coatings

Tested HVOF coatings of the same materials revealed higher volume loss during wear than the AC-HVAF coatings (Table 1). Among HVOF samples, the best wear resistance was found for the DJ2600 and JP5000 coatings sprayed of sintered/crushed powder.

Comparison with Hard Chrome and Spray-Fused Coatings

According to the data presented in Fig. 8, the WC-base AC-HVAF coatings wear resistance was 10-20 times better than electroplated chrome and spray-fused coatings. The difference was even greater when using the coarse quartz sand for testing. In particular, under these conditions the WC-10Co-4Cr AC-HVAF coating was performing 30 times better than electroplated hard chrome coating.

Specific Applications of AC-HVAF Sprayed Carbides

The AC-HVAF-sprayed tungsten carbide coatings are currently applied in many cases originally developed using other thermal spray processes. However, due to quality or economical factors several applications were only possible to develop using advantages of the AC-HVAF technology, winning competition against hard chrome electroplating, hardface brazing, casting and weld-overlay. Below are few examples of those specific applications.

Hard Chrome Replacement in Fatigue- Sensitive Applications

Those cases are typical for aircraft parts and components. In 2005 the AC-HVAF coatings were accepted by OEM as alternative to HVOF sprayed tungsten carbide for already certified parts, such as landing gear for commercial and army aircrafts. However, further development targets more heavy loaded parts of Navy aircrafts where the brittleness of HVOF coatings does not allow using them as hard chrome alternative.

Optical Mirror Finishes

High density, specific morphology and consistency of quality of the AC-HVAF sprayed carbides allows super-finishing of the coatings to optical mirror (better than R_a 0.012 micron), also avoiding common defects of sprayed coatings known as “pinholes”. Chill rolls of acetate film machine were coated with WC-Co-Cr coating and polished to R_a 0.010 micron, not revealing a single defect on 6 m² surface of the roll.

Small Target Parts

Narrow spray powder jet of the AC-HVAF guns (less than 4 mm for TSR3000H) provides efficient deposition of coatings on small diameter parts such as rods, bushings, seats, as well as into small openings of sophisticated shape parts (impellers, pump housings, etc.). For instance, target efficiency of the AC-HVAF process for the 10-mm internal diameter bushing (Fig. 9) exceeded 90% making spray powder consumption 3-4 times lower than for HVOF spraying.



Figure 9: Application of WC-Co-Cr coating with TSR3000H gun to 10 mm internal diameter of a bushing.

Thick Carbide Layers

The WC-10Co-4Cr and WC-12Co AC-HVAF coatings are routinely applied to thickness 1-2 mm on wire drawing capstans, jet mill walls and wear plates, hydro needle valves, rotary valves, airlocks, etc. Those applications efficiently replace hardface casting, brazed carbide cladding and spray-fuse overlay. Growing usage of thick carbides is driven by noticeably improved performance of wear parts, as well as cost reduction due to absence of parts heat distortion, better tolerances and smooth finish of as-sprayed coatings (Ra 2.0-2.5 micron) not requiring their post-machining. For example, peripheral wall of a jet mill, originally protected with 2.5 mm thick layer of fused NiCrBSi-WC coating, performed less than 2 months. Required 6-month performance was achieved by applying the 1.0 mm thick WC-10Co-4Cr AC-HVAF coating (Fig. 10) at a fraction of original hard surfacing cost.



Figure 10: Application of 1.0 mm thick WC-CoCr coating with SB9300 gun on 0.8 m diameter peripheral wall of a jet mill.

Conclusions

Activated Combustion HVAF allows deposition of tungsten carbide –based coatings in solid particle spray mode, which has significant effect on coating properties. Critical parameters of the process for deposition of wear resistant coatings were analyzed and new improvements in the technology developed.

1. The method of the WC-Co-Cr spray powder manufacturing was found a significant factor influencing coating deposition and quality. The coatings of agglomerated/sintered and sintered/crushed materials revealed higher deposition efficiency but lower hardness than those of fused/crushed powders. During ASTM G-65 wear tests the coatings performed similar, however, when using coarser test sand the coatings of fused/crushed powders noticeably outperformed their counterparts.
2. Increasing the WC-Co-Cr powder spray rate up to 28 kg/hr did not affect its deposit efficiency, being 60-65% when spraying with propylene or MAPP-gas and 50-55% when spraying with propane. Further

increase of spray rate to 32 kg/hr resulted in the decline of the deposit efficiency about 1/10 of initial value. Spray rate within 5-28 kg/hr did not affect coatings wear resistance.

3. It was found that increase of the flow rate of nitrogen, used as a carrier gas for spray powder, gradually reduced the powder deposit efficiency, however, had no influence on the coating wear resistance. A set of powder injectors was developed and nitrogen mass-flow controller added as an option for the AC-HVAF equipment as a result of those findings.
4. Injections of hydrogen with the spray powder into combustion chamber improved the deposit efficiency of WC-Co-Cr coatings, now increased over 70% when spraying with propane using single-nozzle gun setup and up to 80 % when spraying with MAPP-gas using cascade combustion nozzle. Injections of hydrogen noticeably improved wear resistance of the coatings sprayed with all types of powders.
5. In ASTM G-65 wear tests all WC-Co-Cr AC-HVAF coatings outperformed their HVOF counterparts, sprayed with JP5000 and DJ2600 systems. In the tests the AC-HVAF tungsten carbide coatings performed 20-30 times better than electroplated hard chrome and spray-fused coatings.
6. Applications of the AC-HVAF tungsten carbide coating expanded thermal spray market for replacement of hard chrome, hardface casting, brazed carbide cladding and spray-fuse cladding. Specific AC-HVAF applications included fatigue-resistant coatings, optical mirror finished coatings, coatings on small-target parts and thick tungsten carbide layers.

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