HVAF – Chance and Challenge for Users and for Powder Producers

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Abstract

The High Velocity Air Fuel (HVAF) Spray process is becoming more and more popular but despite off its long history, the industrial activities to work out differences of HVAF and classical Kerosene-fired High Velocity Oxygen Fuel (KF-HVOF) Spraying are still on a level of "collecting experience" and "not being understood completely". This publication gives an explanation of the differences between HVAF and HVOF and their impact on the metallurgy and coating properties.
Coatings made of Amperit® 543 show an approx. 20% higher Youngs Modulus, approx. 34% reduced weight loss in ASTM G 65 and approx. 10% higher hardness if sprayed with HVAF (AK6) using a higher powder feed rate. Coatings made of Amperit® 554 are characterized by an approx.. 10% higher Youngs Modulus, slightly higher wear resistance in G 65 and similar hardness compared to KF-HVOF if sprayed with HVAF (AK6). The dominating differences can be found in cavitation according ASTM G 32 where coatings sprayed with HVAF (AK6) have a wear reduction by approx. 50%.
An outlook on a potentially new solution is given where thin but corrosion resistant coatings based on s/c WC-CoCr are of interest. Furthermore, it is demonstrated that KF-HVOF can be used to achieve similar results in case of thin, corrosion resistant coatings if the "spray system" – "spray powder" interaction is understood and applied in a suitable manner.

Introduction

Since a few years, the HVAF process has been established commercially and gained its share in the market for thermal spraying. The thermal spray materials being mainly used are those based on tungsten carbide; it seems not to be established yet commercially for other material classes. Users who want to invest into thermal spray equipment and need to decide between the competing technologies of HVOF and HVAF, often decide by economic figures preferentially. In this later aspect, HVAF is captivating, especially in case of larger spray system, by high deposition rates and lower cost. On the other side, resulting coatings are different from HVOF coatings and the differences are not straightforwardly obvious. On this topic, many publications and conference contributions have been published, e.g. [1,2]. Regrettably, coating characterization is not always complete and field test results are missing in most cases. In effect, potential users of HVAF technology get little support for their decision making from the viewpoint of coating performance. Therefore, the challenge for potential users is to become clear about the consequences of a potential substitution of a running HVOF process by an HVAF process, and consider this aspect in an investment decision. The challenge for powder producers consists in providing suitable spray powders and to be able to make recommendations to the users of HVAF technology.

The structure of this publication starts with the fundamental differences between the HVOF and the HVAF process in general. In a second step, the fundamental relationship between spray powder, spray process and parameters on one hand, and coating properties on the other will be touched. The impact of Thermal Spraying on the metallurgy of WC-CoCr will be treated in a third step. Understanding both together, predictions will become possible concerning to coating properties. The forth part presents results from both spray processes together with explanations for the observed differences, stemming from the different spray processes and spray powders. At last, aspects to be considered are listed for potential HVAF users.

The most obvious difference is the use of air instead of oxygen, as directly visible in the acronyms. In addition, gas fuel is being used, typically propane, while HVOF can use gas fuel („GF-HVOF") as well but also more commonly (hydrogenated) kerosene („KF-HVOF"). The use of air has two advantages: at first, flame temperature in case of propane and lambda = 1 falls from 2850 to 1930°C [1], and secondly, due to the nitrogen "ballast", flame velocity can rise due to rising speed of sound, which rises the spray powder particle in turn. Both effects are advantageous in case of thermal spray material classes which are prone to oxidation and decarburization (the later term denotes carbon loss due to oxidation). Fig. 1 highlights the positions of common particle spraying processes in terms of flame temperature and kinetic energy of the particles.

The challenge in case of air as oxidizing gas had been the speed of combustion, being reduced by about two orders of magnitude compared to pure oxygen for the case of propane. Additionally, it depends highly on lambda, so that combustion can become unstable and working range for lambda becomes tighter. The patented invention of a catalytically active burner block [3] can be regarded as the necessary precondition to commercialize HVAF larger spray systems and thereby the technology itself.

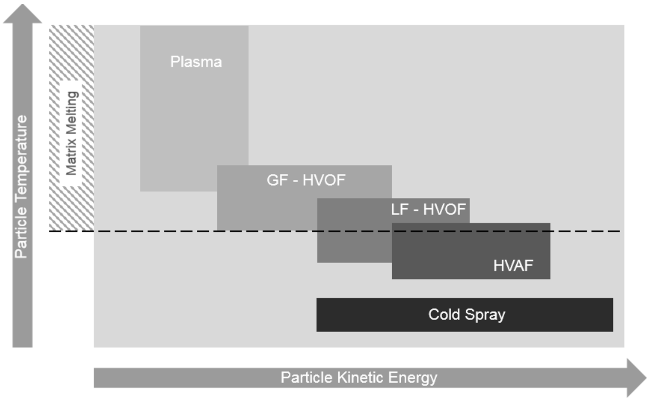


Figure 1: In-about ranges of flame speed and kinetic particle energy for the most important thermal powder spraying processes

Further and essential differences are the energy efficiencies and the maximum nominal energies (= fuel flow rate multiplied with lower calorific value) of both processes. While in case of kerosene fueled HVOF („KF-HVOF“), considerable heat loss is common due to water cooling and high combustion temperature (up to 100 kW), modern HVAF spray systems are mostly designed in a way that compressed air secures the cooling. This air is then being used for combustion, in whole or partly. Consequently, the process needs no cooling water. Resulting heat losses are in the area of GF-HVOF and in the area of less than 10% of the nominal energy input. However, larger and expansive compressors are being needed, releasing larger amounts of heat. Commercial larger HVAF systems have a nominal energy uptake between 100 and 400 kW without high heat losses, while KF-HVOF systems have a net energy input rate of maximum about 150 kW. This large difference in effective energy uptake rate available as input for the spray process is the reason why feed and deposition rates in case of large HVAF systems can be up to 5 times higher in case of WC based spray materials, compared to KF-HVOF. This makes the economical attractiveness of the HVAF process, but the impact on coating properties needs to be considered.

Another aspect of the HVAF spray process is that powder injection is carried out by axial injection, in a similar way to GF-HVOF systems. Compared to the radial injection in case of KF-HVOF systems, this gives more freedom in choice of spray powders (size, melting behavior and feeding properties).

Summarizing, it can be stated that the HVAF process is colder and potentially faster by its nature, and can be performed with higher nominal energy input. The lower flame temperature and the increased particle speed results in the effect that melting of the metallic matrix can be controlled in a way that it is molten during the impact only, and not in the flame. For this reason, it is to be expected that, in comparison to HVOF, less oxidation and decarburization will occur as the matrix has the lowest melting temperature in a carbide spray powder.

Experimental Methods

Thermal Spraying

HVAF Spraying was performed by Kermetico, using their AK6 gun. KF-HVOF was performed using the JP-5000. The related spray parameters such as fuel and gas flow rates, powder feed rates or surface speeds are listed together with coating results in order to simplify the overview on the relation “Spray Parameters” – “Coating Properties”.

Wear Testing and Coating Characterization

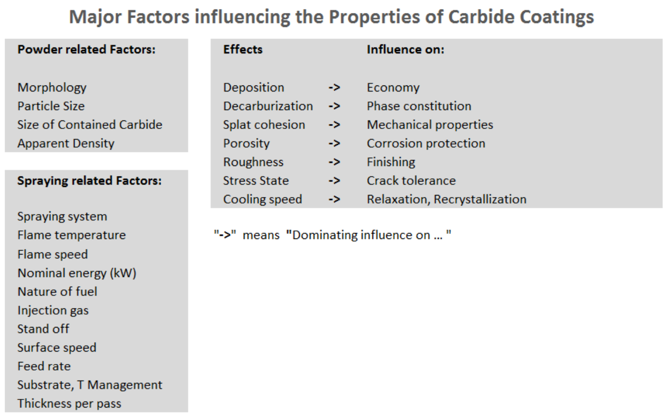
Wear testing was carried out by using dry Sand/Rubber Wheel Testing according to ASTM G 65 Method B, High Stress Abrasion Testing according to JIS H 8306, Cavitation Testing according ASTM G 32. Salt spray testing was performed according ASTM B117. The thermal spray coatings were characterized by chemical analysis of C and O.
E-Modulus was evaluated by using Laser Acoustics (LAwave, Fraunhofer IWS Dresden). Metallography was carried out according internal standards to measure porosity by using optical light microscopy and image analysis from IMAGIC IMS.

Thermal Spray Powders

The thermal spray powders Amperit® 554 (WC-CoCr, 86/10/4, s/c) in the particle size distributions -45+15 (.074), -25+5 (.071) and -15+5 (.067) and Amperit® 543 (WC-CrC-Ni, 42/42/16, a/s) was used in -45+15 (.074) and -30+5 (.059).

Dependence Spray Process – Coating Properties

The relationship between these two factors is complex and difficult to describe. The attempt to provide an overview from the theoretical point of view is presented in Fig. 2. The variable parameters of the powder and of the spray process are listed in the very left column. The column in the middle lists the measurable effects on the coating, while the right column lists their impact on coating performance. It seems clear that the interactions between the parameters are strong, so variation of one of these is hardly possible without a change in more than one coating property. It becomes clear how extensive a really complete coating characterization is and how complete a control of the spray process must be.



Major Factors influencing the Properties of Carbide Coatings

Powder related Factors:

Morphology
Particle Size
Size of Contained Carbide
Apparent Density

Spraying related Factors:

Spraying system
Flame temperature
Flame speed
Nominal energy (kW)
Nature of fuel
Injection gas
Stand off
Surface speed
Feed rate
Substrate, T Management
Thickness per pass

Effects		Influence on:
Deposition	->	Economy
Decarburization	->	Phase constitution
Splat cohesion	->	Mechanical properties
Porosity	->	Corrosion protection
Roughness	->	Finishing
Stress State	->	Crack tolerance
Cooling speed	->	Relaxation, Recrystallization

"->" means "Dominating influence on … "

Figure 2: Dependence of carbide coatings properties on powder and spray process properties

WC-CoCr: Impact of Thermal Spraying on the Metallurgy

The well-known denomination „WC-CoCr 86/10/4“ describes in no way the metallurgy of this material. On the contrary, it is a three phase material with CerMet character, consisting out of tungsten carbide (WC), eta-phase $(W,Cr)_3Co_3C$ and CoCr 90/10. The amount of these phases is controlled by carbon content. If the later one is analyzed, the amount of metallic Co can be calculated. Its content decides about how much the metallic character (“Met-“ of the CerMet) of the coating is pronounced, because CoCr is the only metallic phase existing in this material. Commercial WC-CoCr spray powders bear usually 5,2 to 6% carbon (corresponding to 6 to 10% of metallic Co), coatings bear typically between below 3,8 and 5,5% carbon. The reason for this broad range is decarburization during the spray process. The chemical reactions of decarburizations can be found in Fig. 3. The typical content of metallic Co in coatings are between zero and 8%, so the coatings can both be “Ceramic” or “CerMet”. At 3,8% carbon, no metallic Co exists anymore (it is all bound into eta phase). A further reduction of carbon content results in increased formation of brittle W_2C. The oxides which are present in most WC-CoCr coatings are mostly Cr_2O_3 and are typical for coatings produced with hot and slow spraying parameters.

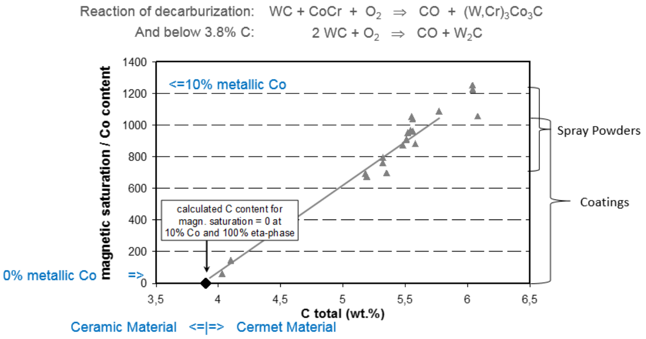


Figure 3: Metallurgical reaction of WC-CoCr on decarburization (chemical analysis)

By experience, decarburization and oxidation depend strongly on the parameters listed in the left column of Fig. 2.

In Practice: Comparison of HVAF and HVOF Coating Properties

A first impression about the different reaction of a less complicated thermal spray material can be won with WC-CrC-Ni, see table 1. Spray systems utilized had been „AK-06“ (Kermetico, USA) for HVAF, and the known KF-HVOF system JP-5000. In about, both had a comparable energy uptake rate for the spray process (after deduction of the heat loss into the cooling water in case of JP-5000). Resulting coatings are very different: splat cohesion is higher in case of HVAF, which leads to a rise in elastic modulus, which expresses itself in a weak hardness rise only. ASTM G65 wear is reduced considerably. The 30/5µm particle size with HVAF produces better results in all aspects, especially a lower porosity. Albeit 80% higher feed rate, both HVAF coatings are superior in quality to the KF-HVOF coating. In case of the HVAF process, a reduced spray powder particle size leads to better coating quality, which is in line with the practical experience of many HVAF users. Against expectation, decarburization is not lower with HVAF and the same spray powder size (45/15µm). The oxide content of HVAF coatings is reduced, which has been expected.

Spray System	JP-5000	AK6	AK6
Powder size (µm)	45/15	45/15	30/5
Nominal energy input (kW)	225-ca.51	163	163
Feed rate (g/min)	70	125	125
Deposition efficiency (%)	53	>50	>50
Porosity (%)	1,7	3	1,4
ASTM G65 m. B (mg/2.000 rev.)	24	19	16
Elastic modulus (GPa)	208	245	253
HV 0.3	1070	1102	1146
Carbon (%)	7,14	7,06	6,55
Oxygen (%)	0,60	0,29	0,43

Table 1: Coating properties obtained with Amperit® 543

Technical limits in spray powder production cause limits to the fineness of available agglomerate/sintered carbide spray powders. This limit is in about the nominal particle size 20/5µm. Such and even finer powders are needed especially for inner diameter (ID) coating HVAF spray systems. Here, acceleration and heat up of the powder particle has only a short distance available. The users are standing in front of a characterization problem of such and even finer spray powders. Spray powder suppliers use different nomenclatures for nominal particle sizes. Additionally, the nominal size limits are below those of standard screen sizes, so that the particle size distribution measurement and definition needs to rely fully on laser diffraction. The problem is, that the measurement results depend highly on the manufacturer and also on the assumptions made on the diffraction mechanism. Micro screen analysis („Air Jet Screening“) delivers much more consistent and plausible results, but is not very common.

Amperit® Powder PSD (µm/µm)	554.067 15/5	554.071 25/5	554.074 45/15
D90 (µm)	22	29	55
D50 (µm)	12	17	34
D10 (µm)	6	9	19
< 62 µm (%)	100	100	95
< 44 µm (%)	100	100	75
C (%)	5,36	5,38	5,40
O (%)	0,14	0,10	0,02
Co (%)	9,53	9,50	9,63
Cr (%)	4,62	4,45	4,4

Table 2: Particle size by Laser Diffraction and analysis of 86/10/4 spray powders

The finest commercial WC-CoCr spray powders are of sintered/crushed or of plasma spherodized type. Compared with the agglomerated/sintered type, such powders bear a slightly higher mass at same size, as practically no porosity prevails inside the particles. Expectations are higher peening effect and a reduced tendency towards oxidation and decarburization.

Potentially negative effects are reduced melting (if melting is desired) and higher inertia (less acceleration in the flame). Table 2 gives an overview on the properties of the finest sintered/crushed powders (15/5µm), which can be used for HVAF processes, in comparison to a standard KF-HVOF powders of same type.

Nominal Powder Size (µm/µm)	15/5	25/5	45/15	45/15*
Deposition efficiency (%)	34	41	41	46
Porosity (%)	2,0	1,8	2,8	0,4
Cavitation wear (mg/h)	-	4,7	3,4	2,2
ASTM G65 w. B (mg/2.000 rev.)	28	17	14	16
Elastic modulus (GPa)	-	266	316	309
Metallic Co (%)	(W_2C)	~ 0	4,7	3,3
Oxygen (%)	1,27	0,92	0,52	0,36
JIS H8306 (mg)	-	11	6,5	4,1

all: 70g/min / 6gal/h / 2200 scf / 4" nozzle, except *(= 8" Nozzle / 6,5 gal/h / 2200 scf)

Table 3: KF-HVOF results with Amperit® 554

Table 3 demonstrates the influence of particle size of a sintered/crushed 86/10/4 spray powder in KF-HVOF. It becomes obvious, that even under very cold and fast spray parameters with KF-HVOF, in case of the 15/5 µm particle size, a very strong decarburization and oxidation has taken place, so that formation of brittle W_2C becomes inevitable. The coatings do not bear any appealing properties. The coatings resulting from the 25/5 µm particle size are positioned in the transition area where metallic Co disappears and W_2C starts to form. Hardness and wear resistance become abruptly better. The classical 45/15 µm particle size delivers also reasonable results with the same spray parameter, but for higher quality coatings, an adjusted parameter set and a 8" nozzle are advisable, as the compact sintered/crushed spray powder of this size is not only more difficult to melt, but also more difficult to accelerate in the flame.

Thin Coatings applied with HVAF and KF-HVOF

As described, in case of carbide based thermal spray powders HVAF can outperform KF-HVOF due to its nature and this can be proofed at thin coatings with 20 – 30 µm thickness, sprayed just in one pass.

The use of the two finer sintered/crushed spray powders in HVAF (Outer Diameter Coating) leads to very surprising results, see table 4. Carbon content is now in the optimum area typical for KF-HVOF (4 to 5 %) with both particle sizes, which means a considerably reduced decarburization compared to KF-HVOF. Results for hardness, cavitation wear, porosity and wear are in the area of best standard for KF-HVOF. Measured elastic modulus of 346 GPa in case of the 15/5 µm powder is more than 10% above known KF-HVOF coatings. Most astonishing is the corrosion protection effect of very thin coatings made of the 15/5 µm powder: all coatings – regardless thickness and even with only one 9-10 µm pass – survive 1008h in the salt spray test without being sealed, see Fig. 4. In total, the HVAF coatings from the 15/5 µm powder give the impression of totally dense coatings, in which the influence of the splat interphases is subordinate, compared to known HVOF coatings. This coating type, also known as „flash coating", has the potential to be used for those applications where the usual coating thickness of 200 to 400µm are too cost intensive and the wear reserve of the thick coating is not needed, but corrosion protection.

Spray System	AK6	AK6
Powder size (µm/µm)	15/5	25/5
Feed rate (g/min)	33	33
DE (%)	~40	~40
Porosity (%)	0,3 - 0,4	0,3 - 0,4
Cavitation wear (mg/h)	1,9	1,5
ASTM G65 m. B (mg/2.000 rev)	12	-
Elastic modulus (GPa)	346	-
HV 0.3	1473	1502
Metallic Co (%)	2,9	2,9
Oxygen (%)	0,68	0,55
JIS H8306 (mg)	8,5	-

Table 4: Coating results with HVAF and Amperit® 554

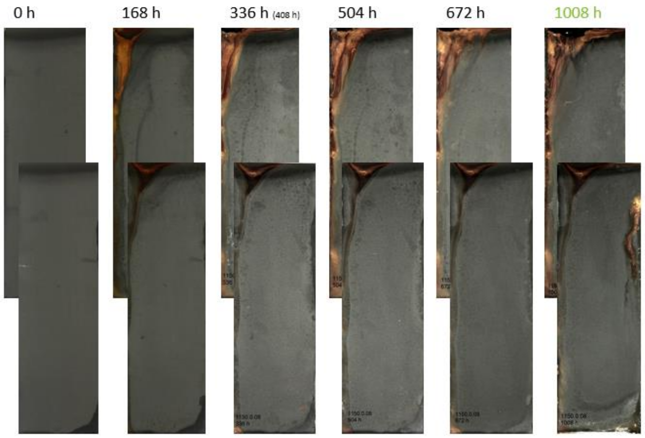


Figure 4: HVAF sprayed Amperit® 554.067 (-25+5) after salt spray testing according ASTM B117

With some simplifications in respect to the fluid dynamics, particle in-flight behavior and material characteristics, it is possible to develop a process that is believed to close the gap between classical KF-HVOF and HVAF. By using some idealizing assumptions, such as that the drag force of the gas is the only component which effects the powder particle acceleration, the flow is idealized along the rotation axis "x" of the nozzle, drag coefficient c_d is constant etc. then some initial statements can be made on the in-flight particle behavior. Fig. 5 presents an exemplary gas flow through a cylindrical thermal spray nozzle which accelerates the thermal spray powder particles along the x axis.

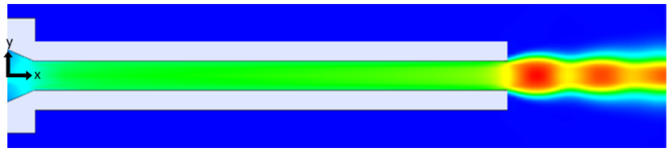


Figure 5: Idealized velocity plot of a gas flow inside a cylindrical nozzle with partially free-jet

The powder particle acceleration can be described with

$$\frac{1}{2}\cdot c_d\cdot\rho_{gas}(x)\cdot A_p\cdot\left(v_{gas}(x)-\left(\frac{dx}{dt}\right)_p\right)^2=m_p\cdot\left(\frac{d^2x}{dt^2}\right)_p \quad \textit{Equation 1}$$

or in a numerical notation with

$$\frac{1}{2}\cdot c_d\cdot\rho_{gas}(x)\cdot A_p\cdot(v_{Gas}(x)-\dot{x})^2=m\cdot\ddot{x} \qquad \textit{Equation 2}$$

which can be solved numerically after being transformed into

$$\Delta\,\dot{x}=\boxed{\frac{1}{2m}}\cdot\boxed{c_w}\cdot\boxed{\rho_{gas}(x)}\cdot A_p\cdot\boxed{(v_{Gas}(x)-\dot{x})^2}\Delta t \qquad \textit{Equation 3}$$

The aim is to understand general influences on the spray particle acceleration $\ddot{x}$ respectively the alteration of spray particle velocity $\dot{x}$ in an infinitesimal time interval $\Delta t << 1$ second. By means of Eq. 3, the different types of contributions to the particle velocity can be shown, highlighted in colors. ”Black” describes the contribution of the gas density in respect to the position along the way through the nozzle which has many complicated influence factors. The chamber pressure of the spray gun is a simple one and its contribution is easier to understand. “Green” is the drag coefficient which is a complex function of flow properties and shape of the spray powder particle, and will vary between different shapes such as agglomerated/sintered and sintered/crushed spray powder particles. “Blue” describes the contribution of the mass of an individual powder particle. The higher its mass, the smaller its possible acceleration to the maximum particle velocity, thus the apparent density of the spray powder respectively density of the individual power particle has an influence. “Red” is describing the relative velocity of a spray powder particle to the gas velocity. This part has a strong, quadratic contribution to the particle acceleration with a decreasing effect at some point where the relative velocity gets smaller. It also explains that a spray powder particle cannot be accelerated to a higher velocity than gas velocity, independently of the gas density or powder particle mass. The knowledge about these individual contributions does not allow to work out the final solutions but provides a guide to understand results and effects in the coating and furthermore, it helps to select the needed influencing spray parameter for a more focused test design.

Another highly relevant effect for dense coatings with compressive stresses is the desired peening effect. Peening occurs when impacting spray powder particles have a high enough kinetic energy to compact the impinged, already deposited splats in a way to achieve further plastic deformation of them, Eq. 4:

$$E_{kin,p}=\frac{1}{2}m_p{v_p}^2 \qquad \textit{Equation 4}$$

In contrast to the particle acceleration and the achievable particle speed, Eq. 3, the mass of an individual spray powder particle has a positive effect in this relation, Eq. 4. Simplified can be summarized: the higher the particle density, the lower the potential particle impact velocity but the higher the kinetic energy at impact. Depending on the m_p/v_p relation, this can tun into a lower kinetic energy at impact, too. The potential optimum between achievable particle velocity and kinetic energy at impact, which are affected by the spray powder particle’s density respectively mass, is worked out in this publication by trials.

It presupposes that the impacting particles are not “fully molten” or overheated and are in a state that allow them to deform material plastically without being spalled themselves. Melting indices which can be calculated with particles surface temperature and melting point, spray distance, particle velocity, Biot number etc. are ideally described elsewhere [3]. In order to increase the plastic deformability is seems to be beneficial when the area which has to be peened is locally heated in order to reduce heat conduction out of that area and to increase ductility of the deposit. Therefore, high kinetic energy and a locally balanced heat level of the spray particles and the to be peened deposit is utmost important.

As can be followed, the influences that have an effect on spray powder particle velocity, kinetic energy at impact and peening efficiency are manifold and complex to describe and are not touched here completely, therefore the provided simplifications shall indicate some fundamental guidelines for the choice of suitable spray parameters, particle size distribution and Apparent Density of the spray powders. The guidelines shall provide an assistance to understand effects on the coating properties, too.

Spray System	**JP-5000**	**JP-5000**
Powder	A554.071	A554.067
Powder size (µm)	25/5	15/5
Fuel/Oxygen Flow Rates (gph/scfh)	6/2200	6/2200
Feed rate (g/min)	70	70
Surface Speed (m/min)	25	25
Deposition efficiency (%)	43	35
Thickness per Pass (µm)	17	12
$C_{total,feedstock}$ (%)	5,38	
$C_{total,coating}$ (%)	3,63	2,57
ASTM G65 m. B (mg/2.000 rev)	17	27
Cavitation wear (mg/h)	3,58	13,02
HV0.3	1338	1051

Table 5: Spray parameter settings and results for thin coatings with Amperit® 554

The concept behind the spray parameter settings in Tab. 5 is to reduce surface speed by keeping the feed rate on an acceptable high level in order to increase the local temperature level for more efficient peening and taking into account the higher thickness per pass. The use of Amperit® 554 leads to surprising results in salt spray testing when applied in one and two layers in the mentioned finer particles size distributions, see Fig. 6 and Fig. 7.

Figure 6: Amperit® 554.071 double-layer after 1008 h (left) and single-pass after 168 h only (right)

Figure 7: Amperit® 554.067 double-layer after 1008 h (left) and single-pass after 168 h only (right)

Based in these achieved results it seems to be possible to spray thin corrosion resistant coatings also with KF-HVOF and Amperit® 554.071 and .067 when two layers are applied. Both powders sprayed in just one single pass shows strong corrosion after 168 h in salt spray testing. Amperit® 554.071 leads to superior coating properties compared to .067 (15/5 µm) regarding hardness and wear resistance against abrasion and cavitation (these coating properties were determined at thicker coatings applied with the same parameters). The further investigation is reduced on the .071 (25/5 µm) to have the focus on that particle size distribution. Obviously, the coating with the .067 (15/5 µm) is still dense after two layers but has a ceramic character due to the low carbon content which indicates that the metallic matrix turned completely into eta phase and W_2C. The high wear in cavitation reveals the low splat cohesion caused by the previously described effects: spray powder particle speed cannot be increased from 25/5 to 15/5 µm but lower particle mass turns into a reduced kinetic energy at impact.

The challenge is to understand the reason why the double-layer coating can pass 1008 h in salt spray testing while a single-pass coating corrodes after 168 h already.

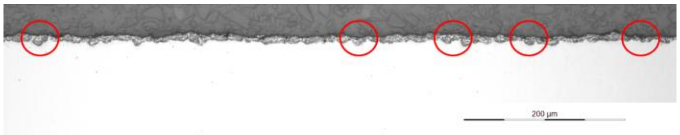


Figure 8: Microsection of Amperit® 554.071 single-pass coating

Fig. 8 reveals the secret of the observed corrosion: the not negligible relation between substrate surface roughness and coating thickness. In this case, grit blasting leads to a profile with hills and valleys that cannot be covered in a reliable way. A further influence on substrate roughness from peening whilst deposition cannot be excluded. At some points, the peaks from the substrate go through the coating, so the substrate is still locally exposed to the corrosive media. At other points, the coating might be too thin to provide corrosion resistance.

Based on the gained experience, the next coating is applied with the same parameter as previously used. The base material is simply brushed and not grit blasted in case of a single-pass coating. In case of a double-layer coating, soft grit blasting is used to active the substrate surface and to remove the scale on the mild steel coupon. This allows to reproduce previously gained results and to see the difference between grit blasting and brushing.

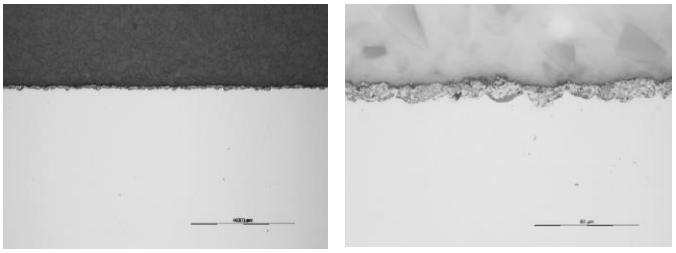


Figure 9: Microsection of Amperit® 554.071 single-pass coating on a brushed mild steel coupon

Both coatings in Fig. 9 and Fig. 10 show acceptable microstructures. Decarburization is not analyzed but qualitatively comparable to classical KF-HVOF Amperit® 554 coatings. The coating thickness is between 11 and 16 µm for the single-pass coating and 33-37 µm for the double-layer coating.

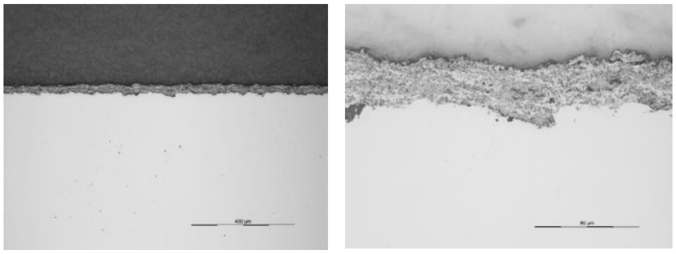
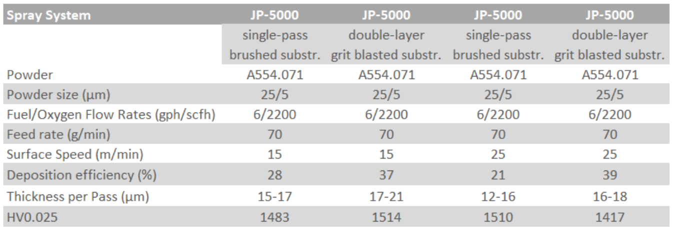


Figure 10: Microsection of Amperit® 554.071 double-pass coating on a grit blasted steel coupon

Substrate roughness is still high compared to the coating roughness in case of simple substrate brushing, Fig. 9 and it is assumed that corrosion resistance is not given. Some substrate roughness peaks penetrate the coating almost completely so that the coating would most likely locally exposed to the corrosive media in salt spray testing. Surprisingly, the scale on the mild steel surface is almost completely removed by the spray powder particle peening or blasting effect. The scale is expected to be very thick as can be seen in Fig. 9, middle of the right image, and just low amount of scale residuals remaining in the interface. Therefore, it is assumed that peening occurs and is comparably strong. The initial assumptions for the spray parameter selection seem to bring the desired effects.

The double-layer coating, Fig. 10, is optically dense and peening from the second layer on the first layer can be identified. No separation or transition from one to the other layer is visible and both layers seem to be compact and “kneaded” together. Also here, the coating shows a homogeneous microstructure.



Spray System	JP-5000	JP-5000	JP-5000	JP-5000
	single-pass brushed substr.	double-layer grit blasted substr.	single-pass brushed substr.	double-layer grit blasted substr.
Powder	A554.071	A554.071	A554.071	A554.071
Powder size (µm)	25/5	25/5	25/5	25/5
Fuel/Oxygen Flow Rates (gph/scfh)	6/2200	6/2200	6/2200	6/2200
Feed rate (g/min)	70	70	70	70
Surface Speed (m/min)	15	15	25	25
Deposition efficiency (%)	28	37	21	39
Thickness per Pass (µm)	15-17	17-21	12-16	16-18
HV0.025	1483	1514	1510	1417

Table 6: Spray parameter settings and coating results for thin coatings with Amperit® 554.071

The concept of locally lower heat transfer out of the deposition zone by reducing surface speed while thermal spraying and therefore higher temperature level which supports plastic deformation of deposited splats is expected to take place with the first spray parameter settings. With a further reduction of surface speed from 25 down to 15 m/min, Tab. 6, thin coatings with homogeneous microstructures can achieved, too, Fig. 11 and Fig. 12.

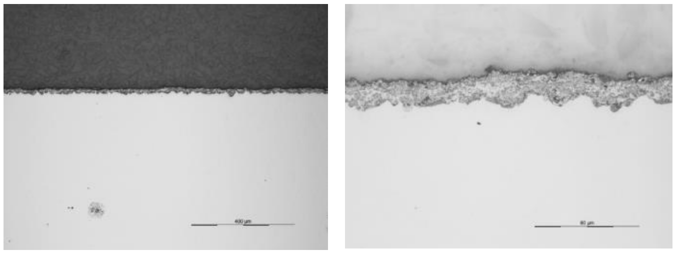


Figure 11: Microsection of Amperit® 554.071 single-pass coating on a brushed mild steel coupon

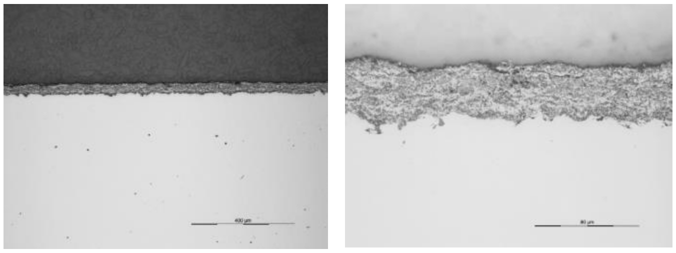


Figure 12: Microsection of Amperit® 554.071 double-layer coating on a grit blasted steel coupon

The coating on simply brushed mild steel substrate, Fig. 11, still shows a low amount of scale residuals remaining in the interface. Substrate roughness is still high. Due to the reduced surface speed, the single-pass coating thickness is increased from 11-16 to 15-17 µm and is expected to cover the substrate completely. The double-layer coating is still characterized by compact layers which seem to be “kneaded” together. The righthand image of Fig. 12 shows a deep penetration of spray powder particles into the substrate. That indicates a strong peening (or impingement) effect of the impacting spray powder particles.

Conclusions

As preliminary summary, it can be stated that dominating influences such as gas flow – powder particle interactions and resulting peening whilst the spray powder deposition can be explained and used to spray thin, corrosion resistant WC-CoCr coatings. Obviously, HVAF offers new opportunities and delivers results which hardly can (in some cases cannot) be achieved with classical KF-HVOF. But it is believed that it is possible to develop a process with KF-HVOF which steps into the gap between classical HVOF and HVAF. Therefore, the beneficial results such as thin compact, dense coatings while keeping the decarburization acceptable low can be achieved with the choice of the suitable spray powder and with understanding of the kinetics of the used spray system and is not a pure unique feature of HVAF, Fig. 13 and Fig. 14.

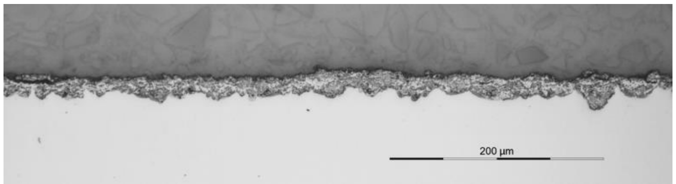


Figure 13: Microsection of Amperit® 554.071 single-pass coating

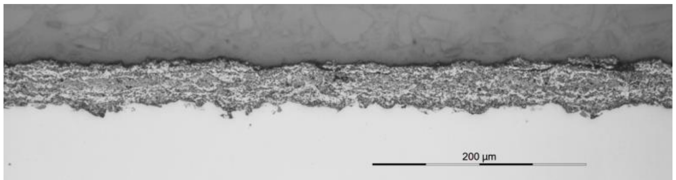


Figure 14: Microsection of Amperit® 554.071 double-layer coating

Despite the KF-HVOF coatings are dense with promising wear test results, a direct comparison to HVAF reveals the limits of HVOF: higher decarburization of WC-CoCr and lower splat cohesion. Especially for thin coatings, it is important to keep some ductility left in the coating and to have a high cohesion of the splats.

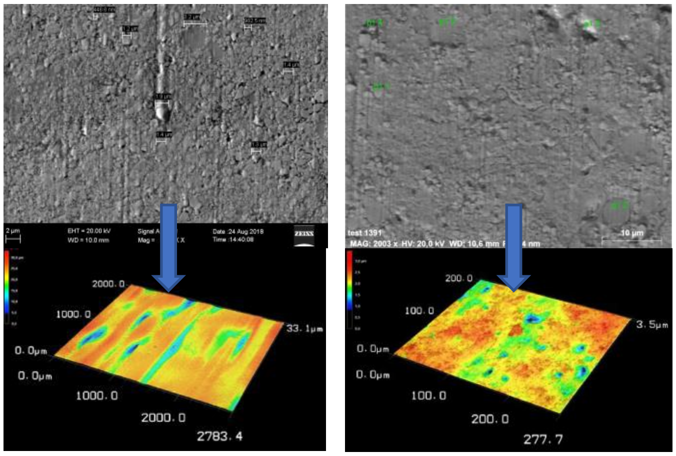


Figure 15: ASTM G65 wear scar topography of Amperit® 554.071 sprayed with HVAF (left) and HVOF (right)[Images: BTU Cottbus]

A topographic comparison of ASTM G65 wear scars, Fig. 15, shows the different behavior of coatings sprayed with KF-HVOF and HVAF. Whilst the HVAF coating still has “CerMet” character and shows the ability to provide some residual matrix ductility (ploughing), the KF-HVOF coating appears “ceramic” and therefore more brittle (local material pullout). The ability to behave in a ductile way and to provide a high splat cohesion is needed for thin coatings. Depending on the “thinness”, local material pullout exposes substrate to corrosive media as consequence and corrosion resistance is not given anymore.

The substrate preparation becomes also important in case of thin, corrosion resistant WC-CoCr coatings. It can be shown that also KF-HVOF coatings with Amperit® 554.071 can pass 1008 h in salt spray testing. Commonly used grit blasting prior to the thermal spraying creates a rough substrate surface profile that can have a negative influence on the corrosion resistance of the coating when just a single pass is used. For a double-layer coating with Amperit® 554.071 and Amperit® 554.067 it was not observed to be critical. On the other hand, a reduced substrate roughness profile can perhaps lower the coating’s bond strength what is not known at the time of this investigation. It is not believed to be a case for HVAF but due to the potentially lower peening effect of KF-HVOF it is still an open topic.

In general, HVAF coatings with Amperit® 543 are characterized by higher hardness and higher E Modulus with superior wear test results in ASTM G65 and cavitation compared to KF-HVOF. The same trends can be seen with Amperit® 554. Even under very cold and fast spray parameters with KF-HVOF, in case of the 15/5 µm particle size, a very strong decarburization and oxidation takes place, so that formation of brittle W_2C becomes inevitable. The coatings applied with HVAF and the same powder show good behavior in wear testing. The achieved E modulus is much higher compared to KF-HVOF.

The HVAF spray process is a colder and potentially faster spray process, compared to KF-HVOF. It leads to less oxidation and (by case) also to reduced decarburization of carbide coatings. This results in a different metallurgy, which in turn causes differences in mechanical properties of WC based coatings. Depending on the choice of spray powder particle size and spray parameter, HVAF coatings can reach a quality level not achievable up to now by HVOF. By tendency, finer spray powders are advisable for HVAF from the viewpoint of coating quality. For potential HVAF users it is important to be aware of the fact that coating performance of HVAF coatings will probably be different to HVOF, and extensive coating characterization of existing HVOF coatings as well as for future HVAF coatings is essential. Field tests are giving more security before a positive decision is being made to invest into an HVAF spray system. This systematic would allow an exploitation of the economic potential of the HVAF process without unnecessary technical product risks.

Thanksgiving

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The ASTM G65 wear scar topography was analyzed by Prof. Ralf Winkelmann (BTU Cottbus-Senftenberg).

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