Innovative Coating Developments Using a New, User Friendly HVOF and Metal Based Powders

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Abstract

The practical experience with the new Castolin Eutectic CJK5 High Velocity Oxy Fuel thermal spray unit has grown since its successful launch in 2011. It has many design features that simplify the user interface and servicing, but maintaining outstanding coating quality. The technical and practical features are described with detailed microstructural characterization of the resulting carbide based coatings using an established powder composition from several powder sources.

With the recent development of a state-of-the-art metal powder manufacturing plant in Europe, highest quality "satellite-free" metal powders can be manufactured. New self-fluxing chemistries have been developed that are also low in Nickel and are designed to have good wear resistant properties. With the growing practical experience and parameter optimization, several innovative powders and coatings have been developed and are presented. Microstructural and mechanical properties and their relationship to processing parameters are presented.

Introduction

Since the launch of the TAFA JP5000 the High Pressure oxygen/kerosene HVOF system has grown in popularity and became an established technology in the thermal spray industry (Ref 1) for delivering high quality coatings and a reasonable operating cost. Over the years, a few other related systems have entered the market (Ref 2). These range from entry level units (which have expanded the market but are limited on quality and reproducibility) or higher end units with more focus on sophisticated control for OEM and aero applications. The later models have traded size and complexity for reproducibility, reliability and monitoring. However, there is a market demand for a high quality kerosene HVOF system, which has the advantages of portability, improved ease of use, lower operating costs (deposition efficiency, capital costs, reliability, reproducibility, consumables, etc.). HVOF portability has long been an important requirement and units have been launched on the market (Ref 3). The newly launched Castolin Eutectic CJK5 unit meets these market demands and this publication will present the latest results of development work with the unit for a range of materials.

In the end, it is the coating quality which is the important product resulting from the HVOF unit, optimized powder and optimized spray parameters. This paper will highlight the sensitivity of the coating characteristics to powder source, powder type and spray parameters.

In the field of HVOF technology, several popular coatings have evolved, for example in the area of hard chrome replacement (Ref 4, 5) and these will be tested/optimized to establish the quality of CJK5 in delivering equivalent or better quality than the current technology.

In addition to the established HVOF powders and coatings, there is a constant demand to develop new coatings with improved performance that also meet the changing commercial and environmental needs. Two such needs that have developed are to reduce the amount of nickel that is used in certain alloys (for cost, environmental and health issues), and also to develop alternative alloys that rely less on high carbides content (WC, CrC) to give good coating wear properties. One option is to use metallic-based self-fluxing alloys which are available most commonly with Ni-Cr-B-Si compositions (Ref 6) and have a hardness range typically between 35-60 HRC. There is a long tradition of successful applications of self-fluxing alloys in tough wear and corrosion environments, including boiler coating (Ref 7), oil, etc. applied and fused with a variety of technologies. Corrosion resistance of these alloys is particularly good due to the high nickel, chrome and closed porosity (Ref 8). Recently, iron-based self-fluxing alloys have been developed but are not widely known or used in the HVOF industry. Several compositions of self-fluxing alloys were manufactured in a new powder production plant using water-water and dry gas atomization. The latter has an advanced system to produce satellite-free particles.

HVOF Spraying

The HVOF unit: The CJK5 (Figure 1) is designed as an operator friendly equipment with intuitive operator interface that creates repeatable high quality coatings. The HVOF process is controlled by an integrated PC with touch screen (Figure 2). The spraying can be done automatically or in manual mode and a full robot interface includes automatically controlled shutdown. The CJK5 has a high pressure combustion chamber: up to 8 bar (120 psi), 250 kW power, coaxial oxy-fuel injection for clean burn with minimal carbon deposits. Radial powder injection into the low pressure region plus the converging-diverging nozzle gives high quality, dense thick coatings. High accuracy mass flow control and mass flow powder feeder ensure repeatability and control. 100mm, 150mm, 200mm nozzles are available and were used in the tests.

Figure 1: Portable Castolin CJK5 core components of Gun, Console with touch screen and powder feeder.

Figure 2: CJK5 touch screen control panel, for monitoring and storage of all parameters during spraying

To ensure reliable and safe operation there is full dust sealing of system and a complete set of interlocks, the software is personalizable with usual USB, Ethernet, RS232 interfaces.

Real time data logging with programmable intervals system logs the required parameters and actual operating parameters, gas and fuel flows, powder feeder speeds, chamber pressure against time and also logs sequence events and faults. Data log output via csv data format through USB, serial port or Ethernet to enable remote analysis. The system also creates a standard report after spraying.

Methodology

Experimental Approach

Two separate sets of tests were performed for this paper. The first (PART A) was with just one powder, WC/10Co/4Cr from one manufacturer. Then the same powder batch was sprayed with the CJK5 with a set of 18 tests being performed, which 3 sets of parameters were varied to determine the sensitivity of the coating quality and Deposition Efficiency (DE). The variables were a) spray nozzle length, b) spray distance and c) fuel flow rate (ml/min). The exact parameters used are given in Table 1. The parameters that stayed fixed during the trials are given in Table 2.

The second set of tests (PART B) used a standard set of spray parameters for WC/10Co/4Cr composition powder, but this time 4 different powder suppliers were used all offering the same nominal composition and nominally identical powder. One of the powders, Powder No. 4, was used for 2 further sets of tests with the CJK5. In these two tests the parameters of the CJK5 were optimized to obtain a lower porosity coating. Once the lower porosity level was achieved, these parameters were further optimized to create an "enhanced optimized sample". All 4 powders were also sprayed with a market leading liquid fuel HVOF unit with the same set of parameters as for the CJK5. All samples from the CJK5 and the market leading liquid fuel HVOF unit were processed in parallel.

Table 1: Test conditions and variables in PART A spray trials

Nozzle	100 mm								
Spray Distance	300 mm			360 mm			420 mm		
Spray Condition	①1	②2	③3	①4	②5	③6	①7	②8	③9

Nozzle	200 mm								
Spray Distance	300 mm			360 mm			420 mm		
Spray Condition	①10	②11	③12	①13	②14	③15	①16	②17	③18

Condition	Oxygen L/min	Fuel mL/m	Com.Pres Bar G	Powder g / m	Estimate Flame Temp	Estimate Powd. Speed
①	845	435	7.0	80	High	High
②	845	360	7.0	80	Low	Low
③	845	400	7.0	80	Mid	Mid

Table 2: Fixed test conditions in PART A spray trials

Powder	WC/10Co/4Cr
Robot movement	Traverse: 300 mm/s Pitch: 5 mm
Substrate	S235JR (300 x 200 x 5 mm)
Spray Time	1.2 mins
Powder Feed	80 g/min

Powder Samples

All of the WC/10Co/4Cr powders that were sprayed were purchased from established manufacturers and suppliers of tungsten carbide HVOF powders.

The metallic powders sprayed were manufactured at Castolin Eutectic Ireland Limited, in Dublin, Ireland which possesses a state-of-the-art gas-gas powder atomization tower, incorporating a novel design that can produce "satellite free" metallic powders. These have better flow parameters, a lower specific surface area and have been shown to give better quality coatings and deposition characteristics over conventional metal powders. Scanning Electron Microscope (SEM) images of the powders are given in Figure 3, to show the difference between conventional and a satellite-free, metallic powder.

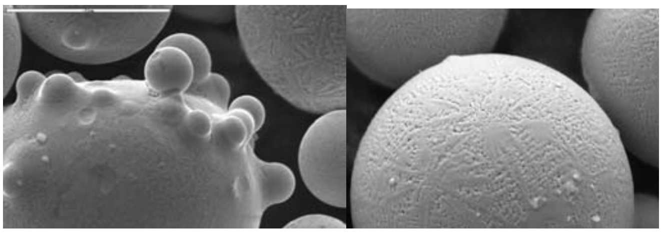

Figure 3: SEM photos of metallic powders produced with conventional and satellite-free powder atomizer towers.

Sample Preparation and Testing

In Table 3 is an overview of the parameters used for analyzing the various coatings sprayed. Specific details are below.

Sample preparation: Standard 300 x 200 x 5 mm S235JR mild steel plates were used for all tests. Prior to spraying they were grit blasted to remove all rust, oxide and any dirt. The sample was then weighed before and after spraying, and the amount of powder sprayed was also weighed before and after.

Microscopy: After spraying the samples were sectioned using a Presi Mecatone T260 cut off machine, mounted and polished on a Presi Mecapol P230 polishing machine. All samples were studied in cross-section on a Leica DM4000M optical microscope. The samples were not etched.

Porosity measurement: Coating porosity was measured by two distinctly different methods. One was with the polished cross section in the optical microscope using the Motic Images Advanced 3.2 image analysis software. The other method used was the water absorption method (Ref 9) performed at the Swedish research institute Swerea IVF AB.

Microhardness: Microhardness on WC/Co/Cr samples was measured on polished cross sections on a Vickers hardness machine with a 300 g load ($HV_{0.3}$). For the NiCrBSi and Fe-based self-fluxing coatings hardness was measured using a Vickers hardness machine with a 2 kg load (HV_2). All values quoted are average values.

Bond strength measurement: Bond strength was measured at the Swedish research institute Swerea IVF AB using the EN 582 procedure.

Surface roughness measurement: The surface roughness of the samples in PART A trials was measured and standard Ra and Ry values were given in microns.

Table 3: Test procedure overview

Porosity	Water absorption + image analysis
Bond strength	EN 582
Coating thickness	Micrometer and in optical microscope
Hardness	$HV_{0.3}$ and HV_2
Flow ability	Hall flow
Powder chemistry	Induction Coupled Plasma
Particle size distribution	JEL sieves
DE%	EN ISO 17836
Powder feeding	Weighing and ocular from gun
Parameter optimization	Varying parameters
Temperature influence	Temperature measurement
Surface roughness	Ra and Ry

Results

PART A

An overview of the PART A trial results are given in Table 4, with the number of the sample corresponding to the spray conditions given in Table 1. What is clear is the large variation in the values of DE (%), hardness and surface roughness, and quite a poor correlation between the parameter in terms of quality. The best all-rounder appears to be sample 16, which offers a $HV_{0.3}$ value of 1229 and a DE of 42% with one of the lowest Ra/Ry values. However even higher DE values were measured at 46% in 2 samples but at the expense of lower hardness values. The highest $HV_{0.3}$ values of 1423 and 1351 were obtained but both at a DE of 32%.

Table 4: Test results overview from PART A trials.

Test No.	1	2	3	4	5	6	7	8	9
Roughness									
Raμ	4.47	4.04	3.65	4.25	5.11	4.42	3.61	4.61	4.16
Ryμ	24.10	22.72	22.09	24.77	29.03	25.64	21.62	24.32	23.42
Hardness									
Hv 300g	1351	1260	1209	1273	1047	823	1169	1089	1132
DE%	32	28	32	35	35	39	39	32	35

Test No.	10	11	12	13	14	15	16	17	18
Roughness									
Raμ	3.80	4.39	4.24	3.89	4.79	4.71	3.64	4.38	4.68
Ryμ	21.75	25.33	25.45	22.03	20.04	22.77	21.82	23.65	25.20
Hardness									
Hv 300g	1423	1238	1131	1318	1137	1147	1229	997	989
DE%	32	35	39	39	35	18	42	46	46

PART B

An overview of the PART B trial results are given in Figure 4 for hardness measurements and Figure 5 for porosity measurements. In both Figures are included the additional "optimization parameter" which is seen in Sample No. 4 and the "enhanced optimized sample" found as Sample No. 5. Both of these were performed with the powder Sample No. 4.

WC/10Co/4Cr Alloys

Hardness measurements: The results in Figure 4 show that for all the 4 different suppliers of WC/10Co/4Cr chemistry that the hardness obtained were all above 1100 $HV_{0.3}$, but with Powder No.4 giving the highest value of 1300 $HV_{0.3}$ with standard parameters. The hardness values obtained with the same 4 powders sprayed with the market leading liquid fuel HVOF unit were generally similar +/- 100 $HV_{0.3}$, in either direction. Optimization of the Powder No. 4 did not modify the hardness significantly with the CJK5. The highest measured hardness was however obtained with the CJK5 in this series of trials.

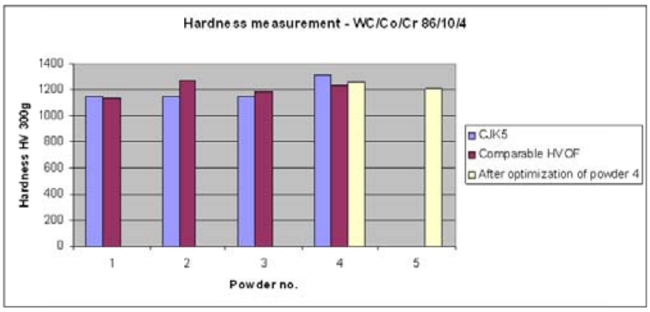

Figure 4: Hardness $HV_{0.3}$ *values measured for the same composition powder from 4 different suppliers with standard CJK5 spray parameters (samples 1-4).*

Porosity measurements: The porosity results in Figure 5 for 4 different suppliers of WC/10Co/4Cr chemistry show a large variety of results. This could reflect the sensitivity in the measurement of porosity at these low levels, but also the critical effect on porosity of powder supply and spray parameters. For the 4 powders with the CJK5, all porosities were measured to be below 2.3%. With the market leading liquid fuel HVOF unit the variation in the porosity measurements were even greater, showing a range from 3.2 to 0.75%.

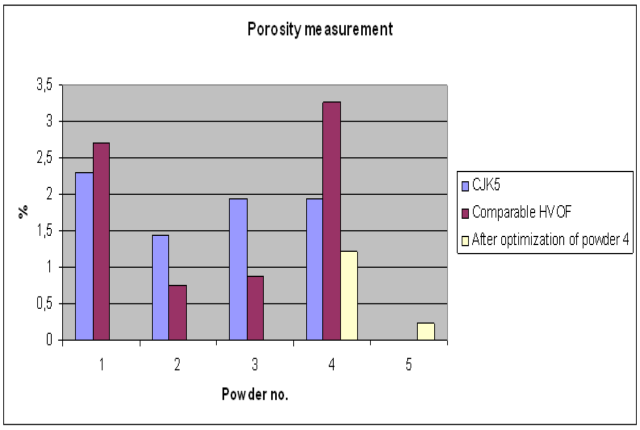

Figure 5: Porosity (%) values measured for the same composition powder from 4 different suppliers with standard CJK5 spray parameters (samples 1-4).

The interesting results came from the optimization experiments with the Powder No. 4 and the CJK5. Here it was possible to reduce the porosity level from around 2% down to 0.2% purely with the changing of spray parameters. This is an excellent level of porosity and the microstructure is shown at two magnifications in Figure 6.

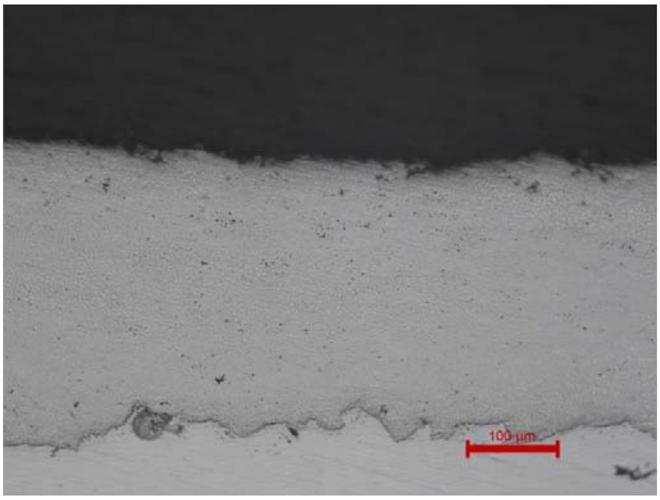

Figure 6: Polished cross-sections of Sample 5, the WC/10Co/4Cr chemistry with "enhanced parameter optimization" and low porosity.

Metallic Alloys

Hardness measurements: The hardness of the NiCrBSi alloy sprayed with the CJK5 with 2 sets of different parameters was recorded at 30 and 38, with the highest hardness being related to the lower spray rates, which also gave the highest DE. The Fe-based self fluxing alloy was sprayed and a HRC value of 60 was recorded.

Porosity measurements: For the NiCrBSi as sprayed with non-optimized parameters a first analysis of the microstructure gave a 0.25% porosity level. The Fe-based alloy porosity was also recorded at under 1%.

DE measurements: For the NiCrBSi alloy as sprayed with the 2 sets of parameters, both gave very good DE results of 65% and 71%. This later value is very high for HVOF coatings. The DE for the Fe-based self-fluxing alloy was measured at 67% on the single test performed.

Table 5: NiCrSiB Powder spray parameters and measured properties. HRC values are converted from HV2 values.

				HVOF Testing					
Powder	Hardness (HRC)	Hall Flow (s/50g)	Apparent Density (g/cm3)	Spray Rate (g/min)	Nozzle Length (mm)	Spraying Distance (mm)	Carrier Gas	Feed Rate	DE (%)
NiCrSiB	30	12.1	4.4	71	100	350	12	14.5	65.1
NiCrSiB	38	12.2	4.4	64	100	350	8	11.5	71.1

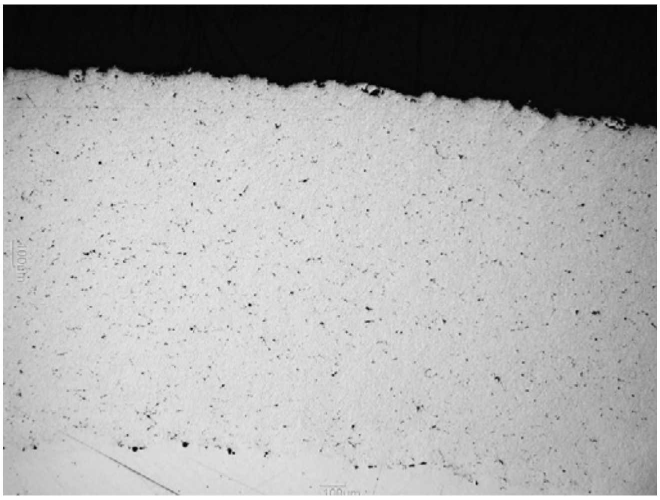

Figure 7: Optical micrograph of the CJK5 sprayed Fe-based self-fluxing alloy powder.

Bond Strength Measurements

All WC/10Co/4Cr coatings had their bond strength measured according to the EN 582 standard and all samples failed in the adhesive which shows that all coatings had a minimum bond strength of 71MPa, which is typical for quality HVOF coatings today.

Discussion

There are several interesting things that came out of this work. Firstly, the new CJK5 HVOF unit has proven that it is capable of producing high quality, reproducible coatings. The hardness values of 1300 $HV_{0.3}$ and porosity levels of 0.3%, with measured DE of up to 46% for the WC/10Co/4Cr chemistry alloy reflect this. The direct comparison with identical coatings produced with the same powders on a leading comparable liquid fuel HVOF system, shows superior results in terms of porosity and hardness.

The importance of powder source was also demonstrated for essentially identical powders in terms of chemistry and specification. The differences were most significantly observed in the porosity measurement. However, an even bigger difference was observed when the CJK5 parameters were optimized in 2 stages for a single powder, that of Powder No. 4. Here it was possible to reduce the porosity level from around 2% down to 0.2% purely with the changing of spray parameters. At the same time the hardness reduced slightly with increasing porosity. However, if a correlation is sought between hardness and porosity for the range of parameters, systems and powders in both A and B trials, no clear correlation can be found. A stronger correlation between DE and hardness is found for WC/10Co/4Cr powders (inverse). However, the opposite was found for the self-fluxing alloys, where a direct increasing hardness was achieved with higher DE.

The first results with the Ni- and Fe-based self-fluxing alloys are very promising in terms of their very low porosity below 1% and high DE above 65%.

Conclusions

The new CJK5 HVOF unit has proven that it is capable of producing high quality, reproducible coatings. The importance of the powder source for the one alloy (WC/10Co/4Cr) studied in detail and shown to have an important effect. More important was the effect of parameter optimization on the porosity of this coating. The first results of HVOF spraying of Ni- and Fe-based self-fluxing metallic powders showed DE levels above 65% and porosity below 1%. The high DE and chemical/hardness flexibility of these self-fluxing alloys could provide an advantage over conventional HVOF coatings in wear and corrosion applications. The results for the Fe-based alloys were encouraging and could be the basis for development of lower cost, more ecological coatings with excellent mechanical properties. The above results are just the preliminary work on a new system and also with some new powders. The results will be repeated in the on-going work program to confirm sensitivities of coating quality with this system. Future work on the sensitivity of DE, porosity, hardness and wear results of these alloys and others.

References

1. J.R. Davis, Introduction to HVOF Thermal Spray Processing *Handbook of Thermal Spray Technology*, ASMI and TSS 2004, p 3-13
2. R. Schwetzke and H. Kreye, Microstructure and Properties of Tungsten Carbide Coatings Sprayed with Various High-Velocity Oxygen Fuel Spray Systems, *Journal of Thermal Spray Technology*, Volume 8, Number 3, 433-439, September 1999
3. G.R. Heath, R.J.Dumola, M. Dvorak and R. Torday, Practical Experience with the New Generation of Low-Cost, Portable HVOFs, *International Thermal Spray Society* 1998, poster.
4. HCAT, "The Hard Chrome Alternatives Team Introduction to Thermal Spray Processing" http://www.hcat.org/about.html, Feb. 25, 2008
5. G. Bolelli, R. Giovanardi, L. Lusvarghi and T. Manfredini, Corrosion Resistance of HVOF-Sprayed Coatings for Hard Chrome Replacement, *Corrosion Science*, 2006, Vol. 48, Issue 11, p 3375-3397
6. M.P. Planche,, H. Liao, B. Normand and C. Coddet, Relationships between NiCrBSi Particle Characteristics and Corresponding Coating Properties Using Different Thermal Spraying Processes, *Surface and Coatings Technology*, Volume 200, Issue 7, 21 December 2005, Pages 2465–2473
7. G.R. Heath, R. Polak, T. Tsujita and S. Gustafsson, *Role of Thermal Spray Coatings in Boilers; Development of Reliable Spray and Fuse Coatings for Boiler Protection*, National Thermal Spray Society, 1996, p 1-8
8. G.R. Heath, P. Heimgartner, G. Irons, R. Miller and S. Gustafsson, An Assessment of Thermal Spray Coating Technologies for High Temperature Corrosion Protection, *4th International Conference on High Temperature Corrosion*, Les Embiers (1996)
9. J. Skogsmo and P. Andersson, Comparison of Different Techniques for Porosity Measurements of Thermally Sprayed Coatings, *MC International Metallography Conference*, Colmar, France, 10-12 May 1995