Investigation of HVOF-ID spraying with WC-CoCr -15+5 μm feedstock powder

W Tillmann, C Schaa*, I Hagen and M Dildrop
TU Dortmund University, Institute of Materials Engineering, Germany

* e-mail: christopher.schaak@udo.edu

Abstract. High velocity oxygen fuel (HVOF) spraying of WC-Co(Cr) with different chemical compositions, different powder size fractions, and different mean carbide sizes is a well-established research field for outer diameter (OD) applications. These coatings are typically applied as wear protective layers for different types of industries. Current demands for internal diameter (ID) coatings lead to great interest in HVOF-ID spraying. This field of application necessitates a special spray gun equipment and spray powders with particle size fractions smaller than 20 μm. At the same time, the process control concerning both the spray gun configuration and the use of fine powders leads to new challenges which differ from those of OD HVOF spraying. In this study, HVOF-ID spraying using a WC-CoCr 86-10-4 (-15+5 μm) feedstock with a mean WC particle size of 400 nm is investigated with respect to the resulting coating properties. A statistical design of experiments (DoE) is utilized to enable a systematic analysis of various process parameter settings along with their interaction on the microstructural characteristics as well as the deposition efficiency (DE). Based on the results, a desirability-based multi-criteria optimization is carried out in order to produce adequate coating properties. The obtained knowledge about the spray system enables to realize dense WC-CoCr coatings with a porosity of approximately 1 %.

1. Introduction
Thermal spraying processes have significant disadvantages regarding the coating of inner surfaces such as cylindrical parts with small diameters or hard-to-reach undercuts when compared to other coating techniques, such as dip coating techniques, electroplating, or chemical vapour deposition. The reasons for this are mainly the process characteristics of thermal spraying processes, such as the perpendicularly directed particle spray jet, the long stand-off distance (SOD), and the large build-up of common spray guns. Current developments in research and industry aim to solve these problems with new spray gun concepts for ID applications. One research focus is prompted by the automotive industry with the cylinder liner surface coating and bore coating for combustion engines to lower the friction and wear [1,2]. Typical spray systems for this purpose are atmospheric plasma spraying (APS), twin wire arc spraying (TWAS), plasma transferred wire arc (PTWA) spraying, and rotating single wire (RSW) spraying [1,2,3]. In contrast, there is a lack of research and development in the field of high velocity oxygen/air fuel spraying with regard to ID applications. Nevertheless, high performance HVOF/HVAF-ID systems are already available for small IDs up to 43 mm [4]. To realize the coating of small IDs, the spray gun has to be smaller compared to conventional spray guns while, at the same time, the SOD has to be shorter. In addition, the compact design of the spray gun is associated with a lower combustion energy when compared to conventional spray guns. Consequently, the lower flame enthalpy leads to a reduced heat input into the spray particles while under many
circumstances (i.e. depending on the process parameters to be used, or the geometry of the parts to be coated) the spray particles are simultaneously subjected to a reduced dwell time. Hence, it is necessary to use spray powders with particle sizes smaller than 20 µm as feedstock [4,5]. Besides Cr₂C₂-NiCr coatings, WC-Co(Cr) coatings have already been established as appropriate candidates in the field of thermal spray technology to protect tribologically stressed surfaces against wear. In terms of HVOF spraying, typical agglomerated and sintered WC-Co(Cr) feedstocks feature agglomerate sizes larger than 15 µm or 20 µm (lower limit value), respectively. Fine powder particles smaller than 20 µm with submicron carbides (WC < 1 µm) tend to overheat during spraying, which in turn favors the oxidation and decarburization of carbides. For WC-Co(Cr), decomposition phenomena can lead to the formation of W₂C eta carbides such as (W,Cr)₃Co₃C, as well as Co(W,C) [6,7]. Moreover, the incorporation of Cr favors the formation of an intermetallic CoCr phase. Such phase transformation processes can provoke the formation of brittle phases, and thus reduce the metallic character of the binder [7,8]. As verified for WC-Co coatings, which were tribologically stressed during technological testing, the decomposition of WC results in a degradation of the mechanical properties [9]. With respect to the process control (i.e. injection of the feedstock), powders with small agglomerates exhibit a poor flowability. By applying conventional powder flowability characterization techniques (e.g. Hall Flowmeter), tests will fail with the result that the powder seems to have no flowability. Hence, customized powder feeder systems are necessary to provide a constant flow rate without demixing. During spraying, fine particles tend to follow the gas flow trajectories [10]. Due to the gas flow deviation close to the surface of the substrate, the so-called bow shock effect [11], which is known for cold gas spraying, could affect the particle impact velocity as well as the deposition efficiency.

In this study, a systematic analysis using a DoE is carried out to understand the influence of various spray parameters on the resulting microstructural characteristics as well as the DE. For this purpose, a fine-structured WC-CoCr 86-10-4 powder is sprayed utilizing a specialized HVOF-ID equipment.

2. Experimental details and methods
An agglomerated and sintered WC-CoCr 86 10 4 powder with an agglomerate size distribution of -15+5 µm and a WC Fisher sub-sieve size (FSSS) of 0.4 µm was used as feedstock (Figure 1). According to the manufacturer, the feedstock features a bulk density between 4.3 – 5.4 g/cm³.

![Figure 1. Powder specifications Durmat 135.035, chemical composition, size fraction, and SEM-images of the WC-CoCr particles in two different magnifications (a/b).](image)

Within this study, the HVOF-ID spray gun IDCoolFlow Mono (Thermico, Germany) was utilized in order to conduct the spraying experiments. The HVOF-ID spray gun devices (e.g. IDCoolFlow) are described elsewhere [12]. In addition, the CPF2 twin-powder powder feeder system was used, enabling the feeding of fine-sized powder materials into the process due to the fluidization principle.
The spray gun was mounted on an industrial robot (type IRB4600/60, ABB, Switzerland) to ensure a robot-controlled movement within the experiments.

In this study, five independent variables were subjected to a central composite design (CCD) with 27 runs, including a single center run. In addition, two center runs were added to the design in order to reduce the residual variance of the model. This approach has already been used to develop thermally sprayed coatings [13]. The level settings considered in the CCD are based on the findings obtained from preliminary tests.

In terms of the CCD, the kerosene level (KL), oxygen level (OL), powder feeding rate (PFR), stand-off distance (SOD), and track pitch (TP) of the meander-shaped spray path were selected as independent variables. The level settings of the independent variables were converted to -1 (low), 0 (center), and +1 (high), whereas the so-called star points –α and α were converted to -1.664 and 1.664 to compute orthogonality within the CCD. The hydrogen level (HL), the backside cooling pressure, as well as handling parameters such as the spray angle, gun velocity, and amount of overruns were kept constant. The spray parameter settings are summarized in Table 1.

In terms of the statistical analysis, the Vickers microhardness (MH), porosity (Po), mean roughness depth (Rz), and deposition efficiency (DE) were set as response variables. Statistically significant influencing factors and factor combinations were determined by means of significance tests of the null hypothesis H0 as demonstrated in [13]. Hence, p-values were calculated based on a t-distribution with n - 1 degrees of freedom (where n is the number of experiments) according to t-statistic. Within this study, the significance level was set to 10% (α = 0.1). The software Statistica (Statsoft, Oklahoma) was employed for regression and graphical analyses of the data obtained. Afterwards, optimized spray parameter settings were identified based on multi-criteria optimization, using the Derringer’s desirability function [14].

In the spraying experiments, the coatings were deposited on rectangular (70 x 50 x 10 mm) C45 steel (1.0503; 258 ± 4 HV0.3) substrates. Prior to the coating deposition, the substrates were grit blasted with corundum using a grit size of F100 according to FEPA (blasting pressure: 3.5 bar; blasting angle: 45°; stand-off distance: 100 mm) and cleaned in an ultrasonic ethanol bath. Afterwards, the substrates were pre-heated to approximately 100 °C for 30 minutes. As verified by tactile measurements, the substrates exhibit an average roughness Ra of 1.42 ± 0.11 µm after grit blasting.

The response variables were obtained from metallographic investigations of the produced WC-CoCr coatings. Initially, the produced WC-CoCr coatings were cut and metallographically prepared (cross-section) using various grinding and polishing steps. Cross-section images were taken by means of light-microscopy (LM) and scanning electron microscopy (SEM). The MH was measured at the cross-section with a M400 hardness tester (Leco, Germany) applying a load of 2.942 N. Five indents per coating were used to calculate the average for MH. The Po of the coatings was optically measured at five different positions at the cross-section using a light-microscope with integrated software.
AXIOPHOT (Carl Zeiss, Germany). The DE was calculated based on the measured weight of each sample before and after the coating deposition, considering the robot path over the sample as well as the powder feed rate for each individual experiment. Rz was measured with a tactile measuring device (Hommel Tester T-1000, Hommelwerke, Germany). For selected samples, the phase composition was analyzed by means of X-ray diffraction (XRD) using an Advanced D8 diffractometer (Bruker, Massachusetts) with Fe Kα radiation. For the experiments, the step width and exposure time were set to 0.05° and 3 s for each step. The measurements were conducted at an angle of incidence of 5 degrees. For selected spray parameter settings, the in-flight particle temperature and velocity were measured with an Accuraspray-g3 device (TECNAR Automation, Canada). The measuring position was varied to simulate different SODs.

Table 2 summarizes the factor levels of the independent variables, with the corresponding results taken from metallographic examinations. The statistical design allows to estimate the linear (L) and quadratic (Q) effects and also the interactions between the variables.

Table 2. Level settings of the independent variables and results for MH, Po, Rz, and DE.

| Run | KL [l/h] | OL [l/min] | SoD [mm] | PFR [g/min] | TP [mm] | MH [HV0.3] | Po [%] | Rz [μm] | DE [%] |
|-----|---------|-----------|---------|------------|-------|------------|------|-------|-------|
| 1   | 1       | 1         | -1      | -1         | 1     | 976        | 2.1  | 21.0  | 38    |
| 2   | -1      | 1         | -1      | 1          | 1     | 1006       | 1.9  | 20.7  | 27    |
| 3   | 0       | 0         | 0       | 0          | 1.664 | 1027       | 2.9  | 20.0  | 32    |
| 4   | 1       | 1         | -1      | 1          | 1     | 997        | 3.1  | 23.2  | 44    |
| 5   | -1      | -1        | 1       | 1          | 1     | 942        | 5.1  | 20.0  | 36    |
| 6   | 1       | 1         | 1       | -1         | 1     | 934        | 3.3  | 19.5  | 43    |
| 7   | 0       | -1.664    | 0       | 0          | 0     | 1009       | 4.7  | 21.3  | 46    |
| 8   | 1       | 1         | 1       | 1          | 1     | 971        | 3.9  | 20.1  | 42    |
| 9   | -1      | -1        | 1       | -1         | 1     | 973        | 2.7  | 19.6  | 29    |
| 10  | -1      | -1        | 1       | 1          | -1    | 1032       | 2.5  | 19.2  | 28    |
| 11  | -1      | 1         | 1       | 1          | -1    | 971        | 3.9  | 19.6  | 52    |
| 12  | -1      | -1        | 1       | 1          | -1    | 1022       | 2.4  | 19.4  | 32    |
| 13  | -1.664  | 0         | 0       | 0          | 0     | 906        | 3.0  | 19.9  | 30    |
| 14  | 1       | -1        | 1       | 1          | 1     | 1074       | 3.6  | 21.6  | 50    |
| 15  | 0       | 0         | 0       | 0          | 1.664 | 999        | 2.9  | 21.3  | 38    |
| 16  | 1       | -1        | -1      | -1         | 1     | 969        | 1.3  | 21.6  | 43    |
| 17  | 0       | 0         | -1.664  | 0          | 0     | 1012       | 2.7  | 20.2  | 35    |
| 18  | 1       | 1         | 1       | 1          | 1     | 1078       | 2.7  | 19.5  | 38    |
| 19  | 1       | -1        | -1      | 1          | 1     | 993        | 4.2  | 20.8  | 50    |
| 20  | 0       | 0         | 1.664   | 0          | 0     | 946        | 3.5  | 18.6  | 38    |
| 21  | 1.664   | 0         | 0       | 0          | 0     | 954        | 3.5  | 19.7  | 52    |
| 22(C)| 0       | 0         | 0       | 0          | 0     | 985        | 3.2  | 21.1  | 39    |
| 23  | 1       | -1        | -1      | 1          | 1     | 919        | 3.4  | 21.6  | 41    |
| 24  | 0       | 0         | 0       | 1.664      | 0     | 948        | 3.3  | 21.9  | 37    |
| 25(C)| 0       | 0         | 0       | 0          | 0     | 953        | 2.9  | 19.5  | 37    |
| 26  | 0       | 0         | 0       | -1.664     | 0     | 976        | 2.7  | 19.2  | 31    |
| 27(C)| 0       | 0         | 0       | 0          | 0     | 974        | 2.7  | 19.8  | 36    |
| 28  | -1      | -1        | -1      | 1          | -1    | 903        | 5.6  | 21.6  | 39    |
| 29  | 0       | 1.664     | 0       | 0          | 0     | 971        | 2.9  | 19.1  | 28    |

3. Results and discussion

3.1. Main effects and interaction

Table 3 shows the effect estimates and the p-values for each response variable (MH, Po, Rz, DE). The independent variables affect the response variables positively or negatively, which does the sign of the
estimate show. The significance level was set to 10 % (α = 0.1), and the significant effects are marked in bold. The line with (Q) and (L) refer to linear or quadratic effects.

Table 3. Effect estimates and p-values (α = 0.1) of the response variables.

| MH [HV0.3] | Po [%] | Rz [µm] | DE [%] |
|------------|--------|---------|--------|
| Est. p-value [10^-4] | Est. p-value [10^-4] | Est. p-value [10^-4] | Est. p-value [10^-4] |
| KL (L) | 28.28 | 969.5 | 0.0 | 0.0 |
| KL (Q) | -25.72 | 1869.5 | 0.10 | 5501.7 |
| OL (L) | 19.81 | 2244.5 | -0.21 | 1703.3 |
| OL (Q) | -25.72 | 1869.5 | 0.10 | 5501.7 |
| SOD (L) | 7.37 | 6373.3 | 0.48 | 92.6 |
| SOD (Q) | 9.47 | 6094.2 | 0.02 | 8868.7 |
| PFR (L) | 11.42 | 4699.9 | 0.66 | 15.7 |
| PFR (Q) | -2.55 | 8901.1 | -0.06 | 7331.3 |
| TP (L) | 11.51 | 4661.7 | 0.01 | 9574.4 |
| TP (Q) | 34.09 | 921.0 | -0.12 | 4793.9 |
| KL * OL (int.) | -39.78 | 521.8 | 0.82 | 10.0 |
| KL * SOD (int.) | 6.57 | 7162.1 | 0.22 | 2096.7 |
| KL * PFR (int.) | 51.57 | 1387.3 | -0.03 | 8470.4 |
| OL * SOD (int.) | -19.55 | 2952.1 | -0.03 | 8586.5 |
| OL * PFR (int.) | 51.57 | 1387.3 | -0.03 | 8470.4 |
| OL * TP (int.) | -32.23 | 1020.8 | -0.58 | 77.9 |
| SOD * PFR (int.) | 18.30 | 3251.0 | -0.64 | 44.0 |
| SOD * TP (int.) | 8.57 | 6364.4 | 0.19 | 2895.5 |
| PFR * TP (int.) | 8.73 | 6306.4 | -0.25 | 1638.8 |

Based on the effect estimates in Table 3, the MH is influenced by KL, TP, and the interactions KL*OL and KL*PFR. Po is mainly affected by OL, SOD, PFR, and the interactions KL*OL, KL*TP, OL*SOD, and OL*PFR. The interaction KL*OL directly refers to the Lambda (λ) value (air–fuel equivalence ratio). The explanation for the observed relations is similar for all effects. Changes in the OL or KL result in differing flame temperature and gas velocities. Hence, these changes directly influence the powder heating and acceleration in the flame jet. Due to thermally induced microstructural changes, e.g. formation of brittle phases or the decomposition of WC to W2C, the coating MH can be affected [15]. A high OL with a high KL combined with a high λ value result in a large total amount of combustion media (TAOCM), that leads to an increase in the particle velocity and reduction of the particle temperature. The impact velocity on the surface influences the compaction of the WC-CoCr coating and hence the porosity [16]. Further, the MH correlates with the Po. Based on a low heating, solid particles can re-bounce or are integrated into the coating and particles that are molten to a too high degree can burst during the impact. Both effects lead to a higher Po due to imperfections in the WC-CoCr coating. A similar effect occurs when PFR is increased or when SOD is varied.

The correlation between the PFR and Po as well as Rz depends on the higher mass flow of WC-CoCr particles [17]. To melt more particles, a higher combustion energy is necessary. If the flame energy is not increased parallel to the higher powder feed rate or limited due to the process control, the particles are not well heated and remain solid. Furthermore, Rz is affected by the named variables (OL, SOD, TP). A low particle velocity results in a rougher surface due to a lower compaction of a single sprayed layer.

With respect to the commercial use of the HVOF ID coating process, the DE is a very important value. As shown in Table 2, the DE fluctuates strongly within the range of 27 to 52 %. Based on Table 3, the DE is affected by KL, OL, and hence λ. Figure 2 shows the main effect plots for the DE.
A higher $\lambda$ means an oxygen excess during combustion. This excess is based on a reduced fuel level or an increased oxygen level. With higher $\lambda$, the combustion energy and the combustion chamber pressure are decreased [18]. The effect of $\lambda$ is similar to the effect of the PFR: the particles are not sufficiently heated or melted to adhere on the substrate and to form a coating.

![Figure 2. Effect plot for the deposition efficiency (DE).](image)

Based on the results in Table 3, the response variables can be fitted by a second order model (1), enabling a correlation of the response variables to the independent variables [19].

$$Y_i = b_0 + \sum_{i=1}^{n} b_i x_i + \sum_{i=1}^{n} b_{ii} x_i^2 + \sum_{i<j}^{n} b_{ij} x_i x_j + \varepsilon$$

(1)

where $Y_i$ is the predicted response, and $x_i$ and $x_j$ are independent variables that influence the response variable $Y$ while $b_0$ is the intercept and $b_i$ is the linear coefficient. Furthermore, $b_{ii}$ is the quadratic coefficient and $b_{ij}$ is the linear-by-linear interaction between $x_i$ and $x_j$, where $i$ ranges from 1 to 5. The residual standard error $\varepsilon$ is the square root of the residual sum of squares divided by the residual degrees of freedom. Moreover, the data allows the generation of 3D-surface plots, showing the effect of each interaction of the independent variables on the response variables. To support the consistency and readability of the text, the 3D-surface plots are not given at this point. The regression models for the MH, Po, Rz, and DE are given within the SI data (SI data, Figure S1).

### 3.2. Optimization and verification

Multi-criteria optimization, using the Derringer’s desirability function [14], was employed to find an optimum combination of the independent variables. In this respect, the response variables were transformed into in a common scale. The desirability $d$ of each response variable is assigned a value between 0 and 1, corresponding to the optimization goal (desirability at a maximum or minimum), as shown in Table 4. The desirability of a response variable takes the value 0 when the response drops to a lower specification limit (LSL). The value 1 is defined when the response variable exceeds the upper specification limit (USL). Values in between the limits are also assigned a desirability, whereby the transformation is linear (i.e. between 0 and 1).

Following the desirability transformation, the desirability index $D$ is calculated as shown in [13]. Within this study, $D$ is calculated with the same weight for all criteria (response variables). With regard to the multi-criteria optimization, the theoretical optimum with a desirability index of 0.8833 is reached. The resulting optimized spray parameters to deposit WC-CoCr in combination with the HVOF-ID gun are shown in Table 5. Furthermore, the predicted values for the MH, Po, Rz, and DE are given.
Table 4. Parameters for desirability transformation.

| MH [HV 0.3] | Po [%] | Rz [µm] | DE [%] |
|-------------|--------|---------|--------|
| MH (max) d (MH) | Po (min) d (Po) | Rz (min) d (Rz) | DE (max) d (DE) |
| LSL 900 0 | 2 1 | 19 1 | 25 0 |
| USL 1080 1 | 4 0 | 23.5 0 | 45 1 |

Table 5. Optimized spray parameters and predicted response values.

| KL [l/h] | OL [l/min] | SOD [mm] | PFR [g/min] | TP [mm] | D |
|---------|-----------|---------|-------------|--------|---|
| 5.0 | 293 | 91.6 | 43.3 | 3.17 | 0.8833 |

| MH [HV0.3] | Po [%] | Rz [µm] | DE [%] |
|------------|--------|---------|--------|
| Predicted values | | | |
| 1162 | 2.4 | 19.9 | 35.8 |

WC-CoCr coatings were produced, based on the calculations using Derringer’s desirability function in order to verify the predicted values of the response variables. All other spray parameter settings were kept constant according to Table 1. Three substrates were coated for the verification experiments. As shown in Table 6, the results reveal a significant deviation between the predicted and experimentally determined values (green: positive deviation, red: negative deviation).

Table 6. Predicted response values and experimentally determined values.

| MH [HV0.3] | Po [%] | Rz [µm] | DE [%] |
|-------------|--------|---------|--------|
| pred. exp. DV [%] | pred. exp. DV [%] | pred. exp. DV [%] | pred. exp. DV [%] |
| 1162 | 1051 - 10.57 | 2.4 | 1.1 | - 119.27 | 19.9 | 14.4 | - 38.24 | 35.8 | 25.3 | - 41.42 |
| 1162 | 1046 - 11.06 | 2.4 | 1.1 | - 113.39 | 19.9 | 13.1 | - 51.95 | 35.8 | 24.2 | - 47.91 |
| 1162 | 994 - 16.92 | 2.4 | 0.5 | - 378.00 | 19.9 | 13.9 | - 43.31 | 35.8 | 25.0 | - 43.18 |

However, the measured values for Rz and Po are lower than the predicted data. Thus, an average for Po of 0.9 % is measured, whereas an average for Rz of 13.8 µm is determined. The MH and DE tend to be lower than predicted as well. Especially, the DE determined by the experiments demonstrates a distinct reduction. Thus, the experiments reveal an average for DE of 24.83 %, which corresponds with a reduction of approximately 44 % in average. It can be concluded that the mathematic regression models seem to be inaccurate, leading to significant deviations. The reasons are not yet clear. Nevertheless, cross-section analyses of the produced WC-CoCr coating using optimized spray parameters confirm the low porosity, macroscopically dense microstructure, and smooth surface (Figure 3). However, the cross-section images (Figure 3a, b) showing the coating microstructure at higher magnification, reveal a heterogeneous microstructure and distinct micro-porosity. With the calculated SOD of 91.6 mm the minimal coatable internal diameter can be calculated as 171.6 mm, based on the HVOF-ID gun dimensions, i.e. housing of the spray gun with a diameter of approximately 80 mm.
Based on the optimized spray parameter settings, further investigations on certain spray parameter variations were conducted in order to analyse the effect of changing the KL and TAOCM on the resulting MH. The cooling power and combustion chamber pressure (CCP) were measured as well. Furthermore, the in-flight particle velocity and temperature were determined. It was determined that a higher KL (which corresponds with a reduced $\lambda$, when OL and HL are kept constant) leads to a higher CCP and cooling power (Figure 4). As indicated by the increased cooling power during spraying, the spray particles are subjected to an increased heat input across the spray plume when they accelerate towards the substrate.

As demonstrated for higher KL (i.e. reduced $\lambda$), in-flight particle analyses (Figure 5) confirm the fact that the spray particles exhibit an increased temperature. At the same time, the velocity of the spray particles is slightly reduced. As a result, the spray particles have almost the same dwell time. It is
assumed that the increased heat input could lead to more pronounced WC decomposition phenomena. XRD analyses (Figure 6) reveal that the WC-CoCr feedstock is mainly composed of WC, Co, as well as some traces of Co$_3$W$_3$C, Cr, and W. In contrast, the WC-CoCr coatings consist of WC, W$_2$C (or W$_2$C$_{0.84}$), Co$_3$W$_3$C, and W. In addition, there is only a small amount of Co and Cr, which can be found within the experimental resolution. For a decreased $\lambda$, the XRD pattern indicates an increased amount of Co$_3$W$_3$C and W. As discussed in [20,21], the hardness of the W-rich hard phases might decrease in the sequence of W$_2$C $>$ WC $>$ Co$_3$W$_3$C (e.g. 29.4 GPa for W$_2$C, 16-22 GPa for h-WC, 23.5 GPa for WC, and less than 15.6 GPa for Co$_3$W$_3$C). As a result, the higher the content of Co$_3$W$_3$C and W, while the amount of WC and W$_2$C decreases simultaneously, the lower the microhardness. However, the data for MH deviates significantly, which might be related to the heterogeneous microstructure as shown previously (Figure 3).

Similar findings are observed for a change in the TAOCM. At a KL of 3.9 l/h and a OL of 234 l/min, the spray particles exhibit a temperature and velocity of 1931 ± 26 °C, and 536 ± 29 m/s, respectively. In contrast, a temperature of 1977 ± 6 °C and velocity of 620 ± 13 m/s is measured at a KL of 5.5 l/h and OL of 320 l/min. Hence, for a reduced TAOCM but at the same $\lambda$ (KL: 3.9 l/h, OL: 234 l/min vs. KL: 5.5 l/h, OL: 320 l/min) the spray particles are subjected to an increased dwell time when compared to an increased TAOCM. Simultaneously, it is assumed that the spray particles sustain a high heat input, which is also indicated by the cooling power. This in turn, favors the phase transformation phenomena as previously described, leading to a possible degradation of the mechanical properties, indicated by a reduced microhardness (Figure 4).

**Figure 5.** In-flight temperatures and velocities of WC-CoCr particles for different Lambda ($\lambda$) values.

**Figure 6.** XRD analyses of the feedstock and different WC-CoCr coatings.

### 4. Summary and conclusion

In this study, a CCD experimental plan was used to describe the behavior of a HVOF-ID system in combination with a fine-structured, agglomerated and sintered WC-CoCr feedstock (~15+5 µm, WC particle size of 0.4 µm FSSS). A desirability-based optimization was conducted to determine optimal spray parameters (KL 5.0 l/h, OL 293 l/min, SOD 91.6 mm, PFR 43.3 g/min, TP 3.17 mm). The results obtained from the verification experiments differ from the predicted values based on a multi-criteria optimization using Derringer’s desirability function. Hence, a low Po (0.9 %) and a reduced Rz
(13.8 µm) were achieved. Furthermore, the MH and DE were significantly lower than predicted. A reason for these results could be the inaccuracy in the mathematic regression model or in the desirability limit. Nevertheless, the systematic analysis by means of DoE is a promising approach to describe the system behavior of a HVOF-ID system, enabling to identify a usable SOD for ID applications. The SOD and dimensions of the spray gun determine the smallest coatable ID to achieve promising coating properties. For the present HVOF-ID system and WC-CoCr feedstock used within this study, the smallest coatable ID is 171.6 mm. Both the SOD and the combustion media, i.e. KL and OL, represent significant influencing factors as they affect the heat input into the spray particles, and thus, the phase transformation processes.

Acknowledgments
The results have emerged within the framework of the IGF Project No. 19.914 N with the subject of „Untersuchung der Einflussgrößen und prozess-technischen Randbedingungen auf die Schichtqualität beim Beschichten von rotationssymmetrischen Innenflächen mittels HVOF/HVAF“. We thank the research association „Forschungsvereinigung Schweißen und verwandte Verfahren des DVS“ and the Federation of Industrial Research Associations (AiF) for the promotion. The project was funded by the German Ministry of Economic Affairs and Energy via AiF within the framework of joint industrial research (IGF).

References
[1] Barbezat G and Herber R 2001 Durchbruch für Motorenbeschichtung Sulzer Technical Review 2 8-11
[2] Bobzin K, Öte M, Königstein T, Dröder K, Hoffmeister H-W, Mahlfeld G and Schläfer T 2018 Development of novel fe-based coating systems for internal combustion engines J. Therm. Spray Tech. 27 736–745
[3] Krauß B 2015 Trend: Beschichtete Zylinderlaufbahnen VDI-Z Integrierte Produktion
[4] Matthäus G 2018 Applications for HVOF and plasma coatings based on ultra-fine powder < 10 µm Proceedings 11. HVOF Kolloquium Erding 73-83
[5] Gutleber J, Molz R, He J, Weber C and Colmenares J 2017 New developments in HVOF spraying for internal diameter coatings Proceedings International Thermal Spray Conference 501-504
[6] Yuan J, Zhan Q, Huang J, Ding S and Li H 2013 Decarburization mechanisms of WC–Co during thermal spraying: Insights from controlled carbon loss and microstructure characterization Mater. Chem. Phys. 142 165–71
[7] Berger L-M 2018 Hardmetal coatings – history and perspective Proceedings 11. HVOF Kolloquium Erding 93-100
[8] Gries B 2018 HVAF- Chance and challenge for users and for powder producers Proceedings 11. HVOF Kolloquium Erding 57-72
[9] Shipway P H, McCartney D G and Sudapraser T 2005 Sliding wear behaviour of conventional and nanostructured HVOF sprayed WC–Co coatings Wear 259 820–827.
[10] Marble F E 1963 Dynamics of a gas containing small solid particles Combustion and Propulsion (5th AGARDograph Colloquium) Pergamon Press 175-213
[11] Pattison J, Celotto S, Khan A and O’Neill W 2008 Standoff Distance and Bow Shock Phenomena in the Cold Spray Process Surf. Coat. Technol. 202 1443-1454
[12] Bobzin K, Ernst F, Zwicky J and Matthaeus G 2007 Analyse von Partikeleigenschaften beim Thermischen Spritzen von Mikropulvern. Materialwissenschaft und Werkstofftechnik 38 149-154
[13] Tillmann W, Vogel E, Baumann I, Kopp G and Weihl C 2010 Desirability-Based Multi-Criteria Optimization of HVOF Spray Experiments to Manufacture Fine Structured Wear-Resistant 75Cr3C2-25(NiCr20) Coatings J. Therm. Spray Technol. 19 392-408
[14] Derringer G and Suich R 1980 Simultaneous Optimization of Several Response Variables J. Qual. Technol. 12 214-219

[15] Tucker R C 2013 ASM handbook: Thermal Spray Technology (ASM International)

[16] Oksa M, Turunen E, Suhonen T, Varis T and Hannula S-P 2011 Optimization and Characterization of High Velocity Oxy-fuel Sprayed Coatings: Techniques, Materials, and Applications Coatings 1 17-52

[17] Xie M, Lin Y, Ke P, Wang S, Zhang S, Zhen Z and Ge L 2017 Influence of Process Parameters on High Velocity Oxy-Fuel Sprayed Cr3C2-25%NiCr Coatings 7 1-10

[18] Baumann I T 2012 Hochverschleißfeste und konturnahe Werkzeugoberflächen durch Hochgeschwindigkeitsflammpritzverfahren Werkstofftechnologische Schriftenreihe 5

[19] Weihs C and Jessenberger J 1999 Statistische Methoden zur Qualitätssicherung und -optimierung in der Industrie (Weinheim: Wiley VCH Verlag GmbH)

[20] Tillmann W, Hagen L and Schröder P 2017 Tribological Characteristics of Tungsten Carbide Reinforced Arc Sprayed Coatings using Different Carbide Grain Size Fractions Tribology in Industry 39 168-182

[21] Li Y, Gao Y, Fan Z, Xiao B, Yue Q, Min T and Ma S 2010 First-principles study on the stability and mechanical property of eta M3W3C (M= Fe, Co, Ni) compounds Physica B: Condensed Matter 405 1011-1017