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Investigation about the Chrome Steel Wire Arc Spray Process and the Resulting Coating Properties

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Nowadays, wire-arc spraying of chromium steel has gained an important market share for corrosion and wear protection applications. However, detailed studies are the basis for further process optimization. In order to optimize the process parameters and to evaluate the effects of the spray parameters DoE-based experiments had been carried out with high-speed camera shoots. In this article, the effects of spray current, voltage, and atomizing gas pressure on the particle jet properties, mean particle velocity and mean particle temperature and plume width on X46Cr13 wire are presented using an online process monitoring device. Moreover, the properties of the coatings concerning the morphology, composition and phase formation were subject of the investigations using SEM, EDX, and XRD-analysis. These deep investigations allow a defined verification of the influence of process parameters on spray plume and coating properties and are the basis for further process optimization.

Keywords design of experiments (DoE), microstructure, online process monitoring, process analysis, wire arc spraying, X46Cr13 stainless steel

1. Introduction

Since its development by Schoop in the beginning of the 20th century (Ref 1), the wire-arc spray process had become one of the most successful techniques for thermal-spray applications. The simple and cost efficient process set up and the high variety of usable wire materials are just some reasons for this success. However, minimizing the porosity and oxygen-content in the coating and a defined splat formation at the substrate are major challenges for a further process improvement which leads to a deep analysis of influencing parameters on the wire arc spray process.

Subject to be investigated is X46Cr13 chrome steel wire, which gained an important role in corrosion and wear protection applications as well as scientific research (Ref 2-4). Due to its martensitic solidification this chrome steel shows excellent mechanical properties. However, mechanical and corrosion properties are not subject to be introduced in this publication. The objective of the investigations is a process optimization based on an extensive knowledge of the influence of the spray parameters on the process as shown in Fig. 1.

This work utilizes online process monitoring, high-speed camera recordings, oscilloscope recordings, microstructure analysis to investigate the droplet formation, particle temperature, particle velocity and plume width as well as the surface roughness and the resulting coating properties depending on the spray parameters. In (Ref 5-15) some other research works concerning particle and plume properties as well as the resulting coating properties are presented.

By using Design of Experiment (DoE) based experiments in combination with online process monitoring a high content on information at a minimum number of experiments can be achieved. However, there are only few publications concerning DoE based experiments in wire arc spraying, for example (Ref 13, 16).

As a final result, this work should enable a defined process adaptation regarding to the required coating properties, so the process parameters can be optimized to improve the coating properties significantly.

2. Process Setup

The process setup as shown in Fig. 2 is arranged by several parts, described below. As wire material a conventional copper coated X46Cr13 solid wire was used to investigate its behavior in the wire arc spray process under diverse conditions.

The measuring devices (online process monitoring and high speed camera) are placed in front of the spray head

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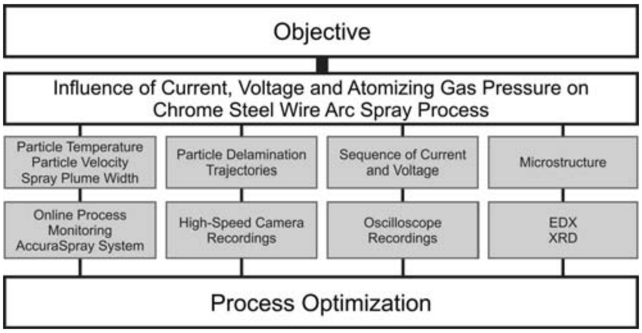

Fig. 1 Objective and procedure for process optimization

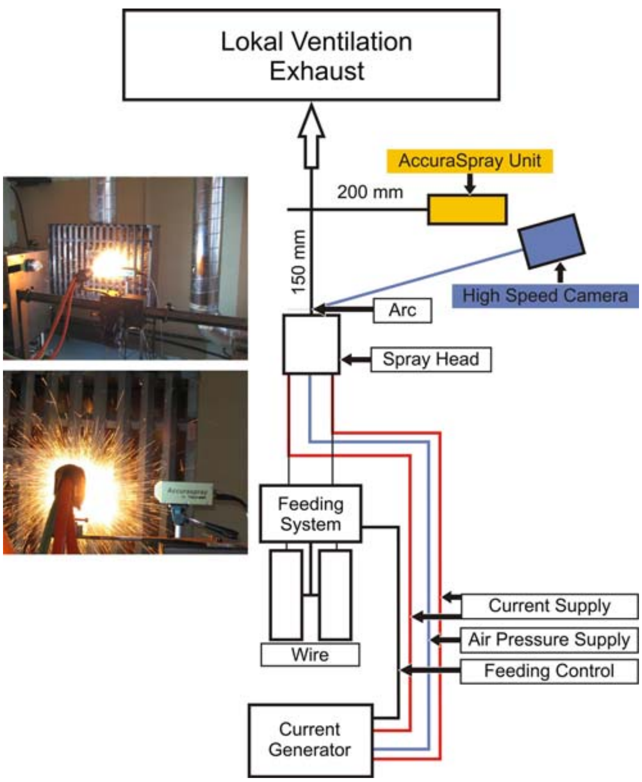

Fig. 2 Process setup (schematic)

to measure the spray-plume properties. Optimum results for measurements with the AccuraSpray sensor head unit can be achieved at 200 mm distance of the unit to the spray plume axis. With respect to the common spray distance of 150 mm, the distance between the recording axis and the arc is 150 mm as well, to get information of spray-plume properties at coating distance. Depending on the light irradiation a measurement error is given. Low-radiating spray plumes (e.g. Zinc) could not be monitored, as the measurement error is very high. High radiating spray plumes as, for example, the used chrome steel allow a defined and precise measurement. The internal setup of the measurement device is adjusted by the manufacturer and remained unchanged. During the measurement a rate of 1 Hz is given. In order to minimize the error, minimum 300 values had been recorded and saved in ASCII data files that allow comprehensive spreadsheet analysis. After import into spreadsheet the mean values and standard deviation had been calculated to be displayed in diverse charts.

High-speed camera recordings are necessary to get information about the droplet formation at the wire tips and the particle trajectory in the plume. In the last few years the technology of high-speed cameras show high advantages, so the high speed camera, used for the investigations (Photron Fastcam), is able to record at a frame rate up to 250,000 fps (frames per second). For the investigations the frame rate had been reduced down to 30,000 fps at a shutter time of 1/86,000 s to maximize the frame resolution.

Main part of the process setup is the VisuArc 350™ arc spray system (Fig. 3). This new developed primary chopped power supply with a special designed feeding and nozzle system enables stable spray conditions and a uniform coating process as spray voltage fluctuations can be reduced significantly. Further specifications of this system are listed in Table 1.

For investigations of the microstructure, coatings on a steel substrate had been processed, as well. The steel substrates had been abraded by grit blasting using steel gravel (mean diameter 0.6 mm) and subsequently coated in a spray distance of 150 mm. After preparation by cutting, grinding, and polishing, the cross sections of the coatings had been investigated using EDX (Energy-Dispersive-X-Ray) analysis and XRD (X-Ray Diffraction) analysis.

3. Results

With respect to the limited space, only some of the selected results are shown.

For the DoE a two-level full factorial model with three different parameters (voltage, current and atomizing gas pressure) was used. This results in $3^2 = 9$ measurements. In order to expand this area, further measurements had been conducted and displayed via spreadsheets. Due to the linear regression between the minimum value (24 V,

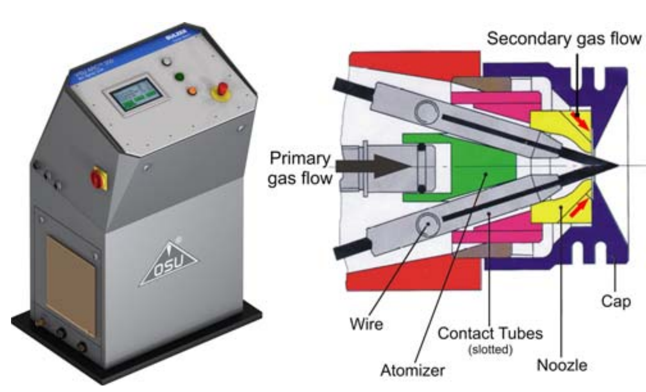

Fig. 3 Arc-spray system (current generator and spray head) (Ref 17)

100 A, and 0.2 MPa) and the maximum value (36 V, 200 A, and 0.4 MPa) no statement regarding to minima and maxima between this regression could be given. This may lead to false conjectures, so the statistic analysis should be studied in combination with the pure data charts; both are given in the context. The error bar is given by the standard deviation from at least 300 values recorded during online process monitoring.

3.1 Particle Velocity

The particle velocity is influenced by fixed parameters, such as the nozzle design, and adjustable parameters, for example atomizing gas pressure, voltage and current. As shown in Fig. 4, this parameter set has significant influence on the particle velocity. The velocity itself varies in the range from 60 to 130 mps and shows the high potential and necessity of optimization. Clear tendencies are given by voltage and current level, too. This show the high influence of the melting pool at the wire tips. Hence the basis of further optimizations by reducing disturbances in this region is given. As shown in Fig. 4, especially at high voltage level a strong influence of current on particle velocity could be observed, which describes the influence of disturbances on particle velocity.

The statistical analysis of the Design of Experiments (DoE) ascertained the atomizing gas pressure as most significant influencing factor on the particle velocity. As shown in Fig. 5, the influence of melting amount at the wire tips on particle velocity is approved, too.

Table 1 Technical data of the VisuArc 350™ arc spray system

Current	Max. 350 A
Spray voltage	15-50 V
Duty cycle	100%
Gas pressure	Max. 0.6 MPa, controlled
Weight	170 kg
Gas consumption for atomizing	83 m^3/h (on 0.4 MPa)
Nozzle System	Closed
Wire diameter	1.6, 2.0, 2.5 mm
Wire feeding	Pull-push (electronic controlled)

3.2 Particle Temperature

The knowledge of the influencing parameters on particle temperature allows the use of process adapted parameters regarding to melting and vaporizing point or phase formation. Furthermore, several coating properties depend on particle temperature, e.g. surface roughness, particle, size and spray rate. The measurements show a particle temperature in plume at spray distance between 2070 and 2180 °C, while the melting point in the binary phase diagram Fe-Cr at 13% chromium is about 1550 °C,

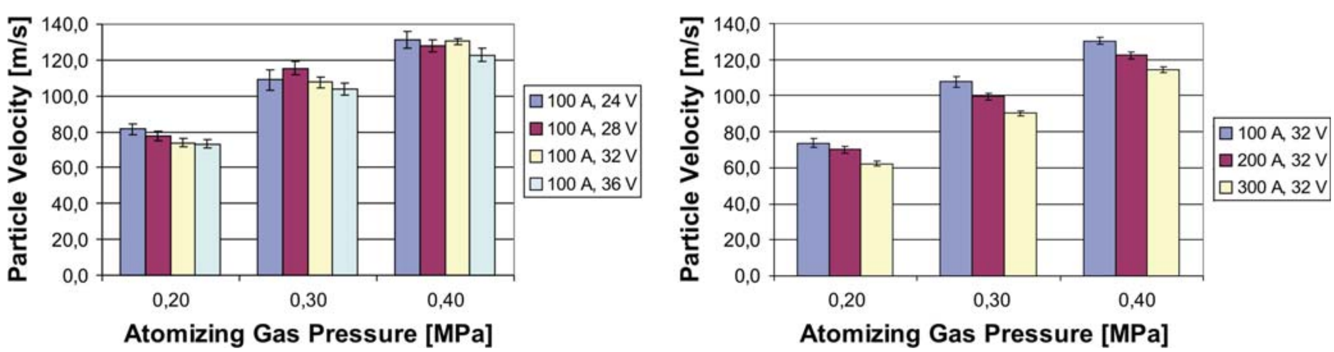

Fig. 4 Particle velocity depending on spray parameters

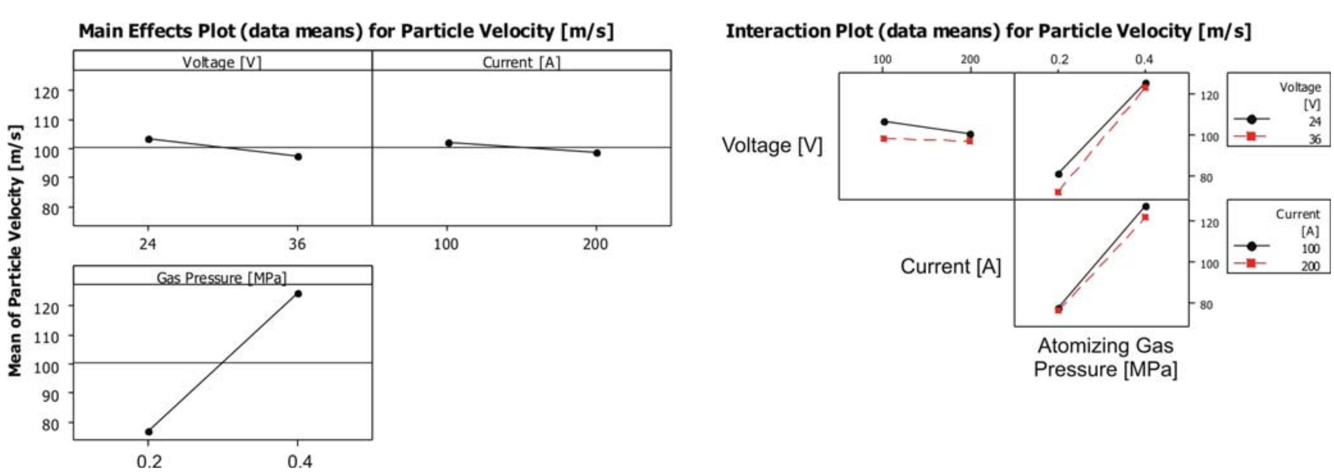

Fig. 5 Influence of factors on particle velocity

so the melt at measuring point is overheated. A further description of phase formation in the coating is given in part microstructure.

In the spreadsheet diagram (Fig. 6) clear tendencies could be ascertained. At first the voltage level has a high influence on particle temperature. An increase of the voltage level results in a longer arc, hence the temperature of the melting pool increases in combination with higher viscosity. This fact is proved by the high-speed camera recordings, too.

The quantity of the melting at the wire tips influences the particle temperature as well. This is shown in Fig. 7. In this diagram the influencing factors on the particle temperature are displayed. By changing the current to the high level, the particle temperature is decreasing at low-voltage level and increasing at high voltage level which is caused by the different melt off performances. At low voltage level and high current the melt pool at the wire tips increases so the arc is shortened which result in a reduced particle temperature. At high voltage level the energy input is high enough to ensure a low viscosity melting pool and an improved droplet formation, so the current level has no decreasing influence. Another effect to be accentuated is the cooling effect of the gas flow at high pressure.

3.3 Spray Plume Width

Further information about the spray plume width are necessary for a fine definition of the coating area and reduced overspray. As shown in Fig. 8, the plume width is influenced by spray voltage, current, and atomizing gas pressure, as well. Attention should be paid to the small differences of the plume width which varies between 15 and 35 mm. As shown in Fig. 8 the plume intensity depends strongly on current level, so it seems to be some kind of measurement error especially at reduced plume intensity. This could be one explanation of this behavior. Of course, some tendencies could be observed. Increasing the arc current dilates the plume width considerably. This is affected by the fluidic effects concerning the melting quantity and the viscosity of the melt at the wire tips. By adjusting the atomizing gas pressure from 0.2 to 0.4 MPa, the plume is focused at different current levels.

Due to the absence of a clear tendency and the presence of minima and maxima within, the statistic analysis displayed in Fig. 9 is not convincing. At least it confirms the major tendencies, for example the influence of atomizing gas pressure and current.

In order to give an overview over the different influencing parameters on spray plume width, eight spray plumes at different parameters are shown in Fig. 10. The

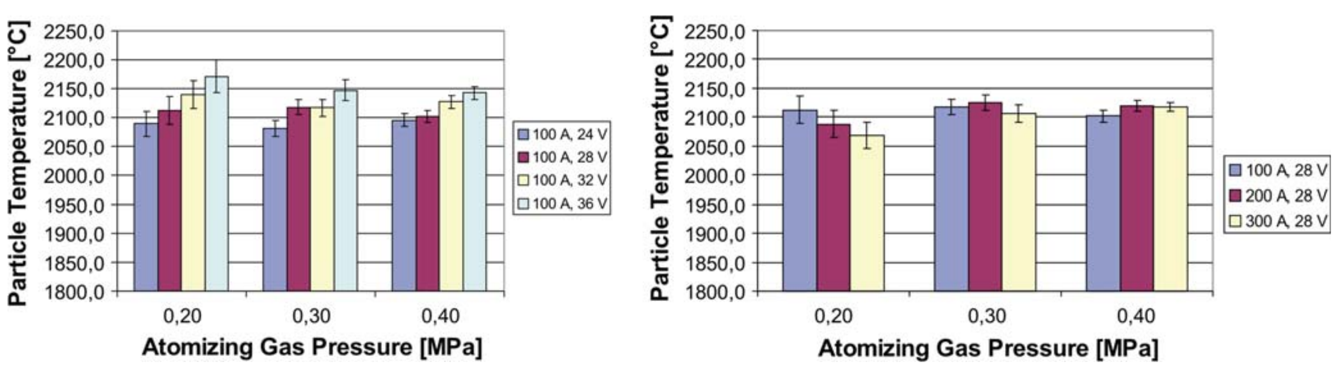

Fig. 6 Particle temperature depending on spray parameters

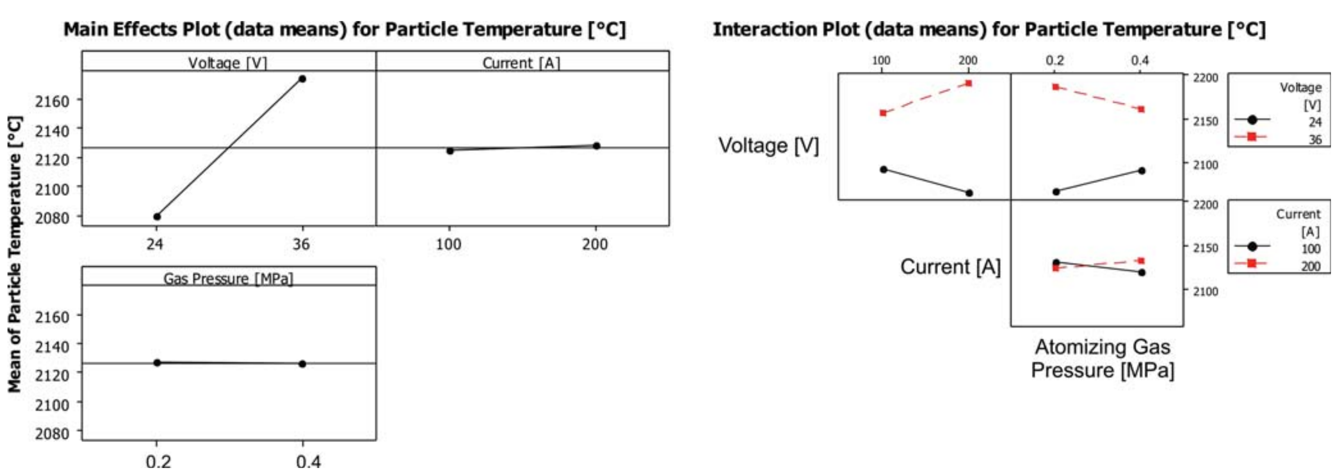

Fig. 7 Influence of factors on particle temperature

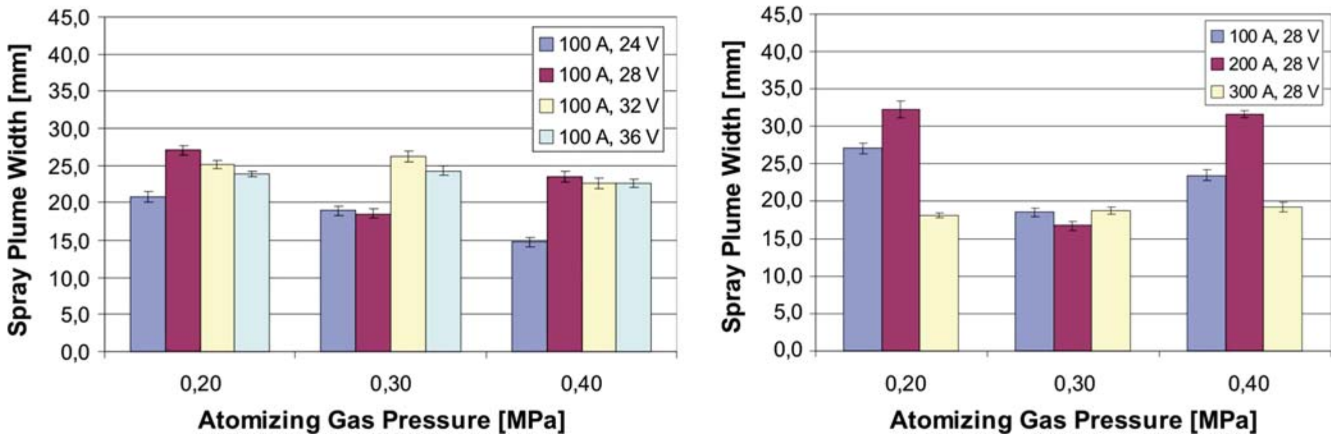

Fig. 8 Spray plume width depending on spray parameters

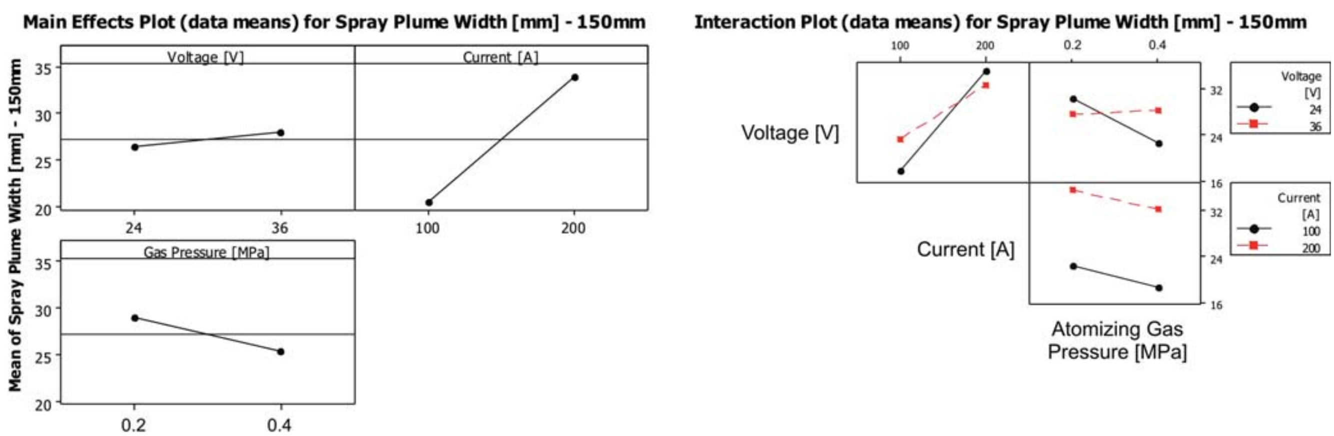

Fig. 9 Influence of factors on spray plume width

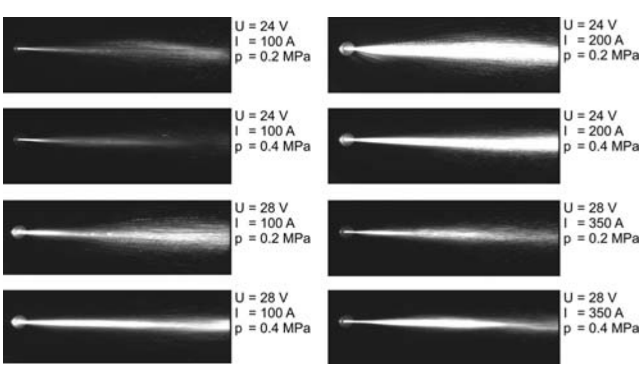

Fig. 10 Spray plumes at different parameters

parameters had been varied between 24 to 28 V and 100 to 200 A, respectively 350 A as at 24 V a spray current of 350 A is not processable for this wire. Moreover the atomizing air pressure had been varied between 0.2 and 0.4 MPa. At first, the focussing effect of a high atomizing gas pressure is remarkable. This effect seems to be independent from other spray parameters. Due to the higher melt amount in the plume at increased current level the plume becomes brighter. At higher energy input a pinching of the plume shortly behind the arc is detectable that results from the variations of gas flow.

Depending on the desired applications, the plume width can be adjusted by the spray parameters for spraying on small substrates or coating of large areas. The most influencing effect on the plume width is the spray current, which is proved by the DoE analysis.

3.4 Droplet Formation

The pictures of the arc and droplet formation were recorded by a high-speed camera system at a frame rate of 22,500 or 30,000 fps (displayed in the frames) and a shutter time of 1/86,000 s. As shown in Fig. 11, a periodically movement of the arc between the wire tips occurs at frequencies of more than 1000 Hz. This is caused by the melting behavior especially at low voltage level. As mentioned above, a high current in combination with a low voltage level cause a high melt quantity on the wire tips and the disturbance of the fluidic conditions. This high quantity melt shorts the arc at first at the front area of the

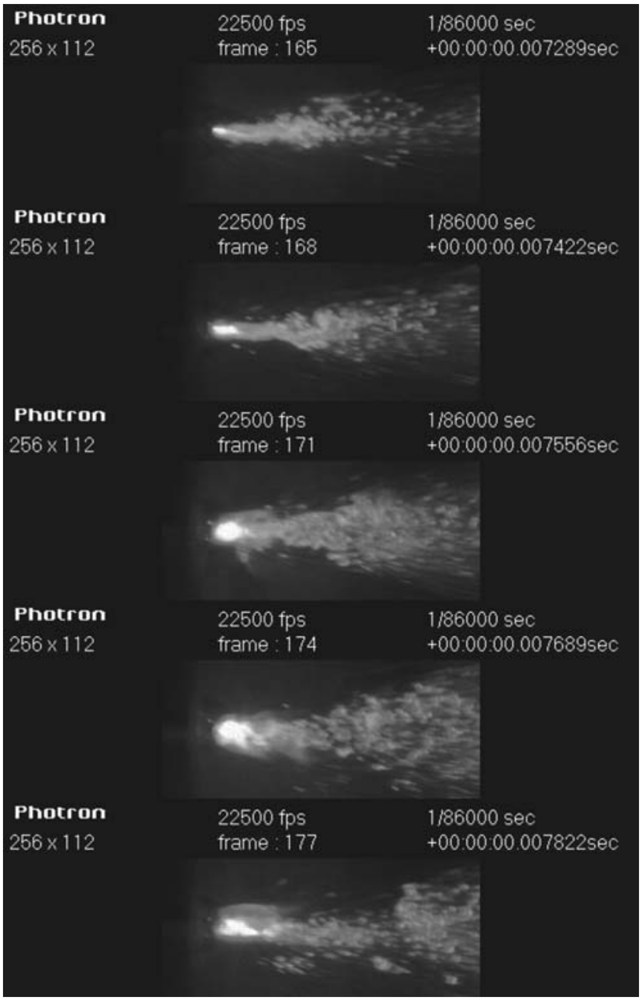

Fig. 11 Movement of the arc at 24 V, 200 A, and 0.2 MPa

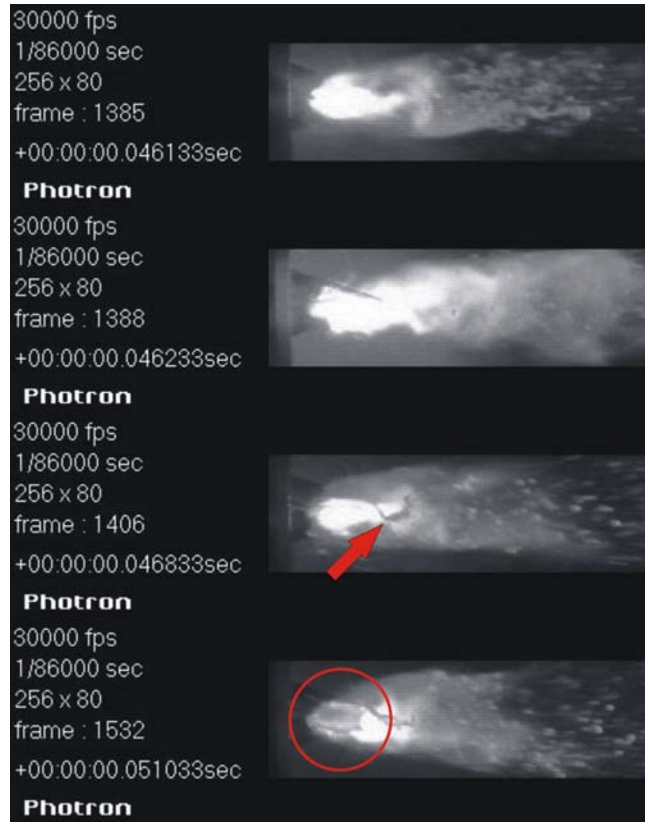

Fig. 12 Droplet formation at 36 V, 200 A, and 0.3 MPa

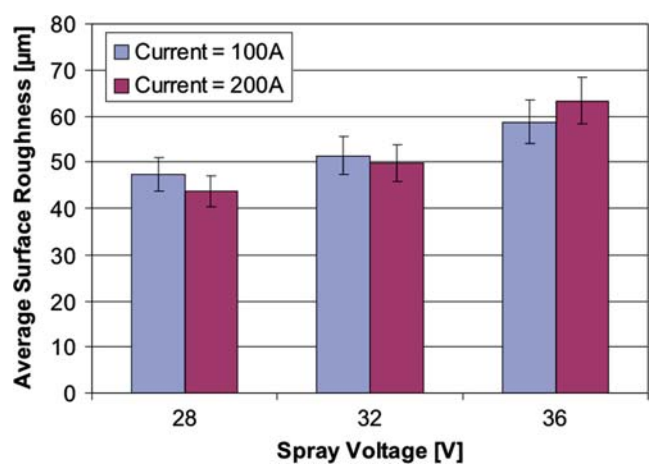

Fig. 13 Average surface roughness at different spray voltage and current

tips. Hence the arc recedes back towards the spray head. After diluting the partially ohmic heated melt, the arc can be established in the front again. At higher voltage level the arc elongates and the temperature depending melt viscosity decreases.

Therefore, a movement of the arc was not observed. Large particles delaminate from the tips (marked by the arrow in Fig. 12) and the tips are almost melt-free. The arc melts the wire only locally and the molten material delaminates directly. Due to this, a stable arc can be established. Secondary atomizing of the large molten droplets reduces the particle size.

Caused by the high temperature among the wire tips at high voltage level, the wire tips get partially vaporized. This leads to a reduction of the spray efficiency as well as the lower melt viscosity due to the high-energy input.

3.5 Surface Roughness

The average surface roughness depend largely on the spray voltage as shown in Fig. 13. By raising the voltage level from 28 to 36 V, the average surface roughness (Rz) increases about twenty percent up to 65 μm. The error bars display the standard deviation of six measurements. Adjusting a higher current affects a decrease of the surface roughness at lower voltage and an increase at higher voltage.

A low voltage results in a lower particle temperature as shown in the measurements above. Increasing the current at a low voltage level means that the temperature of the melt decreases as well. This is caused by the higher wire feed rate at higher current level, so the melt volume at the wire tips increases. Thus, the arc is shortened and the particle temperature significantly decreases. Only small particles with low viscosity separate from the wire tips and are accelerated to the substrate. This behavior could also be described by high-speed camera recordings. At a higher voltage level the energy of the arc is high enough to ensure a high melting temperature at the wire tips. Thus, large particles with a high viscosity delaminate, which can be observed by high-speed camera recordings. These particles become partially atomized by other particles or by gas stream and at the impact on the substrate. The impacting particles are bigger compared to that at low voltage that results in a different coating composition, for example more lamellar structures and less spheroid particles within the coating.

3.6 Microstructure

As shown in Fig. 14, the sprayed coatings of chrome steel are featured by low porosity and excellent bonding to the substrate. As mentioned above, the particle size depends on the spray voltage significantly. This can be ascertained in the coating microstructures, too.

At low voltage level, spheroid particles are present in the coating which indicates that the particles solidify in-flight caused by the lower temperature at the delaminating point. This behavior correlates with the results of the particle temperature measurements and high-speed camera recordings.

By using the EDX-Analysis only iron and chromium are detectable as carbon and oxygen show a high measurement error in EDX-analysis. The area analyses show a very similar composition of the coatings at all parameters. Due to the fraction of 13 weight percent chromium and 80 weight percent iron a fraction of 7 weight percent impurities are contained within the coating. SEM-micrographs show the existence of three different phases, a dark gray phase, a light gray phase and a phase with microstructure. The light gray phase contains an increased fraction of iron and a reduced chromium fraction. Within the dark gray phase the results are high fluctuating. A significant tendency depending on the process parameters is not determinable. The microstructured phase shows a

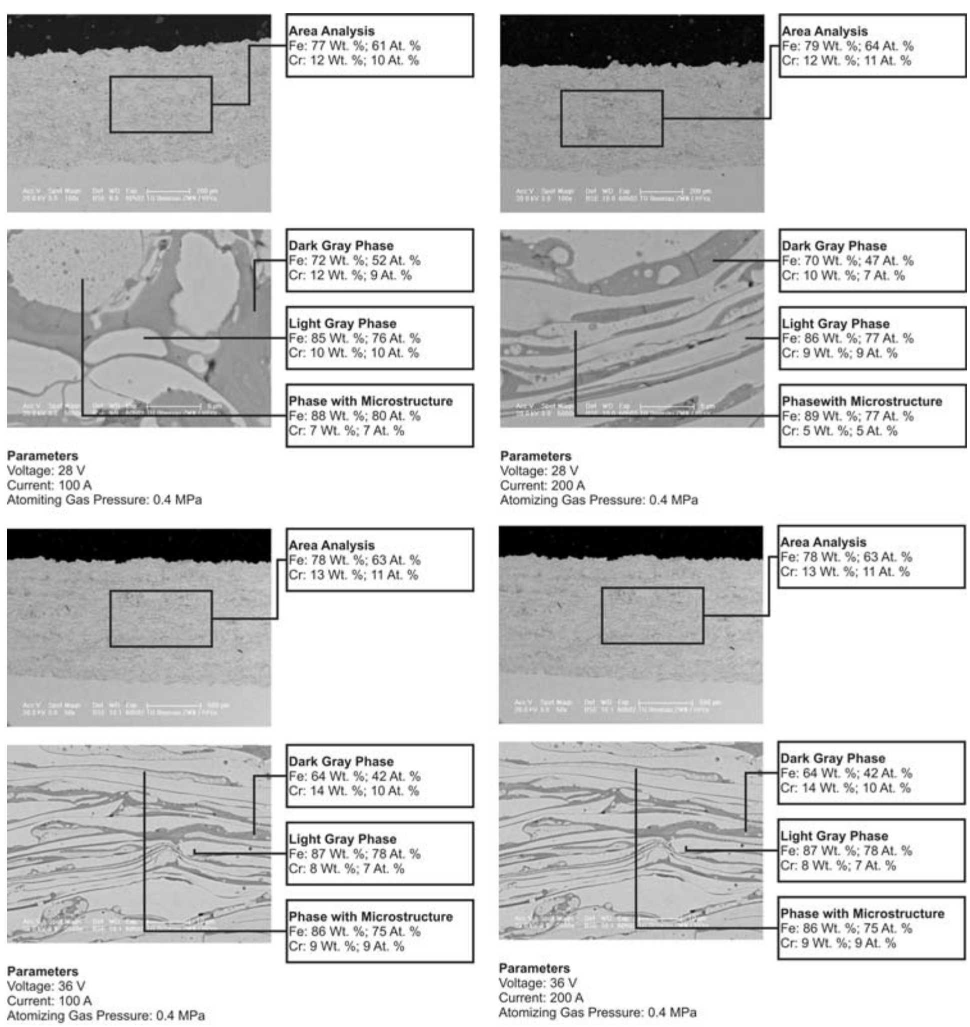

Fig. 14 EDX-analyses of the microstructure of chrome steel coatings

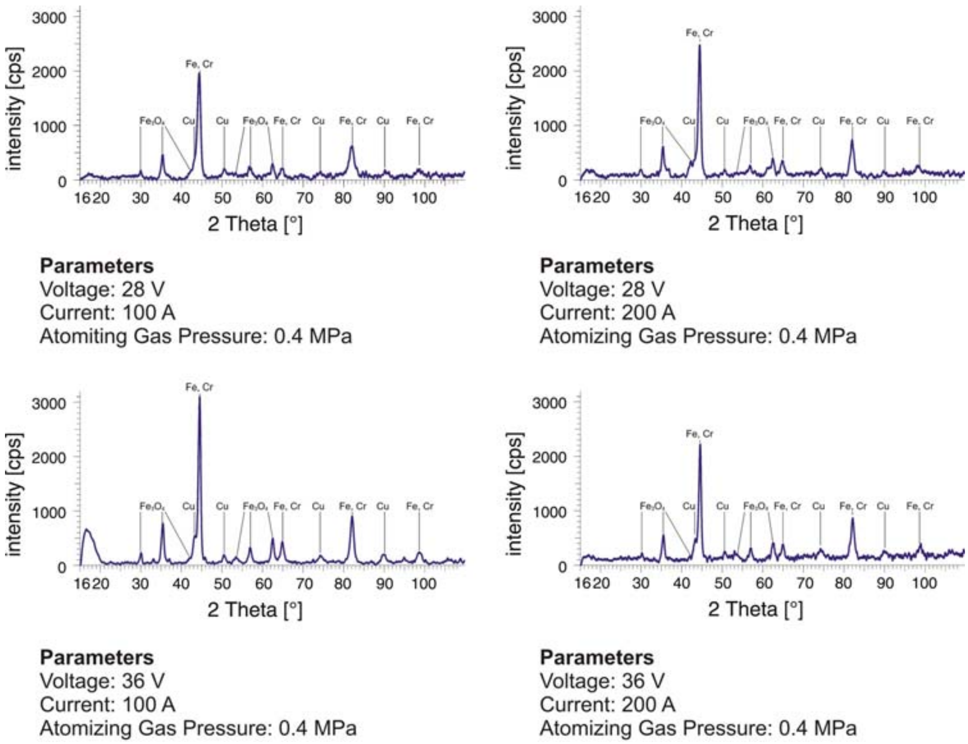

Fig. 15 XRD-analyses of the microstructure of chrome steel coatings

high fraction on iron, comparable to the light gray phase. Of course, the dark gray phases are the phases with high oxide (magnetite) content as the sum of chromium and iron is reduced significantly compared to the light gray phases and the area analyses. Altogether the part of the dark gray phases vary from 20 to 40% and a reduced content of dark-gray phases can be achieved at higher voltage level.

A further definition of the phase fraction can be given by XRD-analysis. Basically the XRD-analysis in Fig. 15 shows the existence of three different phases within the X46Cr13 sprayed coating. Main parts are the body-centered cubic α-iron and chromium. Moreover magnetite resulting from the oxidation of iron exists. The copper peaks result from the copper coated wire.

Examining the diffraction graph dependences among the voltage levels at 100 A and the intensity of the Fe-Cr phase can be ascertained. At higher current level the magnetite intensity increases significantly, which can be caused by the different droplet formation compared to lower current level.

4. Summary and Conclusions

The spray parameter current, voltage, and atomizing gas pressure influence the droplet formation, the particle velocity, the particle temperature, and the plume width as well as the coating properties in different ways. For each attribute, significant factors had been ascertained. This deep analysis allows a defined parameter adjustment regarding to the requested properties, thus the basis for an extensive process optimization is given.

DoE based investigations combined with high-speed camera recordings and online process monitoring had been used to adjust the processing parameters for various coating applications of chrome steel coatings.

The most significant factor on the particle velocity is the atomizing gas pressure. Particles with a high velocity can be achieved by high voltage and atomizing gas pressure levels. A decrease of the current leads to an increase of the velocity, due to the lower melt mass to be accelerated. Furthermore, the particle velocity has besides the particle temperature a major influence on impact behavior of the particles on the coating, so the surface roughness can be adjusted as well.

For spraying alloys, it is important to reduce the burn-off of elements. A respectively low particle temperature process is often required to maintain the alloy composition. By using low voltage level at high atomizing gas pressure and high current, the particle temperature and surface roughness can be reduced.

Raising the spray efficiency by optimizing the plume width regarding component size seems to be useful. In order to achieve a small plume width for the coating of small areas, a low current combined with a high atomizing gas pressure is necessary.

EDX and XRD-analysis enable a deep view into the microstructure of the coatings, thus a definition of influencing parameters on coating properties is possible.

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