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Recent Developments in Single-Wire Vacuum Arc Spraying

H.-D. Steffens and K. Nassenstein

Reactive materials such as titanium and tantalum are not suitable for the manufacture of pure and corrosion-resistant layers by atmospheric spraying processes, and thus are normally processed by vacuum plasma spraying. However, because of the large specific area of the feedstock, large amounts of previously adsorbed oxygen and nitrogen are included in the coating, often resulting in unsatisfactory corrosion behavior. This can be avoided by vacuum arc spraying using a single wire. The spraying material is a cathodic poled wire that is led without contact through a nonconsumable, water-cooled nozzle. The wire is melted by a high-frequency arc that burns between the wire and the nozzle. The process gas (argon) atomizes the wire and accelerates the particles onto the component being coated. The process parameters strongly influence the stability of the process and the resulting microstructure of the deposit.

1. Introduction

INITIAL studies of the electric arc process were based on conventional arc spraying using two oppositely poled wires. The melting process was achieved by short circuit. A higher pressure just behind the short circuit point was necessary due to the low pressure of the environment. This was achieved by altering the nozzle geometry so that the aerodynamic conditions prevented spreading of the arc. Dissimilar melting behavior of the two wires occurred based on chamber pressure and applied potential. Another disadvantage was the high consumption of argon (20 to 50 N· m^3/h) (Ref 1).

Efforts to produce good coating quality led to the development of a single-wire vacuum arc spraying process. A cathodic poled consumable wire was led without contact through a water-cooled anodic nozzle into the vacuum chamber. A Laval nozzle provided the necessary increase in pressure in the arc spray gun in relation to chamber pressure. The arc was generated between the wire and the nozzle by means of high-frequency ignition. The wire was melted by the arc, which was spread out behind the narrowest cross section of the nozzle. The arc had to rotate around the wire tip in order to prevent overheating of any one point on the nozzle wall.

The supplied process gases (argon and argon/helium) were ionized and served to atomize the melting wire particles. Compared to two-wire vacuum arc spraying, the single-wire method consumes five times less process gas. The atomizing gas, which was expanded through the nozzle guide, also ensured that the process was sealed against the atmosphere. Very fine particles were achieved because of the symmetric melting conditions. Comparable observations have been made by Marantz (Ref 2). Although the wire was led radially into a plasma flame, the particles were finer than those produced by the two-wire process.

The efficiency of arc spraying processes generally is considerably higher than that of plasma spray processes (Ref 3). In conventional plasma spraying, the feedstock is melted by only 5% of the electrical power input (Ref 4). In arc spraying, 60% of the input power can be employed for feedstock melting.

Keywords arc characteristics, hardness, microstructure, porosity, single-wire arc spraying, spray process

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2. Process Development

Optimization of the single-wire vacuum arc spray process and gun nozzle geometry has progressed steadily. The first prototype consisted of components fitted together by soldering. Recent design improvements include modular construction of the

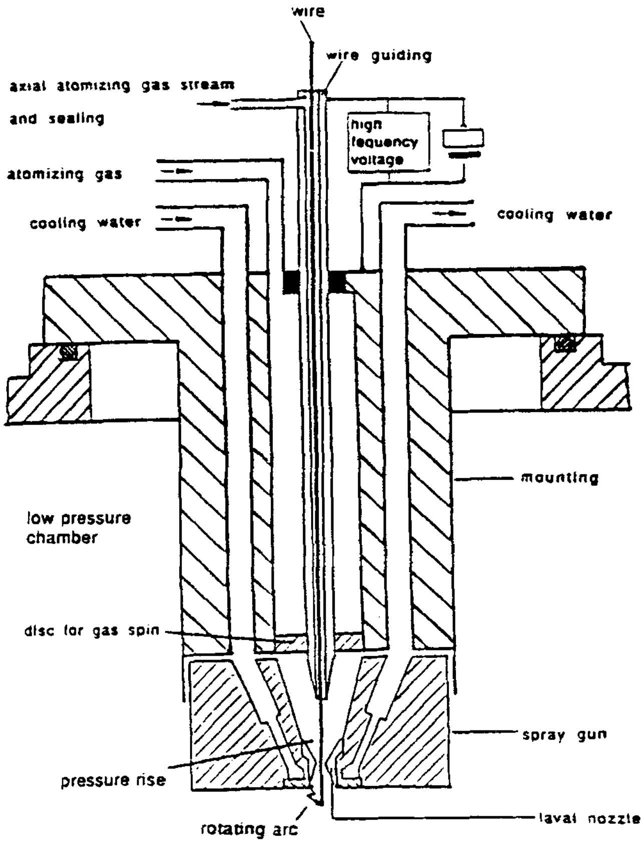


Fig. 1 Schematic of the single-wire vacuum arc spray unit

arc spray head, allowing nozzles to be exchanged. The spin of the spray gas beam can be controlled by use of a special disk behind the nozzle (Fig. 1). This design forces the arc to rotate around the melting wire, thus preventing destruction of the nozzle by overheating at a particular point. Nozzle geometry was optimized for the use of 1.6 mm diam wires. Nozzles with different diameters were designed and tested on the basis of several aerodynamic calculations (Ref 5). The internal diameter of the first prototype nozzle measured 1.8 mm.

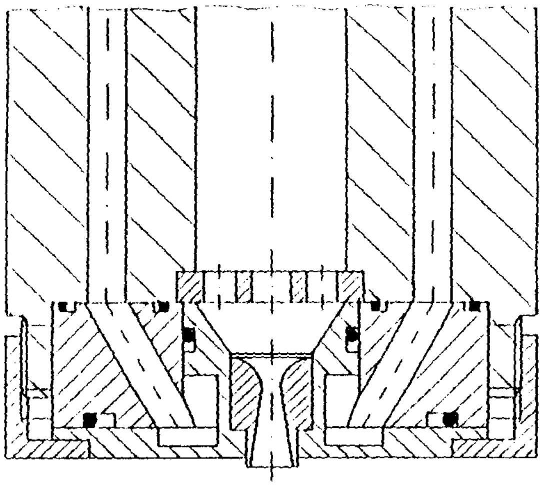


Fig. 2 Optimized modular arc spray gun, showing the changeable nozzle and water-cooling channels

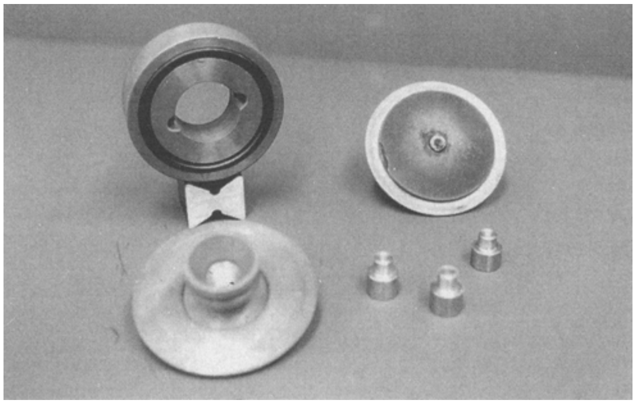


Fig. 3 Spray gun components

Reducing the distance between the wire and the nozzle to 0.1 mm reduces gas consumption as well as the voltage required to ignite the arc and thus ionize the atomizing gas. However, such a small distance can cause short circuits. Although the wire was straightened by rolls and precisely guided through the anode nozzle, short circuiting occurred. The rotation of the process gas stream also enhanced contact between the rotating wire and the nozzle wall.

Thus, the application of wider internal nozzle diameters was investigated. An optimized design (Fig. 2) utilizing a 2.4 mm diam nozzle allowed processing without electrical faults and with reduced gas consumption. The components of the spray gun and various copper nozzles are shown in Fig. 3. The front side of the spray gun was coated with aluminum to prevent the arc from spreading out.

3. Results and Discussion

Process behavior was investigated using three different power sources:

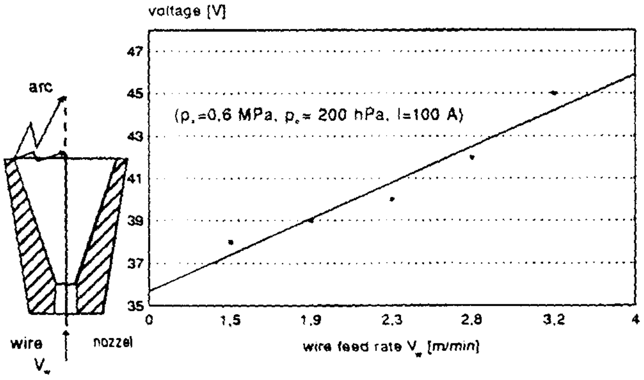
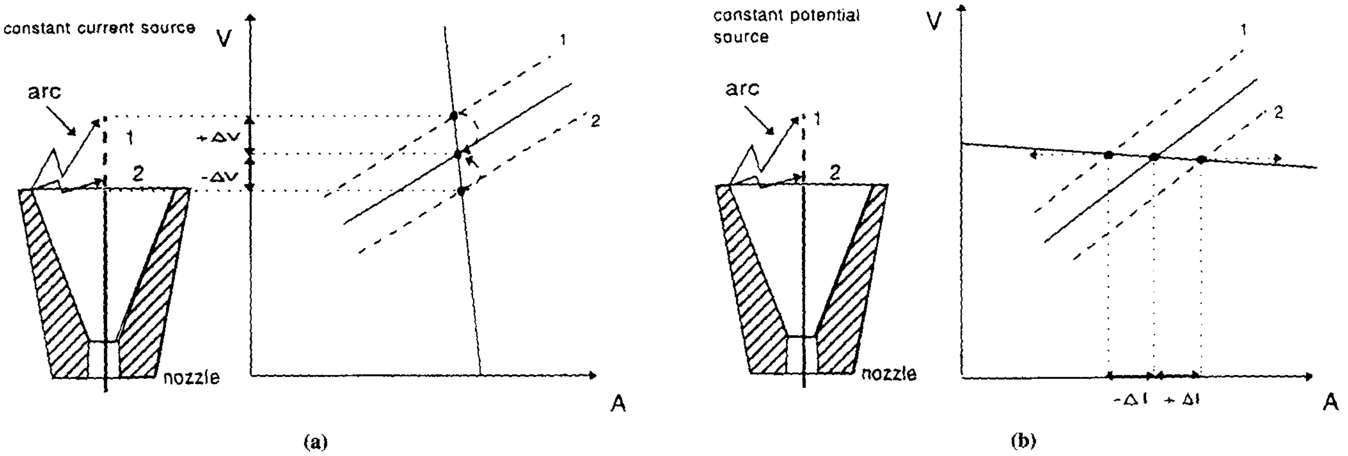


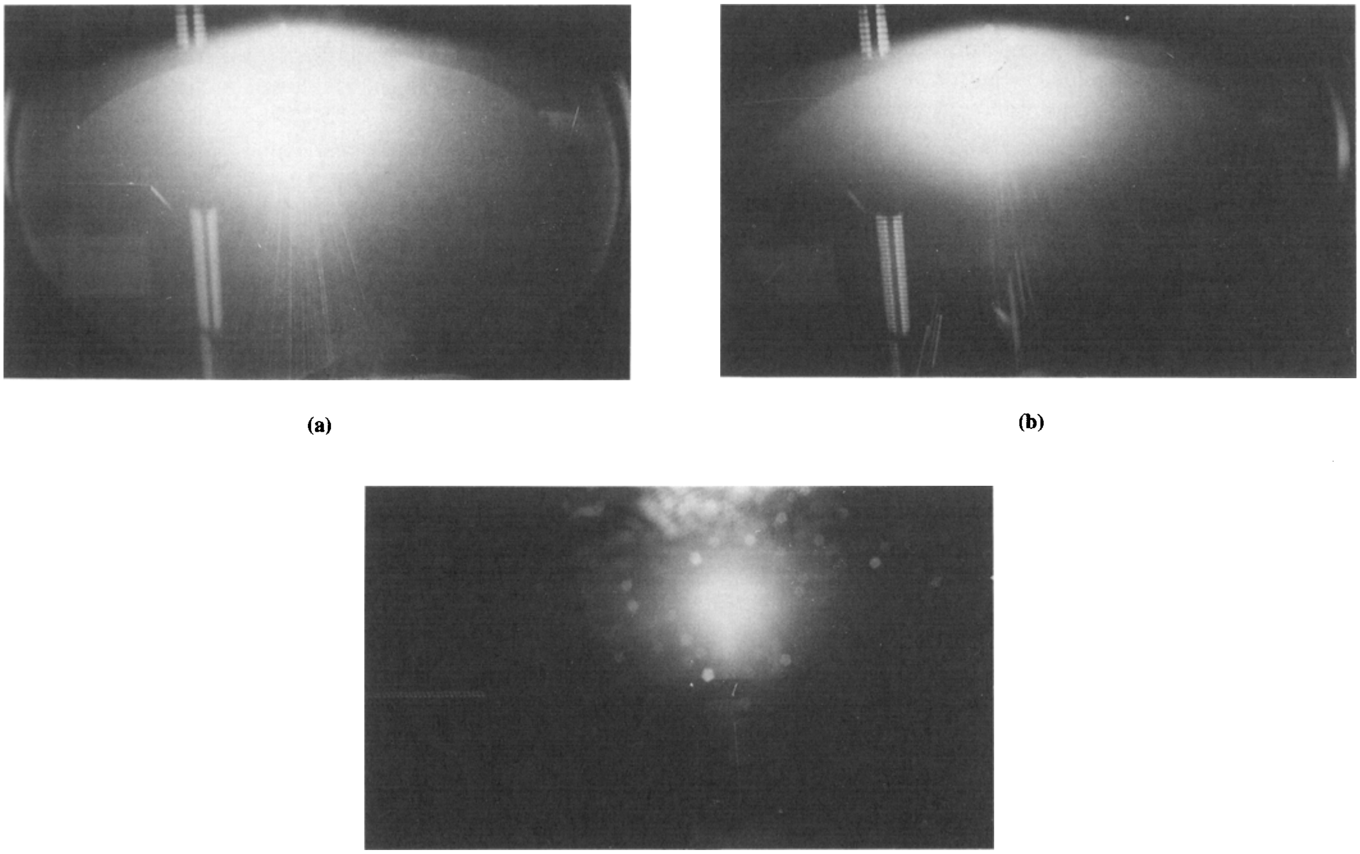
Fig. 4 Arc voltage as a function of wire-feed rate



(a)

(b)

Fig. 5 Influence of electric power source characteristics on arc behavior. (a) Internally controlled. (b) Not controlled


(a)

(b)

(c)

Fig. 6 Plasma spreading as a function of chamber pressure. (a) 200 hPa. (b) 400 hPa. (c) 800 hPa

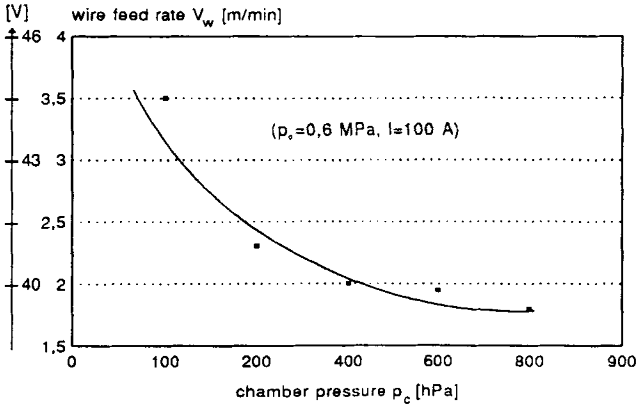


Fig. 7 Maximum wire-feed rate as a function of chamber pressure

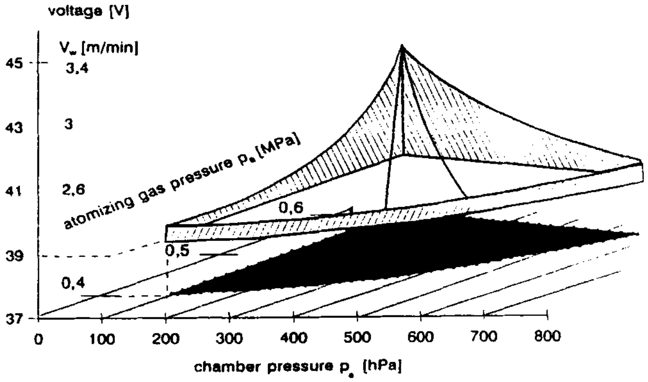
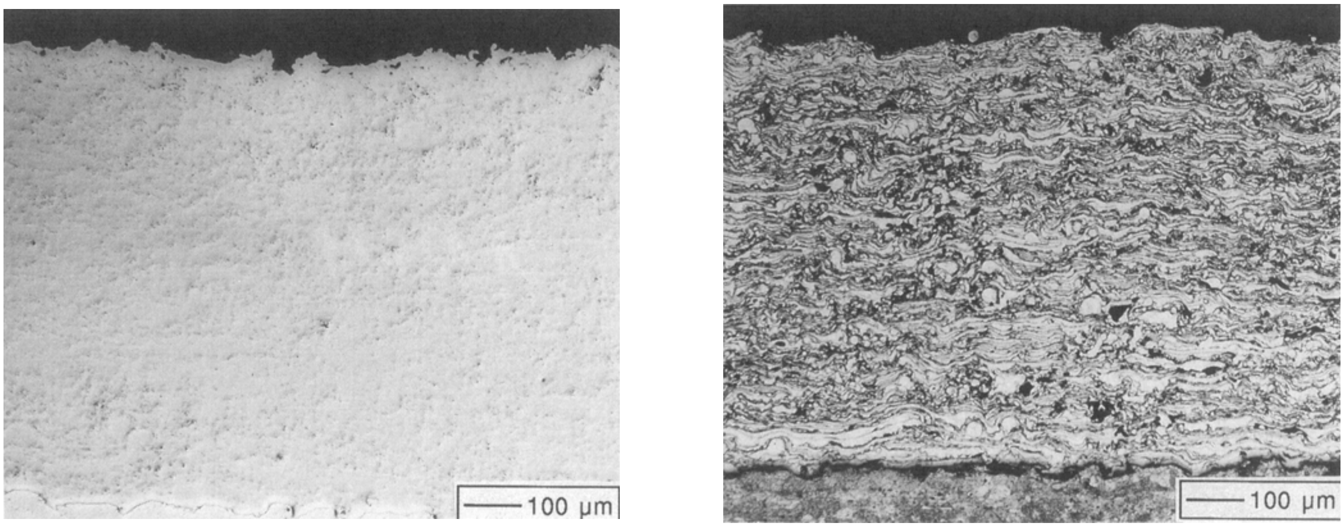


Fig. 8 Volume of stable operating points as a function of spraying parameters. The three axes are voltage (V), chamber pressure (hPa), and atomizing gas pressure (MPa).

- A 12 kW tungsten-inert gas welding power source with a 5 kV high-frequency voltage attachment
- An 18 kW arc constant-current power source with an 8 kV high-frequency voltage attachment
- A modified 40 kW power source for atmospheric plasma spraying

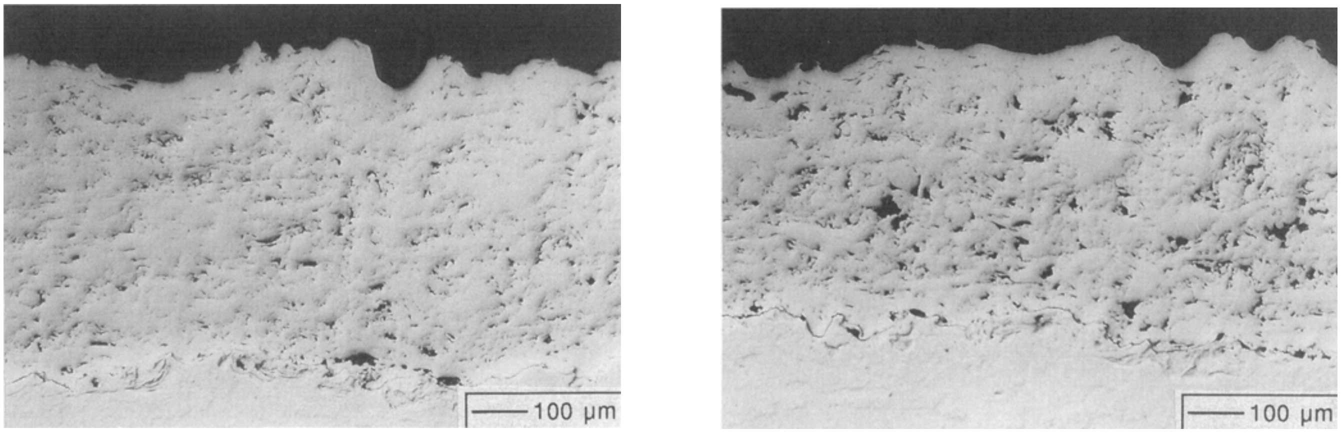
The single-wire arc spray process depends on various parameters, including spray gas pressure, chamber pressure, wire-feed rate, voltage, and current. The voltage ranged from 30 to 45 V. The current depended on the material to be processed, ranging from 100 A for steel to 140 A for titanium. The single-wire process requires a constant-current power source instead of a constant-voltage power source. The wire-feed rate is controlled in-



(a)

(b)

Fig. 9 Cross section of titanium coating produced by single-wire vacuum arc spraying. (a) As received, unetched. (b) Etched with Kroll's reagent



(a)

(b)

Fig. 10 Cross sections of titanium coatings. (a) 600 hPa. (b) 800 hPa

dependently of the power source output. Thus, the arc voltage depends on the wire-feed rate (Fig. 4). For higher feed rates, the length of the arc burning between the wire and the nozzle wall increases and consequently the voltage increases. For decreasing feed rates, the arc length and thus the voltage decrease.

Based on this effect, the process requires an internal control. An increased arc length arises if the wire tip leaves its stable position and moves toward the chamber (position 1, Fig. 5a). The constant-current power source reacts with an increase of voltage output. The melting power rises, and more material becomes molten; thus, the wire tip returns to its initial position in the nozzle. The reverse effect occurs if the wire is forced to a position toward the inside of the nozzle (position 2, Fig. 5a). The arc voltage decreases and thus the output voltage decreases. The melting power is reduced, and the wire tip moves back to its original position.

If a power source with a constant-voltage feature is employed, this effect will not occur. An increase of arc voltage demands a decrease of the current, resulting in a decrease of the melting power. The wire tip moves toward the substrate, increasing the arc length until the process shuts down (position 1, Fig. 5b). A decrease in voltage forces an increase in current and raises the melting power. More wire material melts and the wire tip moves toward the narrowest internal diameter, blocking the nozzle (position 2, Fig. 5b). Experiments designed to restrict the current using special devices were unsuccessful. A further demand is a high idling voltage of the power source superimposed by high-frequency voltage. Investigations have shown that an applied potential of 170 V is sufficient to ignite the arc.

Through continuous development and process optimization, the range of chamber pressure that provides stable processing was increased to 800 hPa by using an atmospheric plasma spray-

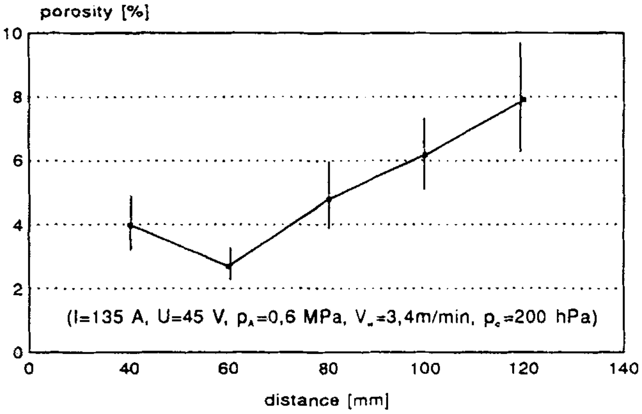


Fig. 11 Porosity as a function of spray distance

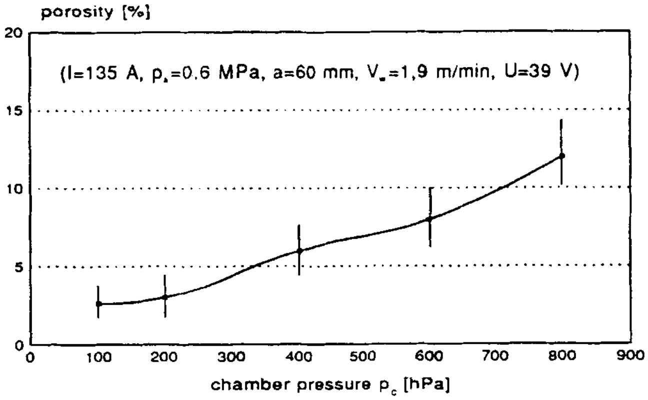


Fig. 12 Porosity as a function of chamber pressure

ing power supply. This power source supplied high voltage and prevented extinguishment of the arc due to the internal control effect.

Figures 6(a) to (c) present the process in action at different chamber pressures. With increasing chamber pressure, the volume of the plasma decreases with respect to that observed in vacuum plasma spraying and the plasma beam becomes increasingly focused; the rotating arc is visible only if special antidazzle screens are used. However, the spreading of the plasma stabilizes the process. At lower chamber pressures, higher wire-feed rates are possible because of a higher ionization of the atomizing gas. At higher chamber pressures, these effects do not occur; the process becomes sensitive against inhomogeneities and only low wire-feed rates provide stable processing. Figure 7 shows the maximum possible feed rates for stainless steel wire and the dependence on chamber pressure.

The plasma does not influence the melting process by causing a higher energy density at higher chamber pressure. Figure 8 is a three-dimensional plot presenting the volume of parameters that provide stable operating points. The shaded regions are the walls of a quarter of a cone that is obtained if the curve in Fig. 7 rotates 90°. Wire-feed rates that are too high extinguish the arc. Feed rates that are too low block the nozzle. The process is further limited by the atomizing gas pressure. The process can be stabilized by high pressure. The lowest possible chamber pressure depends on the nozzle geometry and the pump capacity.

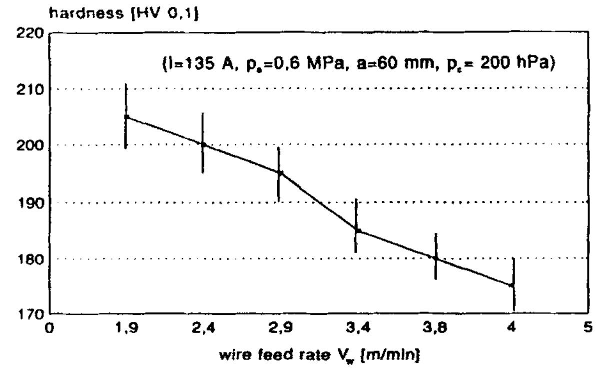


Fig. 13 Microhardness as a function of wire-feed rate

The correlation between the fundamental process parameters of single-wire vacuum arc spraying and the properties of titanium coatings will be discussed in the next section.

4. Coatings

Titanium coatings were produced on stainless steel substrates. Initiating the process was difficult because of the rapid passivation of the titanium wire. Helium addition increases the thermal conductivity of the arising plasma and thus promotes arc ignition. Samples were studied using optical microscopy, porosity was measured using an interactive image analysis system, and microhardness was measured. Selected samples were etched. The bond strength of the titanium coatings on the substrate was investigated according to German standard DIN 50160. Coated and uncoated samples were joined using the adhesive HTK Ultrabond, which ensured a bond strength of up to 100 MPa.

High-quality coatings were achieved using low chamber pressures and small spraying distances. The coatings exhibited good bonding to the substrate and between the single sprayed layers. Some resolidified particles were observed on the etched cross section (Fig. 9). Increased chamber pressure and spray distance deteriorated the coating structure in terms of porosity (Fig. 10), which may be advantageous in the case of coatings produced for biomedical applications.

Porosity measurements for the sprayed titanium coatings are presented in Fig. 11. Due to high thermal and kinetic energy of the atomized particles, the lowest porosity (3%) occurred at a spray distance of 60 mm. As with other low-pressure spray processes, the porosity of the coating was also dependent on chamber pressure (Fig. 12), with the lowest pressure producing the best results. Higher chamber pressures (and, consequently, worse operating conditions) led to inhomogeneous coatings.

Coating hardness depends not on spraying distance but rather on wire-feed rate and thus on voltage. Measurements between 175 and 205 HV demonstrated an increase of 20% compared to titanium coatings produced by two-wire vacuum arc spraying (Ref 1). Decreasing particle size results in an increase in specific particle surface area, which leads to adsorption of oxygen and nitrogen. During solidification, oxides and nitrides were within the coating, thereby increasing the hardness (Ref 6). This result is confirmed by the coating structure. Coatings produced by single-wire vacuum arc spraying have a more homogeneous and dense structure than those produced by the two-wire process.

Figure 13 illustrates the dependence of coating hardness on wire-feed rate. The specific energy for melting wire material is higher for low feed rates and constant power. Consequently, the particle surfaces become hotter and react with the adsorbed oxygen and nitrogen. The resulting oxides and nitrides increase hardness. Coatings with the lowest porosity provided the highest bond strength, with measurements ranging between 55 and 62 MPa. More porous coatings produced at a chamber pressure greater than 400 hPa offered bond strength ranging between 34 and 48 MPa.

5. Conclusions

The basis parameters that influence the single-wire vacuum arc spray process were determined. The employment of a constant-current power source is essential to realize an internal control process. The arising plasma stabilizes the arc and thus the spray process. Consequently, low chamber pressures and an atomizing gas pressure of 0.6 MPa offer stable operating parameters. At low chamber pressure, coatings with good properties in terms of porosity and bond strength were produced. Porous coating structures, such as are required for biomedical applications, can be produced by adjusting the spray parameters.

Acknowledgment

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References

1. H.-D. Steffens and M. Wewel, Recent Developments in Vacuum Arc Spraying, *Mater. Manuf. Process.*, Vol 6, 1991
2. D.R. Marantz, State of the Art Spray Technology, *Thermal Spray Research and Applications*, T.F. Bernecki, Ed., ASM International, 1991
3. W. Elger, A. Grubowski, J. Herbstritt, and S. Travis, Thermally Sprayed Plasma Wire Applications for the United States Navy, *Proc. Int. Thermal Spray Conf.*, Vol 1, The Welding Institute, 1989, paper 67
4. K.D. Borbeck and A.R. Nicoli, The Design and Development of Plasma Torches for the Industrial Fabrication of Surface Protective Layers, *Proc. ATTAC 88*, The Welding Institute, 1988
5. W. Kalide, *Einführung in die technische Strömungslehre*, 5th ed., Hanser Verlag, 1980 (in German)
6. H.-D. Steffens and M. Dvorak, Structure and Electrochemical Behavior of Vacuum-Plasma Sprayed Titanium and Plasma-Beam Alloyed Titanium Coatings, *Thermal Spray Research and Applications*, T.F. Bernecki, Ed., ASM International, 1991