2. It was experimentally found that deposition of a ductile sub-layer with wire Sv-08A provides an approximately 20 % increase in heat resistance of the 40Kh steel specimens clad with flux-cored wire PP-Np-25Kh5FMS.

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PECULIARITIES OF THERMAL SPRAYING OF COATINGS USING FLUX-CORED WIRE (Review)

B. WIELAGE, C. RUPPRECHT and **H. POKHMURSKA**

Institute of Materials Science, Chemnitz University of Technology, Germany

Methods for production and application of flux-cored electrode wires for flame and electric arc spraying of various-purpose coatings are considered. Possibilities of applying advanced 2.0 and 2.8 mm diameter flux-cored wires for electric arc deposition of coatings are noted. It is shown that high-speed filming can provide important information on the nature of running of the spraying process which determines the coating quality.

Keywords: *thermal spraying, coatings, flux-cored wires, designs of wires, coating methods*

The technology of thermal spraying has found wide commercial application, in particular, for deposition of wear- and corrosion-resistant coatings. As reported by Linde AG [1], flux-cored wire is one of the most widespread consumables for thermal spraying, its annual utilisation amounting to over 50,000 t. The use of such wires allowed not only the range of their application to be widened to electric arc, plasma and flame spraying, in contrast to solid wires, but also the properties of the resulting coatings to be changed as needed, this explaining the year to year increase in their production volume and choice.

Designs and materials of flux-cored wires. Flux-cored wire consists of a sheath made from metal strip (steel, nickel, cobalt etc.) and a core, which is a powder of one component or a mixture of powders of alloying components and hardening particles (ferroalloys, pure metals, carbides, borides etc.). The flux-cored wires come in several designs. In practice, the most common designs of the flux-cored wires are overlap butt, tight butt and tubular.

The main groups of flux-cored wires used for spraying of repair, corrosion- and wear-resistant coatings are given in the Table. The iron-, nickel-, cobalt- and aluminium-base flux-cored wires are now available in the market. The main application field of the coatings deposited by flux-cored wire spraying is protection from different kinds of wear, the most-used coatings being coatings of high alloys or coatings containing hard particles, as well as pseudo-alloys.

Another important application field of the coatings deposited by using flux-cored wires is protection from corrosion, including from gas corrosion at increased temperatures, for which the use is mainly made of nickel-base alloys.

Functional coatings, e.g. for improvement of anti-friction properties of friction surfaces, are produced by spraying of flux-cored wires with solid lubricants, e.g. boron nitride, contained in their charge. Alumoceramic coatings sprayed by using tubular flux-cored wires, the charge of which consists of hard ceramic particles, have been developed lately for wear and corrosion protection of surfaces of the parts made from magnesium alloys. These coatings can also be used as anti-sliding ones.

Chemical and phase compositions of the flux-cored wire charge may vary within wide ranges, this opening up considerable opportunities for development of new systems of the coatings and, hence, for further expansion of their practical application fields [2].

Examples of application of flux-cored wires for thermal spraying of coatings

Base	Type of alloying	Properties of coatings and application examples
Iron	FeCrNiMoSiC	Austenitic alloys for wear and corrosion protection
	FeCrAlSi	Protection from gas corrosion at increased temperatures, good machinability by cutting
	Fe + WSC/WC	Protection from abrasive wear
Nickel	NiCr NiAl	Utilisation as a sub-layer to ensure adhesion to base metal
	NiCrB NiCrBSi	Low friction coefficient. Wear protection under thermal loading, hydro- and gas-abrasive protection, chemical stability
	Ni + WSC/WC	Increased wear resistance
Cobalt	CoCrWFeCSiMn	Protection from abrasive wear, boundary friction, cavitation and corrosion
	CoCrMoFeNiSiMnC	Coatings with increased wear, heat and corrosion resistance
Other	Al + Al_2O_3	Anti-sliding coatings
	Cu + BN	Coatings with dry lubrication effect

Methods for deposition of coatings using flux-cored wires. *Flame spraying*. Coatings of flux-cored wires are deposited by using torches designed for solid wire spraying (Figure 1).

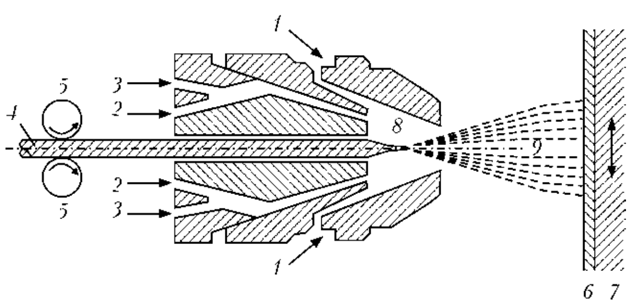

Figure 1. Schematic of the flame spraying torch according to DIN EN 657 [3]: *1* — compressed air; *2* — fuel gas; *3* — oxygen; *4* — wire or rod; *5* — feeding mechanism; *6* — spray coating; *7* — substrate; *8* — melted wire tip; *9* — jet of molten particles

The process of melting of the flux-cored wires differs to some extent from that of the solid wires. With decrease in thickness of the flux-cored wire sheath, as well as with decrease in density of the wire filling, the sharpened shape of the melted wire tip changes into a shorter, rounded or truncated one (Figure 2, *a*, *d*).

The compressing gas flow forming in the melting zone is characterised by turbulence, in contrast to the flow forming in melting of the solid wires (Figure 2, *b*, *e*). This leads to expansion of the jet of molten particles and, as a result, to increased heterogeneity of microstructure of the sprayed coating (Figure 2, *c*, *f*). Inclusions of coarse particles of the sheath material

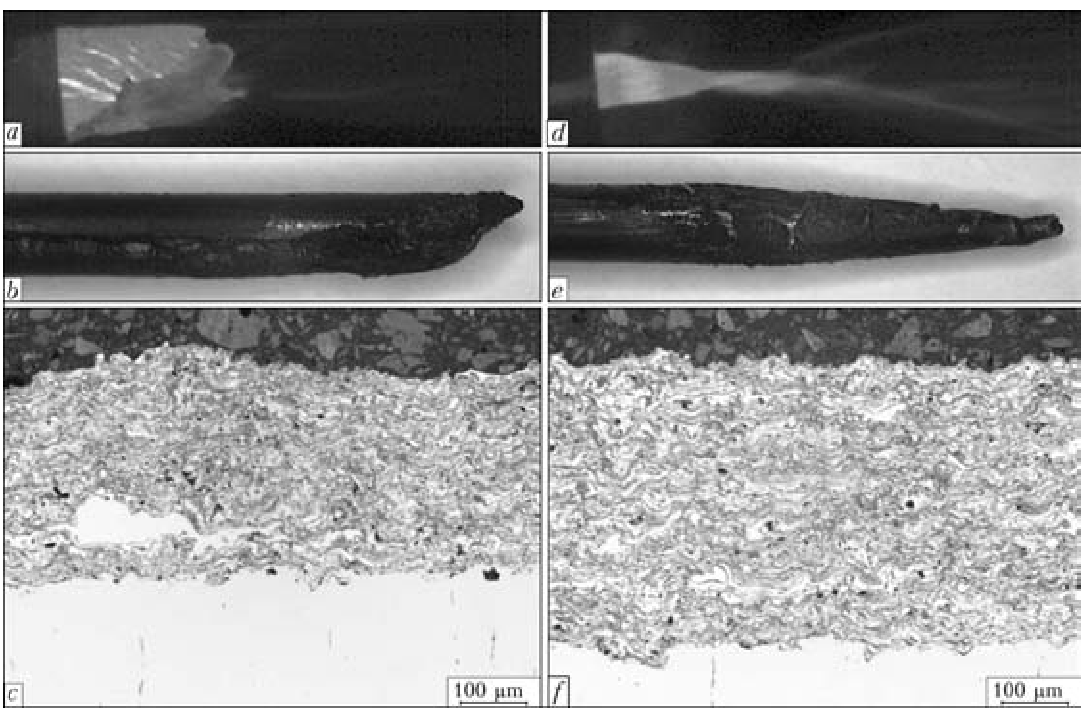

Figure 2. Fragments of high-speed filming of the HVOF spraying process with flux-cored wire AISI 316L (*a*) and solid wire (*d*), appearances of the melted wire tips (*b*, *e*) and microstructures of coatings (*c*, *f*)

(light regions in the coating), which had no time to fully fuse with the charge material in the arc during spraying, can be seen in microstructure of the HVOF coating deposited by using the flux-cored wire with a chemical composition matching that of austenitic stainless steel AISI 316L (Figure 2, *c*). This increase in structural heterogeneity of the coatings may have a negative effect on their service characteristics [4].

Analysis of peculiarities of the spraying process and corresponding microstructures of the coatings deposited by HVOF spraying using different designs (overlap butt, tight butt and seamless tubular) of flux-cored wires of the AISI 316L composition, as well as solid wires, is presented in study [4].

Electric arc spraying. Deposition of coatings by the electric arc flux-cored wire spraying method (electric arc metallising) is performed with the guns used for solid wire spraying. Figure 3 shows flow diagram of the electric arc spraying process.

Electric arc spraying is applicable for spraying of conducting materials. So, it can be applied for spraying of coatings using flux-cored wires with a metal sheath. An important advantage of flux-cored wire spraying, compared to solid wire spraying, is the possibility of adding arc stabilising components to a composition of the powder mixture.

Spraying of metal of the type of austenitic stainless steel AISI 316L in the form of both solid and flux-cored wires with the appropriate optimisation of parameters of the electric arc spraying process can provide coatings of a good quality with very low porosity (Figure 4).

Optimisation of electric arc spraying using large-diameter flux-cored wires. The option of flux-cored wires available now in the market for spraying of different-application coatings is very wide. Almost all

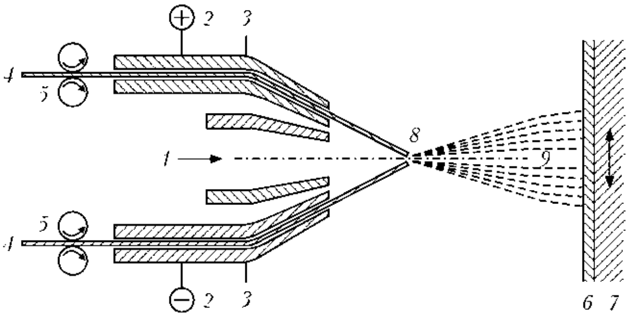

Figure 3. Flow diagram of electric arc flux-cored wire spraying using the gun according to DIN EN 657 [3]: *1* — compressed air; *2* — power supply; *3* — contact tubes; *4* — wires; *5* — feeding mechanism; *6* — spray coating; *7* — substrate; *8* — melted wire tips; *9* — jet of molten particles

wires for thermal spraying of wear-resistant coatings come in diameter of 1.6 mm (e.g. products of TAFA, Castolin, Praxair, Sultze Metco, etc.). A comparatively low factor of filling of this diameter wires with a charge limits the possibilities of adding a higher concentration of alloying elements and hardening particles to a coating. Therefore, in terms of widening the opportunities for development of new compositions of flux-cored wires and raising the productivity of the electric arc spraying process it is of interest to investigate peculiarities of spraying of large-diameter flux-cored wires.

The effect of the operating current, spraying distance and other parameters on the process of formation of structure of a coating and oxidation of molten particles during spraying was investigated. The use was made of the iron-base 2.0 and 2.8 mm diameter flux-cored wires designed for electric arc spraying, providing the following chemical composition, wt.%: 6–7 Cr; <1 Mo; <1 V; 1 Al for the 2.0 mm diameter wire and 1–2 Al for the 2.8 mm diameter wire; <1 (1–2) Si; 1 (1–2) Mn. The 2.0 and 2.8 mm diameter

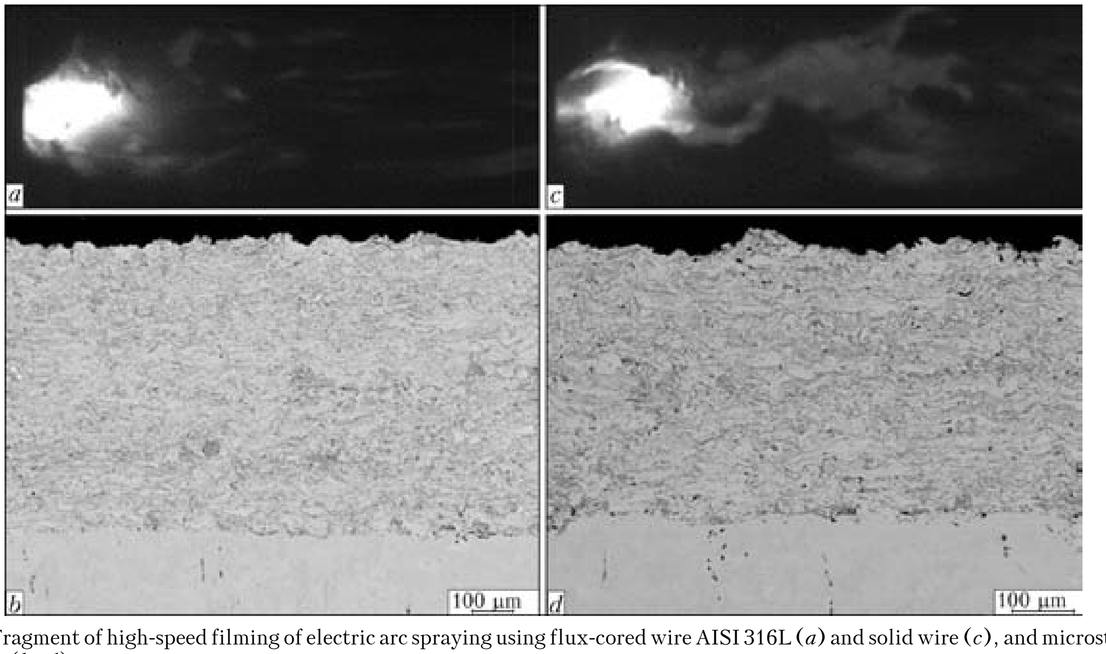

Figure 4. Fragment of high-speed filming of electric arc spraying using flux-cored wire AISI 316L (*a*) and solid wire (*c*), and microstructures of coatings (*b*, *d*)

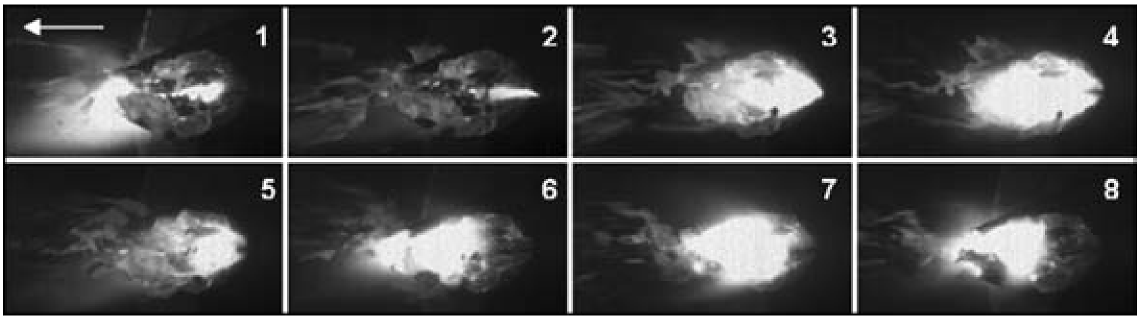

Figure 5. Sequence of frames of high-speed digital filming of the electric arc spraying process using 2.8 mm diameter flux-cored wire (arrow — spraying direction)

flux-cored wires had close chemical composition. However, the larger-diameter wire contained a small addition of flux.

The OSU gun with spraying head LD/U2 was employed for electric arc spraying. The values of the electric current and spraying distance were varied during spraying, the rest of the parameters being kept constant. Parameters of electric arc spraying of coatings using the 2.0 and 2.8 mm diameter flux-cored wires were as follows: current 100–150 A, voltage 25 V, spraying gas pressure 35 MPa, and spraying distance 80, 100 and 120 mm. The surface of the steel substrate was subjected to shot blasting prior to spraying [5]. Spraying of both types of the wires provided dense coatings with good adhesion to the substrate.

Detailed analysis of melting of the wires in the electric arc during spraying was carried out by using a high-speed digital camera. It was shown that the process of spraying of the larger-diameter flux-cored wires was of a stable character. Uniform convective stirring of the molten material with insignificant fluctuations in a flow of particles was observed at the wire tips. As found owing to a high resolution of filming (10,000 frame/s), in spraying of the thick flux-cored wire the spot of the arc root was characterised by a considerable variable displacement, thus providing a uniform heating of the wire (Figure 5).

When spraying the smaller-diameter wire, the trend was to a substantial variation in the arc length, especially after detachment of coarse metal particles, which added to instability of the spraying process.

In spraying of the smaller-diameter wires a change in distance between their tips was more pronounced than in spraying of the larger-diameter wires. The smaller-diameter wires induced lesser disturbance in the spraying particle flow, which had a positive effect on divergence of the flow.

As established as a result of the investigations, the use of the larger-diameter flux-cored wires in electric arc spraying does not necessarily cause deterioration of the coating quality. Moreover, spraying of the larger-diameter flux-cored wires results in a more ho-

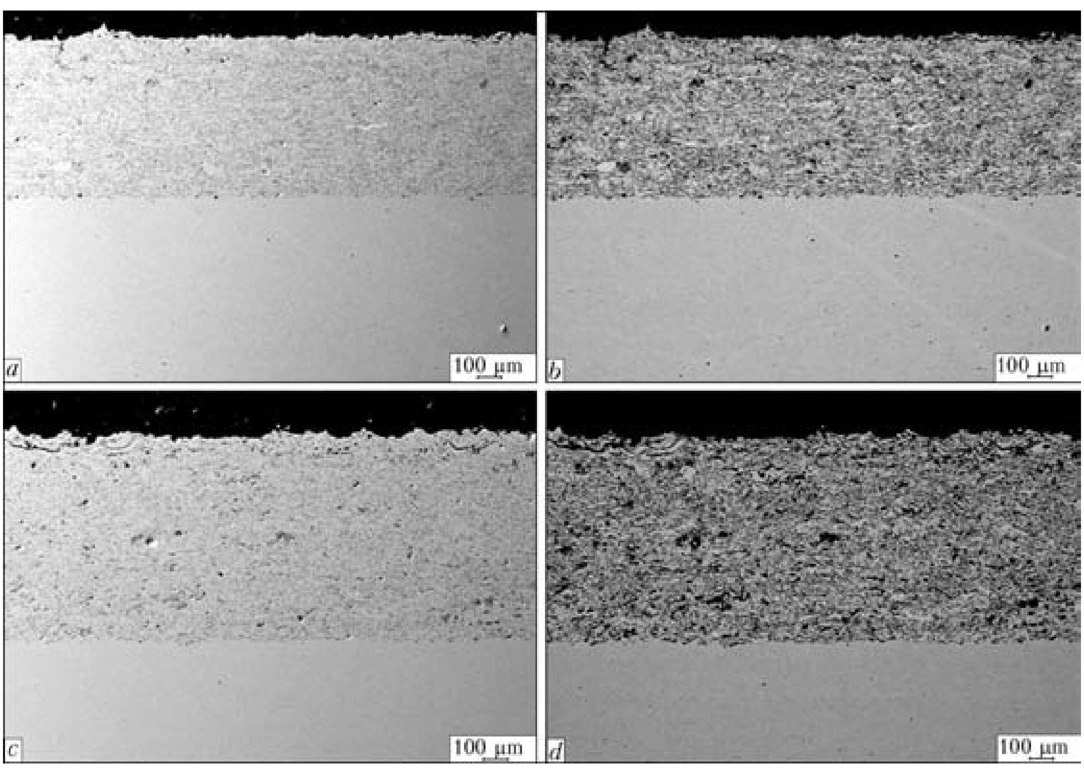

Figure 6. Microstructure of coatings deposited by electric arc spraying of the 2.0 (*a*, *b*) and 2.8 (*c*, *d*) mm diameter flux-cored wires at current of 150 A and spraying distance of 120 mm revealed by secondary (*a*, *c*) and back-scattered electron (*b*, *d*) microscopy

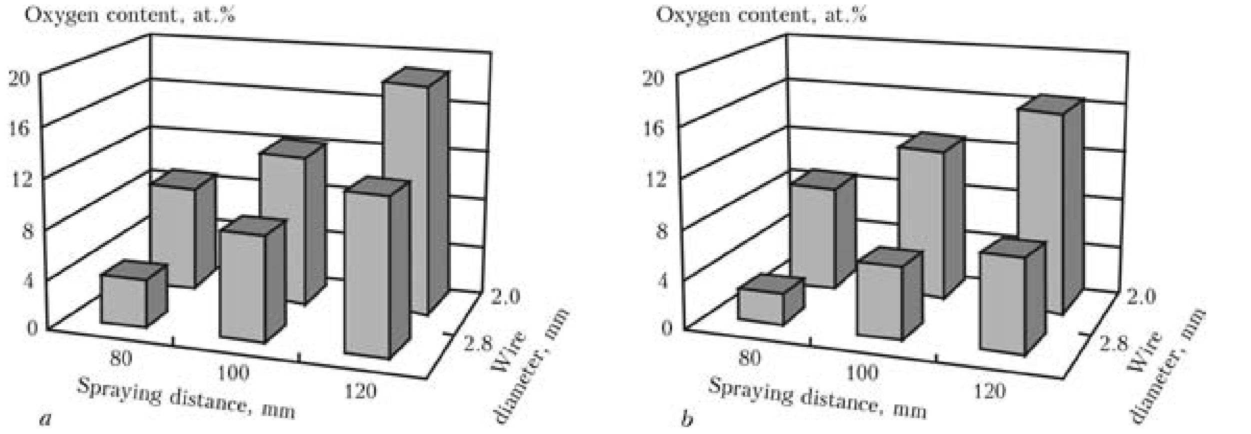

Figure 7. Effect of current (*a* — 100, *b* — 150 A) and spraying distance on oxygen content of the coatings produced by electric arc spraying using flux-cored wires of different diameters

mogeneous microstructure of the coating. Characteristic feature of spraying of the larger-diameter flux-cored wires is that the melt of the charge and sheath stays for quite a long time in a volume confined by the external ends of a wire, this providing a more complete melting of the material, homogenisation of the melt and, hence, decrease in porosity of the coatings (Figure 6).

Analysis of chemical composition of the sprayed coatings conducted by the energy-dispersive X-ray spectroscopy method reveals a clear dependence of susceptibility of the coatings produced by spraying of the flux-cored wires of both diameters to oxidation, which shows up in the oxygen content of the coatings, on the spraying parameters (Figure 7).

Increase in the spraying distance leads to a more intensive oxidation of the coatings because of increase in the time of dwelling of molten particles in the spraying flow. At the same time, the effect of increase in the current on the oxidation process was noted only for the larger-diameter wire containing a flux addition.

It can be noted in conclusion that electric arc spraying using the larger-diameter iron-base flux-cored wires can provide the high-quality defect-free coatings with a homogeneous structure and low porosity. Peculiarities of formation of the melt during spraying were investigated, and regularities in formation of structure of the coatings were established by using high-speed digital filming.

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