Chapter 2
Formation of Plasma Sprayed Coating

2.1 Powder Transport, Flow Trajectory and Velocity of Sprayed Particles

Suitable powder for plasma spraying should possess good flow properties, should easily flow in plasma jet; the powder particles should be of spherical or similar shape and should dispose of identical dimensions defined within the range of the lower limit. In powder spraying with particles of diverse dimension the fine fractions are overheated or evaporated and coarse-grained particles dot not get heated. Important role is played by the orifice of powder feed into plasma jet. The highest effectiveness of powder heating is achieved during its feeding into the centre of the arc burning between cathode and anode in the torch. Such alternative is complicated as to structure. Therefore in majority of modern equipment the powder fed by the flow of carrying gas enters the plasma jet radially from the external part of the nozzle—from the anode.

The powder particle is forced perpendicularly onto the plasma jet axis and copies the trajectory dependent on diverse factors. Particle jet moving to the basic material is of conical shape with angle γ inclining to the plasma jet axis by angle α (Fig. 2.1).

The angle depends on input velocity of particles flowing into the plasma jet and on their size as well as on plasma jet velocity and on classification of velocity in cross section of the plasma jet in the point of particle inflow. Minimal values of angle α assure favourable conditions for spraying as under given circumstances the number of grains decreases. The grains move along the external and colder plasma jet trajectory.

The shape of particle trajectory is determining for the spraying effectiveness. Trajectory of particles depends on a number of factors. The most significant ones include geometry of plasma torch and of powder injector, type and flow rate of plasma and carrying gas, powder characteristics, arc performance, stability of plasma jet, etc. Velocity of molten powder particles is directly proportional to velocity of plasma jet and is regulated by the same parameters as the velocity of plasma jet.

© The Author(s) 2017

J. Ružbarský and A. Panda, *Plasma and Thermal Spraying*,
SpringerBriefs in Applied Sciences and Technology,
DOI 10.1007/978-3-319-46273-8_2

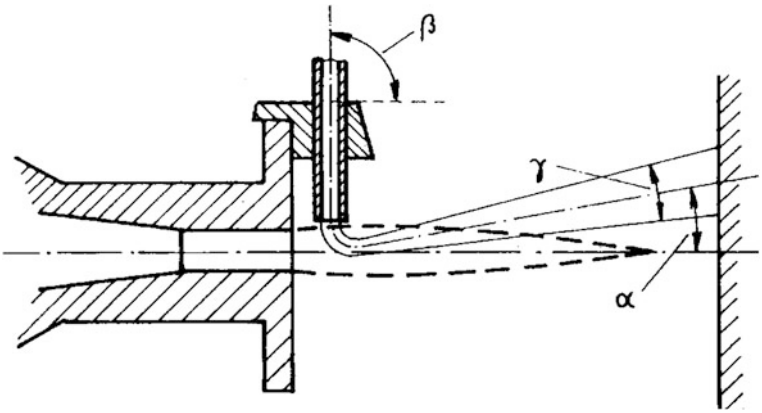


Fig. 2.1 Inclination of the jet of molten particles in the plasma jet

Diverse optic and kinematographic methods allow determination of particle velocity in the experiment. The experiments proved that bigger particles possessed lower velocity when flowing out of the plasma jet yet losing is more complicated. Vice versa, smaller particles are easily accelerated and decelerated by the ambient atmosphere. Detected was also considerable variance of particles which can be explained by radial distribution of velocities in plasma jet and by variability of the individual grains. The relations between velocity and diameter are detected experimentally. In spraying of fine-grained material higher velocities are reached. With increasing distance from the nozzle deceleration of the lighter particles is more frequent contrary to the heavier ones. The particles are accelerated just by certain distance from the nozzle. Both optimal spraying distance, at which the velocity reaches maximal value, and the mean value of this velocity depend on dynamic properties of plasma jet. Their regulation is possible by the torch performance, by the nozzle geometry, by the flow rate of plasma gases, etc.

Calculating method of determination of particle velocity in the plasma jet can stem from the following relation:

$$v = v_{pl}\left[1 - \exp\left(-\frac{2A \cdot l}{v_{pl}}\right)\right] \tag{2.1}$$

with

v particle velocity,
v_{pl} plasma jet velocity,
l particle trajectory,
A 4.5 $\eta.r^2.\rho$ is constant,
η environment viscosity,

r particle diameter,
ρ particle material density.

Velocity calculated as per the relation mentioned afore must be regarded as the approximate one.

2.2 Mutual Influence of Molten Material with Plasma Jet and Ambient Atmosphere

Under the influence of thermal and kinetic effects of plasma jet the fed powder is molten down and accelerated. Mechanism of transmission of heat from the plasma jet to powder is rather complicated phenomenon and has not been clarified up to present. In case of the first approximation an assumption can be made that energy transmitted to powder q is proportional to the temperature, to the length of thermally active zone of plasma jet, and to the coefficient of transmission of heat. The energy is indirectly proportional to the velocity of plasma jet as per the following relation:

$$q = \frac{T \cdot \alpha \cdot l}{v} \tag{2.2}$$

With

q effective output of heat,
T plasma jet temperature,
α coefficient of transmission of heat,
l length of active thermal zone of plasma jet,
v plasma jet velocity.

According to the relation mentioned afore the cause of faulty heating can rest in short time of powder residence in plasma ($T - 1/v = 10^{-14}$ up to 10^{-2} s), insufficient intensity of heat exchange between plasma and powder or difficulties with forcing of powder into high-temperature part of jet.

In examination of powder heating inevitable is to take into consideration the Bi criterion which is determined by the relation between plasma transmission of heat λ_p and particle material λ_l:

$$Bi = \frac{\lambda_p}{\lambda_l} \tag{2.3}$$

The expression $Bi < 1$ (Ar, He, N_2) is applicable for plasma with low thermal conductivity. For plasma with good conductivity (H_2) in heating of oxides and other material with low coefficient λ_l applicable is $Bi > 1$ meaning that for plasmas with the coefficient of $Bi < 1$ the transmission of heat is limited by the processes in the

jet in plasma of other group in heating of non-conducting powders by transmission of heat into the depth of particle.

If powder overheating in case of which the temperature in the centre of the particle reaches 0.9 multiple of material melting temperature is considered to be sufficient obtained can be the following expression for determining of maximal cross section of particles which can heat up in plasma:

$$d_{\max} = \sqrt{\frac{4 \cdot a \cdot \tau}{0,3}} \tag{2.4}$$

With

a coefficient of thermal conductivity $\left(a = \frac{\lambda}{c \cdot \rho}\right)$,
τ time of particle residence in plasma,
λ coefficient of thermal conductivity,
c specific heat,
ρ density.

Derived was the relation for minimal critical diameter of particles which can still reach the sprayed surface:

$$d_{\max} = \sqrt{\frac{18 \cdot \mu \cdot k_{krit} \cdot l}{\gamma_l \cdot v_\infty}} \tag{2.5}$$

with

μ plasma viscosity,
γ_l density of particle material,
k_{krit} critical value of the Stokes number:

$$k_{krit} = \frac{\gamma_l \cdot d \cdot v_\infty}{18 \cdot v \cdot l} \tag{2.6}$$

with

d particle diameter,
v_∞ plasma jet velocity,
v viscosity coefficient,
l torch distance from the backplate.

Dependence of appropriate adjustment of powder and of coating quality on grain composition of powder was proved in the experiment by other authors with determining of particle temperature in plasma in dependence on grain composition of powder and on distance from the nozzle (Fig. 2.2). According to the graph powder grains of WC-Co 40 μm are evaporated and grains of 150 μm remain intact.

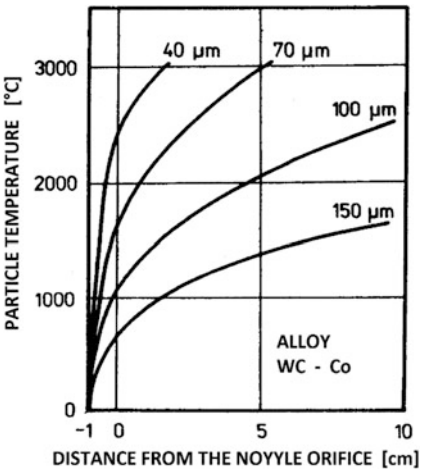


Fig. 2.2 Temperature of particles of WC-Co in dependence on grain composition of powder and on distance of nozzle in argon plasma jet

Pursuant to these facts only the powders with strictly limited dimensions (diameters) offer reliable results.

Along the trajectory in plasma the particles interact with gases of ambient atmosphere and with plasma as all material types demonstrate high chemical activity at melting temperature or at temperatures reaching the melting one. A range of mechanisms of reciprocal interaction of sprayed particles with gases include gas adsorption, chemical mutual reaction and formation of oxide layers and other linkages on the surface of particles, gas dissolution in liquid metal of particles, diffusion processes and mechanical mixing of the products of mutual interaction in particle volume, etc.

2.3 Impingement of Flowing Particles onto the Backplate

During impingement of flowing molten particles onto the backplate their kinetic energy changes into thermal and deformation energy. The processes in the zone of impingement can be theoretically explained by the theory of hydrodynamic impingement of liquid particles onto the hard surface. Pursuant to the theses regarding the sphere in question it is apparent that during impingement of particles kinetic energy causes their deformation and generation of substantial pressures—the dynamic and the impulse ones. At the first moment in the point of contact with the surface the liquid particle is deformed. In the time interval ranging from 10^{-10} up to 10^{-6} a thin layer of diameter D is formed approximating the particle diameter d. Further on the particles are deformed evenly (Fig. 2.3).

Formation of flat coating is connected with impulse pressure p_1 as a result of movement of pressure waves spreading within the particle from the moment of

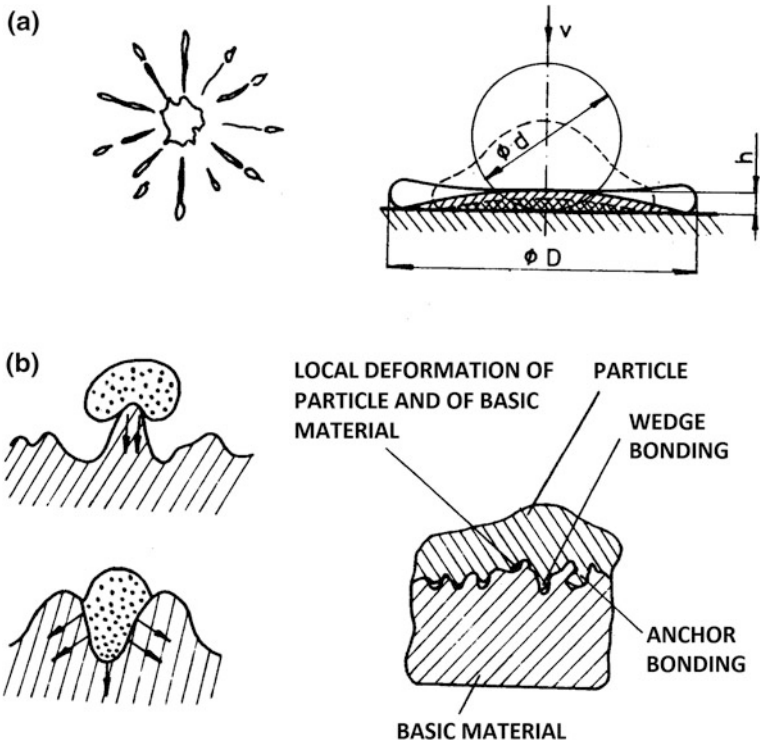


Fig. 2.3 Scheme of deformation of particles on the backplate **a** smooth backplate, **b** rough backplate

impinging onto the surface. Maximal impulse pressure can be expressed by the following expression:

$$p_1 = \frac{\mu}{2} \cdot \rho_{kv} \cdot c_{zv} \cdot v \tag{2.7}$$

with

μ coefficient of particle consistency,
ρ_{kv} liquid density,
v particle velocity,
c_{zv} sound velocity in the liquid.

If c_{zv} = (2 up to 5). 10^3 m s^{-1} is applicable for molten metals and if $\mu = 0.5$, ρ_{kv} = 40 g cm^{-3}, v = 100 m s^{-1} is accepted for spraying conditions, so consequently p_1 = 0.98 Gpa.

Dynamic pressure of current flowing evenly is calculated according to Bernoulli's equation. If assumed is pressure p_d acting upon the part of surface of a backplate dimensionally proximate to particle diameter and if the backplate is

considered to be incompressible and the particle is regarded as ideal liquid the simplest case of impingement is achieved with dynamic pressure

$$p_d = \rho_{kv} \cdot v^2 \tag{2.8}$$

Duration of pressure effect upon particle axes

$$\tau = (d - h) \cdot v \tag{2.9}$$

with h—height of particle solidified during time τ.

Under real conditions of spraying the velocity of particles reaches 100 even 300 m s^{-1} and the values of dynamic pressure can range from 49 up to 98 MPa in the course of effect duration 10^{-5} up to 10^{-7}.

During impingement onto basic backplate the particles which under influence of surface stress take spherical shape and deform substantially deliver their kinetic and thermal energy and solidify in a shape of lamellae or lens with thickness ranging from 5 up to 15 μm. By laying up the lamellae the layer with the characteristic lamellar structure is formed (Fig. 2.4).

Molten drops falling onto, for instance, smooth glass surface burst fast and spread along the backplate area (Fig. 2.3a). The rough surface is prevented from quick spreading of drops by rapid cooling and surface unevenness which causes capturing of the solidifying drops (Fig. 2.3b).

Particles being individually cooled and crystalized generate heterogeneous structure. Apart from boundaries typical for compact materials the sprayed coating includes the boundaries between the deformed particles and the individual coatings (Fig. 2.4). The conditions of formation of boundaries between the coatings differ from the conditions of formation of boundaries among particles especially in the

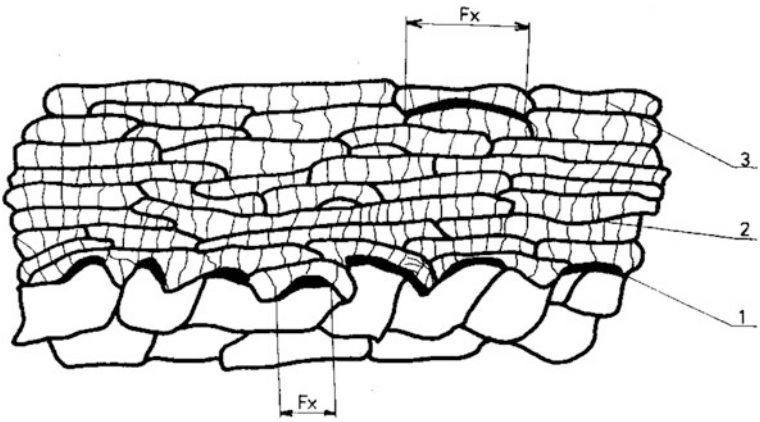


Fig. 2.4 Scheme of film structure. *1* interface between the film and the basis, *2* interface between the individual coatings, *3* interface between particles, F_x—diameter of the surface section onto which a particle was welded

course of duration of contact with the atmosphere. In spraying of the individual coatings the gas adsorption and evaporation of the finest fractions of sprayed material occur on preceding coating. The conditions related to deformation and to bonding with the basic backplate or with preceding coating are not met by all particles during the impingement. The particles reflect from or settle down on the surface as unmolten powder and defects and pores are formed along with material loses and proportion of non-deformed particles is increased. All of the phenomena and specificities of the coating formation in spraying cause that, for instance, hardness of metal coatings reaches 10 even 20 % of hardness of similar compact material.

2.4 Thermic Influence upon the Backplate and Sprayed Coating

Transmitted heat consists of the heat transmitted by plasma jet Q_p and by particle Q_m. These values were thoroughly examined by Kudinov according to whom total amount of heat transmitted onto the backplate per unit of time Q increases linearly with the input supplied into the torch and decreases rapidly with the extending distance of torch from the backplate (Fig. 2.5).

Relation of total amount of heat to supplied input P_e, i.e. to efficiency, is shown in Fig. 2.5 in dependence on spraying distance L. In such case the following is applicable

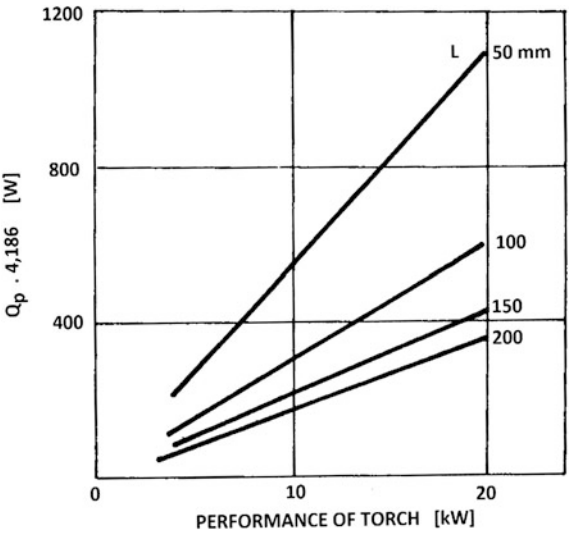


Fig. 2.5 Change of heat amount transmitted onto the backplate in dependence on torch input and spraying distance L

$$\eta = \frac{Q}{P_e} \tag{2.10}$$

$$\eta_m = \frac{Q_m}{P_e} \tag{2.11}$$

and

$$\eta = \eta_p + \eta_m \tag{2.12}$$

According to Fig. 2.6 the heat transmitted by plasma jet decreases considerably faster in dependence on extending of distance contrary to heat transmitted from particle material. To prevent formation of slag bath the sufficient spraying distance must be selected. Adequate spraying distance is 100 even 150 mm as shown in Fig. 2.6.

The temperature of contact between the deforming molten-down particle in impingement and hard cold backplate is expressed by the following relation

$$T_k = \frac{T_m \cdot K_E}{K_L + \phi(d)} \tag{2.13}$$

$$K_E = \frac{\lambda_p}{\lambda_n} \cdot \sqrt{\frac{a_n}{a_p}} \tag{2.14}$$

$$K_L = \frac{c_p \cdot T_m}{1.77 \cdot L} \tag{2.15}$$

with

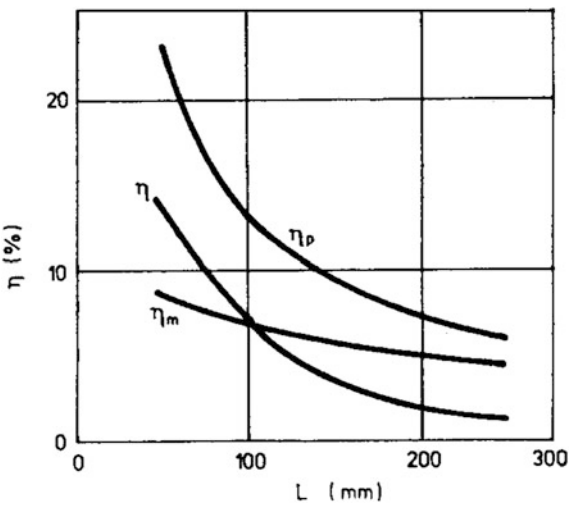


Fig. 2.6 Efficiency of transmission of heat in dependence on spraying distance

K_E coefficient characterizing thermal activity of particle with regards to the backplate,
K_L criterion for evaluation of latent heat L of particle material,
λ_p coefficient of thermal conductivity of particle,
λ_n coefficient of thermal conductivity of backplate,
a_p, a_n coefficients of thermal conductivity of particle and backplate,
c_p specific heat of particle,
T_m melting temperature of particle,
$\varnothing(d)$ function of probability integral.

2.5 Physical and Chemical Changes of Material in Spraying

Subliming materials with boiling point approximating melting point can be sprayed only with certain difficulties. MgO dissociates and disintegrating products are volatile. The disintegration could be prevented by spraying of such materials in argon plasma enriched by 20 % oxygen. Several oxides, for instance ZrO_2, may partially get reduced during spraying in clear and air-free plasma. In spraying $ZrSiO_4$ dissociates to ZrO_2 and SiO_2.

Polymorphic materials are exposed to allotropic changes and fast cooling after spraying can cause their metastabilization. Under high temperature heated γ–Al_2O_3 changes into cubic α–Al_2O_3 which due to rapid cooling acquires unstable structure of passing state referred to as δ–Al_2O_3. By adding nitrogen the δ—crystal lattice can be stabilized. In case of materials the properties of which are changed by phase modifications the danger of the sprayed coating disturbance occurs and thus through consequent thermal treatment stable state must be restored. Therefore, for instance ZrO_2 may be sprayed only by stabilizing admixture of—5 % CaO.

The sprayed particles interact with the gases of ambient environment and with the plasma gases. For instance, the experiments proved that in spraying of low-carbon steel the content of oxide in the sprayed coating reaches from 2.5 up to 5.7 %. The value exceeds percentage of saturation by oxygen in steel at melting point (0.21 %) and in steel heated up to 2000 °C (0.87 %). In spraying of aluminium and wolfram in argon plasma the oxygen and nitrogen content in sprayed coatings is by 1 even 2 degrees higher contrary to basic material. The identical condition occurs in case of molybdenum and titanium.

Oxidation and nitriding phenomena cannot be completely prevented even by application of inert gasses in plasma gas. Especially in spraying in aeriform atmosphere the plasma jet absorbs ambient air and gets mixed rapidly with it. In spraying of borides, nitrides, and carbides the content of boron, of nitrogen, and of carbon changes in them. The X-ray graphic analysis of the sprayed coatings of

carbides of zircon, of niobium, and of tantalum in atmosphere with oxygen content of <11 % detected just a single phase—carbide in homogeneous sphere. By increasing of oxygen content the two phases were detected—in case of zircon carbide it was zircon oxide and carbide oxide, in case of niobium carbide those were oxides of Nb_2O_5 and NbO_2. In case of wolfram carbide the traces of metal wolfram were identified at high temperature as per reaction $2WC = W_2C + C$. The coatings of zircon carbides and of niobium carbides sprayed in environment with 4.5 % oxygen demonstrated a single-phase structure.

http://www.springer.com/978-3-319-46272-1

Plasma and Thermal Spraying

Ružbarský, J.; Panda, A.

2017, X, 108 p. 64 illus., Softcover
ISBN: 978-3-319-46272-1