1 Physical and technological fundamentals of vapor deposition technology for shielding purposes

1.1 Introduction

Metallization is understood as the process where a metallic layer is deposited on a non-metallic (plastics, glass, ceramics, paper, cardboard) or metallic substrate. The aim is to improve the usefulness of a product by coating (surface refinement). Coating can be made in a chemical way (separation by electroplating, chemical separation from the gaseous phase) or in a physical way (thermal spraying, vacuum technology, enameling, lamination).

The metallization by vacuum technology uses the condensation of a metal vapor on the object to be coated. This vapor is generated within vacuum, and diffuses within vacuum. The thickness of the metallic layer is between some 10 nm and some micrometers. Decorative vapor deposition in the first place aims to improve color and gloss of the surface. But also optical, electrical, magnetic, mechanical or chemical characteristics of the substrate surface can be purposefully improved by vapor deposition (functional vapor deposition). Table 1.1 shows typical application ranges for vacuum vapor deposition.

Tab. 1.1: Application ranges for vapor deposition by vacuum technology

Decorative vapor deposition	Functional vapor deposition
Plastic articles	anti-friction and anti-wearing layers
household articles	scratch resistant layers
sanitary articles	barrier layers on packing material
lamp parts	reflectors for light (VIS, UV, IR)
toys	light grids
glass and ceramic products	heat reflecting layers
iron furnitures	architectural glass
jewelry articles	electromagnetic shielding layers and discharge of electrostatic charges
	optical layers
	mirrors, filters, antireflection
	function layers for electronics, microelectronics and microsystem technology

Electric and electronic devices (Figure 1.1) are sources and receivers of electric (E) and magnetic (M) fields and for electromagnetic waves (EM). The reliable function of such devices requires measures to ensure their electromagnetic compatibility (EMC) and to protect the live environment (plants, animals and man).

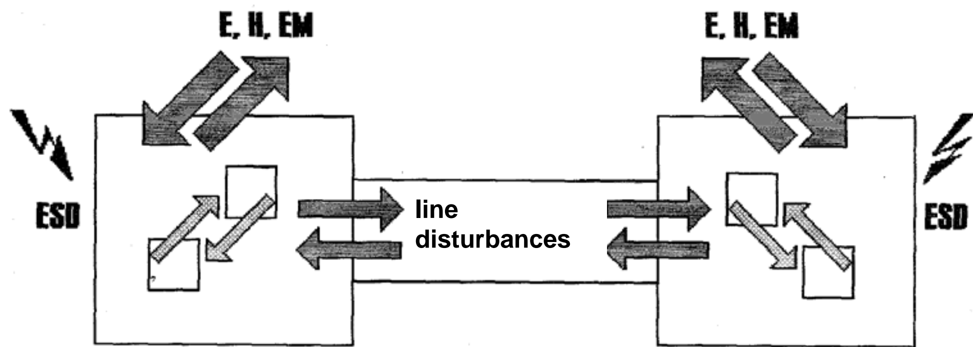

Figure 1.1: Electromagnetic effects of devices

Therefore, such measures are required by laws as quality feature for such devices and must also be proved. Electromagnetic shielding is one of the most important measures and must be ensured especially for plastic cases which are increasingly used. Consequently, it is imperative necessary to have a cost-saving metallization of plastic cases and coverings for electric and electronic devices which is also compatible with the environment. Vapor deposition of shielding layers by vacuum technology meets this requirements and is an innovative future-oriented technology.

The vacuum vapor deposition plant CREAMET EMI is preferably intended for metallization of plastic cases by vacuum technology.

1.2 Physical fundamentals of vapor deposition

1.2.1 Vapor deposition within vacuum

Figure 2.1 shows the principle of vapor deposition within vacuum. The layer material is separated to atoms or atom groups (molecule fragments, clusters) in a source. This *vapor* diffuses in the surrounding vacuum and condenses on the substrate to be coated (e.g. case).

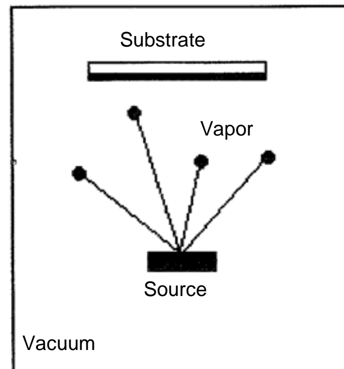

Figure 2.1: Principle of vapor deposition

1.2.2 Vapor generation

The vapor can be generated in a thermal way (that means by heat admission). It is called *evaporation* of layer material. But condensable particles (atoms, atom groups) can also be generated by pulse transmission during bombardment with high-energy ions, the so-called *sputtering*.
Tab. 2.1 gives an survey on the possibilities to generate vapors.

Evaporation	
Indirect method	Heating by heating spiral, heated boats and crucible
Direct method	Heating of the material to be evaporated by current passage induction, arc discharge, electron impact, laser radiation
Combination of direct and indirect method	Current passage through crucible and material to be evaporated
Sputtering	
Cathodic sputtering	DC gas discharge, the material to be sputtered is connected as cathode; for insulators HF gas discharge
Ion beam sputtering	Ion bombardment from an ion source

The most efficient evaporators are the so-called resistance evaporators with current passage through coils, boats or crucibles and through the material to be evaporated. They have a simple design. The thermal stress for the substrates is relative low (see 2.3.2 and 3.1.1).

In the high vacuum vapor deposition plant CREAMET EMI metallization occurs from the evaporation of the layer material (aluminum, copper, nickel chromium) from resistance evaporators which are manufactured from twisted wolfram wires. There are spiral-shaped evaporators for aluminum (figure 2.2), funnel-shaped coils for copper (Figure 2.2.b), and straight-line evaporators for nickel chromium (Figure 2.2c). The charged material is melted down by current passage and heated up to evaporation.

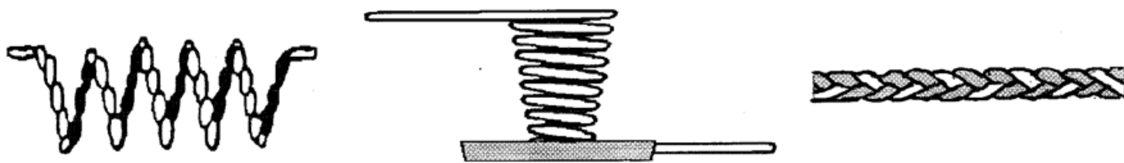

Figure 2.2: Resistance evaporators:
a spiral-shaped coil, b funnel-shaped coil, c straight-line evaporator

The cathodic arc evaporator (Figure 2.3) is preferably used for vaporization of thin layers (here nickel chromium, see 4.6) because of its simple construction and operation. In this case the vapor arises in the root of an arc which is burning (after ignition with a special ignition facility) within the vapor of the layer material. The integration of a vacuum arc evaporator in the high vacuum vapor deposition plant CREAMET EMI is in preparation.

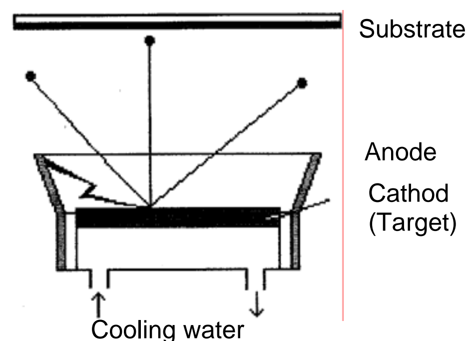

Figure 2.3: Cathodic vacuum arc evaporator

1.2.2.1 Evaporative capacity

The *specific evaporative capacity* for large flat surfaces in thermal equilibrium results from

$$r = \gamma \, p_S(T) \, (M/2\pi RT)^{1/2} \qquad (1)$$

(γ = 0 ... 1 takes into consideration particles which are backscattered to the evaporator by residual gas and vapor particles [see 2.2], M is the relative molecular mass, R is the molar gas constant, and T the absolute temperature), or from

$$r = 0{,}044 \, \gamma \, p_S(T) \, (M/T)^{1/2} \ \text{mg/cm}^2\text{s} \qquad (2)$$

with T in K and p_S in mbar.

The saturation vapor pressure heavily depends on the temperature:

$$p_S(T) = C \, e^{-\Delta H/RT} \qquad (3)$$

(ΔH molar enthalpy of evaporation).

(**Annex 1** includes the vapor pressure diagrams $p_S(T)$ for copper, aluminum, nickel and chromium.)

A saturation vapor pressure in the range of 10^{-2} mbar is necessary for vaporization. Consequently, the required temperature of the material to be evaporated can be seen from the vapor pressure diagram. Alloys evaporate in fractions according to the different vapor pressures, unless the temperature is very quickly increased to the value for the heaviest component (flash evaporation).

The temperature of the evaporator must not be too high to avoid vapor bubbles in the melted material (splashes).

In real evaporators the portion $\delta m/m$ of the totally evaporated mass m which evaporates in the solid angle $\delta\omega$ depends on the direction. This fact is described by the *evaporator characteristic* f (r, θ): (Figure 2.4):

$$\delta m/m = f(r, \theta) \, \delta\omega. \qquad (4)$$

Figure 2.4a shows the evaporator characteristic of an elemental evaporator surface ($f(r,\theta) = A \cos \theta$, $A = 1/\pi$). The evaporation characteristic of a real evaporator mathematically results from the integration of the evaporator characteristics of all its elemental surfaces.

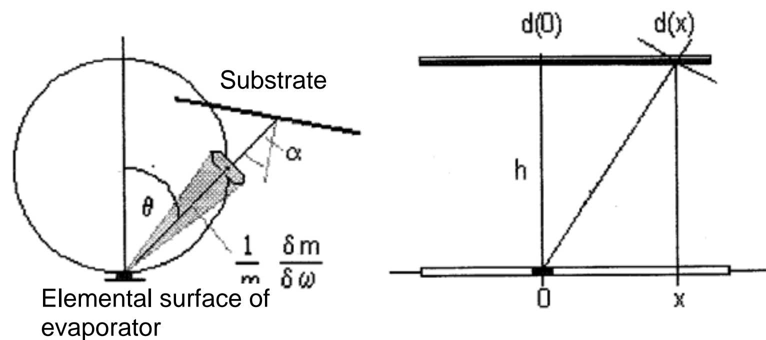

Figure 2.4: Evaporator characteristic of an elemental surface (a) and layer thickness calculation (b)

1.2.3 Vapor diffusion within vacuum

The average free length of path within the residual gas must be larger than the distance between source and substrate to give the vapor particle the possibility to diffuse in a straight line without losses (Figure 2.1). For 60 cm this requires a residual gas pressure (air, 293 K) of *maximum* 10^{-4} mbar.

But this is also the reason why substrate spots which are in the "shadow" (in deep openings, at undercuts) will not be coated.

Impacts with residual gas molecules (or even with vapor particles if the evaporator temperature is too high) lead to scattering of the vapor particles. In general this is considered undesired because it reduces the coating efficiency and may affect the vapor deposition of sharp contoures.

For *gas scattering evaporation* (pressure higher than 10^{-3} mbar) however, this scattering is used to improve the coating of openings and undercuts. But the quality of coating is affected. Gas is included within the layer and reactions between vapor and residual gas may occur (e.g. oxidation). Thereby the specific electrical resistance increases. This is disadvantageous for the shielding effect of metallic surfaces [see 1.4.2 and (11)], but must be tolerated for sophisticated case design.

The *reactive vaporization* uses the reaction between vapor and residual gas to generate connecting layers (e. g. oxides).

Covers between vapor source and substrate serve for control of the coating process. The visual contact is only released if the evaporator has reached its working temperature, and it is interrupted again if the material has been evaporated. This reduces the thermal stresses for the substrates.

A cooled cover is used in the high vacuum vapor deposition plant CREAMET EMI to reduce the thermal stress of plastic parts during vapor deposition with copper.

Partial coating can be obtained with *masks*. They must fit as closely as possible to avoid back vaporization due to scattering and to obtain sharp contoures. Best contoures can be achieved with adhering masks, e. g. tapes with sharp edges.

1.2.4 Condensation of vapor on the substrate

1.2.4.1 Condensation and layer thickness

The vapor particles that impact on the substrate are first adsorbed, and then they move on the surface and form basic units with other impacting particles which grow together in the course of time to a coherent layer below a critical substrate temperature. This condensation process and therefore the quality of layer depend on the temperature, the number of vapor particles impacting per surface element and on the angle of incidence. With low temperature and/or low particle density compact grained layers arise. But there is a high risk that residual gas molecules are included.

The *layer thickness* d is the shortest distance between the boundary surfaces of substrate and vacuum. The *layer growing velocity* v_S (vaporization velocity) results from the layer thickness growth Δd during the time Δt:

$$v_S = \Delta d / \Delta t \qquad (5)$$

The *layer thickness* on the substrate depends on the mass which has totally been evaporated, the evaporator characteristic, the angle of incidence of vapor, and the distance h between source and substrate (Figure 2.4), and on the location. With the arrangement according to Figure 2.4 it results for a surface element and one coordinate from

$$d(x) = d(0) / [1 + (x/h)^2]^2 \qquad (6)$$

or from the integration of all contributions for an extended vapor emitting surface respectively.

An arrangement of some sources (evaporator field) in a row (axis in Figure 4.5), which can individually be considered as surface sources, is of practical interest. The layer thickness shows a characteristic "waviness" around a mean thickness and a thickness reduction in the direction to the edges. For a concentric cylinder substrate with the diameter D and a length L which is large compared with the distances of the sources to each other the mean thickness can be estimated considering the evaporator arrangement as a linear evaporator. The result is

$$d = m/L\pi D\,\rho \qquad (7)$$

with m/L as evaporated mass per length and ρ as mass density. The thickness reduction at the substrate edges can be prevented by making the distance between the individual evaporators shorter in this range or arranging evaporators beyond the length

of the cylinder substrate.

Surfaces with very low inclination of vapor ($\alpha \rightarrow \pi/2$, for example side walls of cases) are critical. The uniformity of layer thickness can be improved by suited arrangement of the evaporators and simultaneous evaporation from various sources and rotation (simple rotation, planetary motion) of the substrate around the vapor sources. For shielding purposes only the internal surfaces of the cases are normally coated. Therefore the case simply rotates around the source in this case (Figure 4.5).

1.2.4.2 Substrate heating

The vaporized substrate is heated by the released *condensation heat*, by the kinetic energy of impacting vapor particles and by the *heat radiation* from the vapor sources. Condensation heat is dominating during vaporization. Because of the necessary relative thick layers of some micrometers for shielding purposes essential heating may occur and must be taken into account for vaporization of plastic products (cases) (see 3.1.1). During vaporization with resistance evaporators as used for the high vacuum vapor deposition plant CREAMET EMI that portion of heating due to kinetic energy of the vapor particles is low because they do only impact with their thermal energy (maximum some 0.1 eV). It must be taken into account, however, for ion-supported coating (sputtering, vacuum arc evaporator, hollow cathode evaporator, etc.). It is the higher the higher the ion portion within residual gas or within vapor is. The portion of heat radiation must be considered for heavily melting or high-boiling metals and especially for longer coating times. Every unnecessary radiation effect must be avoided. This especially applies to the conditions during copper vaporization of plastic cases in the high vacuum vapor deposition plant CREAMET EMI, where constructive and technological measures restrict heat radiation effects to an acceptable extent (see swiveling cover in the section Descripton of design).

1.2.4.3 Adhesion strength of layer

The adhesion of the layer on the substrate is due to physical and chemical interactions between layer and substrate atoms. Substrate material as well as physical and chemical condition of surface determine the obtainable *adhesion*. Contamination (fat, oil, separating agents from the production process, contamination by hand sweat), but also water films or production-specific surface downgradings reduce adhesion or make vapor deposition impossible. Therefore they must be removed or - far better - be avoided.

There are different requirements for adhesion according to the purpose of coating. This qualifies the suited substrate materials or requires special measures to improve adhesion. For vapor deposition of metallic layers on plastic materials their characteristics must be taken into consideration (see 3.1).

Adhesion may be evaluated with the traction-adhesive strength test (DIN 50160) and with the peel test (DIN 53494) in a quantitative way, and regarding quality with the cross-cut adhesion test (DIN 53151, EN ISO 2409, ASTM D 3359-93).

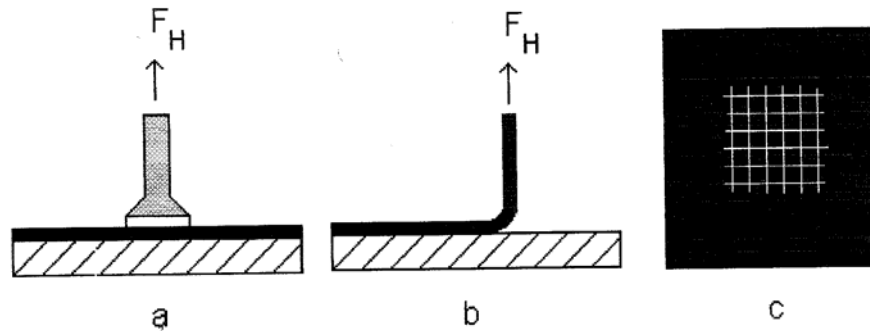

Figure 2.5: Methods to evaluate adhesion

During *traction-adhesive strength test* (Figure 2.5a) a glued on stamp is evenly pulled off. Adhesion results from the force F_H required for this and the stamp surface A with:

$$\sigma_H = F_H/A \qquad (8)$$

and is given in N/mm².

During *peel test* (Figure 2.5b) a strip with the width B (25 mm in the most cases) is pulled off with the force F_H in direction of the layer normal. Adhesion results from

$$\sigma_P = F_H/B \qquad (9)$$

and is given in N/mm. Thin layers must be later reinforced by electroplating up to 20 µm (in the case of copper 40 µm). To obtain comparable data the same width of pulled off layer is required.

Traction-adhesive strength test and peel test are preferably used for fundamental examination into adhesion. To evaluate adhesion under production conditions and in commercial ranges the *cross-cut adhesion test* (Figure 7c) is used which can simply be executed. For this purpose the layer is scratched in form of a grid by parallel grooves, which are vertical to each other, with a special cutting tool or, provisionally, with a razor blade (6 in each direction, 1 mm space). A tape which is parallel glued on in one cutting direction (adhesion 1 N/mm at 25 mm width) is pulled off within 0.5 to 1 s with an inclination of 60° to the pull off direction (ASTM: almost 180°). The resulting pattern is visually evaluated and classified: GF0 means even cutting edges without spallings; GF 1 has little spalled grid lines, spalling approximately 5%; GF 2 to 5 have spallings up to 15%, 35%, 65% and more than 65% (according to ASTM D 3359 these classes are named 5B to 0B).

For a first evaluation which is sufficient in many cases, but not standardized, a strip of scotch tape (TESA tape) is firmly pressed on the layer and evenly pulled off within 1 s under 60° to the pull off direction (Tape test, TESA-film-test). Coating is rejected if spallings occur.

1.2.5 Requirements for the vacuum

The vacuum must meet the following requirements:

- high service life of the evaporators which will be exposed to high thermal stresses
- optimum diffusion conditions for vapor
- low material losses due to scattering at the residual gas
- high quality of layers.

These requirements are met with an operational pressure of maximum $4 \cdot 10^{-4}$ mbar. But the pressure at starting of the vaporization process must be lower as the pressure increases during vapor deposition due to outgassing from the material to be evaporated (use as far as possible vacuum melted material!), desorption from the container walls, and integrated equipment and from the objects to be evaporated. The latter must always taken into consideration, but especially for plastics (see 3.1.2). This requires powerful pumps, optimum design of pipes and components and additional deep frozen surfaces to increase the volumetric displacement for water vapor
(e. g. Meissner trap).

1.3 Metallization of plastics by vapor deposition

1.3.1 Peculiarities

The following peculiarities must be considered for vacuum metallization of plastic materials:

Thermal strength
Outgassing
Adhesion between plastic material and metal
Influence time and conditions of storage

1.3.1.1 Thermal strength

The *thermal strength* of plastics is relative low due to their chemical composition (Table 4) The plastic parts must not be deformed or even decomposed under process-specific heating (see 2.3.2). This qualifies the possibilities to coat a plastic part (obtainable layer thickness, allowed material thickness) and requires a matched process control (duration of vapor deposition, reduction of heat radiation, cooling).

Tab. 4: Short-time thermal strength of plastic parts (according to *Weeke*)

Designation	Temperature in °C	
Polyvinyl chloride	PVC	40 ... 60
Polystyrene	PS	60
Polyethylene	PE	70
Acrylonitrile butadiene styrene	ABS	80
Polymethylmethacrylate	PMMA	80
Polyphenylene oxide	PPO	80 ...100
Polypropylene	PP	110
Polyamide	PA	120
Polycarbonate	PC	120
Polysulfone	PSU	150
Polyoxymethylene	POM	150
Polybutylenterephthalate	PBT	150

1.3.1.2 Outgassing

The *specific outgassing rate* (outgassing surface density) of plastics is higher by up to two orders of magnitude compared with metals and glasses (Table 5). Additionally, water vapor and other included gases or vapors permanently come to the surface of the substrate, but especially at even little temperature rises. The outgassing surface of plastic parts may be 5 m^2 and more in a commodity vapor deposition plant (batch plant). That means the absolute amount of gas may be very high.

Tab. 5: Specific outgassing rate of plastics after evacuation time of 30 min, room temperature (according to *Kienel/Sommerkamp*)

		Specific outgassing rate*) in 10^{-8} mbar l s^{-1} cm^{-2}	Outgassing qualitative
Acryl-butadien-styrene	ABS		low
Polyacrylnitril	PAN		low
Polyamide	PA	308	high
Polycarbonate	PC		low
Polybutylenterephthalate	PBT		
Polyester	PET		low
Polyethylene	PE	19	low
Polymethymethacrylate	PMMA	150	high
Polyoxymethylene	POM		
Polyphenyloxide	PPO		
Polypropylene	PP		low
Polyvinyl chhloride	PVC		low to sensible
Polystyrene	PS		sensible
Polysulfone	PSU		
Polytetrafluorethylene	PTFE	20	low
Polyurethane	PUR	55	sensible

*) Compare with metals: 0.3 ... 30

It is true that the specific outgassing rate decreases in the course of time, but only to the half value after approximately one hour. Outgassing into the vacuum chamber protracts the evacuation time and thus efficiency. The permanent covering of the plastic surface by gases affects layer quality (adhesion, color changes, loss in gloss).

The pumping unit must be adapted to the gas arisings, that means it must have sufficient volumetric displacement capacity for atmospheric gases and especially for the water vapor that releases during heating up of the plastic parts. The glowing process described in subsection 3.1.3 also leads to shorter evacuation time in the high vacuum range and reduction of pressure rise during vapor deposition because of accelerated water desorption from the material to be evaporated, container walls and integrated parts.

Outgassing from inside the substrate can also be reduced by a suitable and sufficiently dried lacquer layer (permeation barrier for water vapor). Drying temperature depends on the thermal strength of the plastic materials (no enamels for thermoplasts!). Also heat treatment under atmospheric conditions may lead to essential reduction of outgassing within vacuum.

1.3.1.3 Adhesion strength

Relative low *specific interfacial surface tension* (20 to 40 mN/m), foreign layers, missing

material bridges via chemical compounds in the interfacial layer or mixed layers due to interdiffusion, and also the high outgassing are responsible for normally *bad adhesion* of vaporized metallic layers.

To improve adhesion plastic surfaces are treated with a *plasma process* (low-pressure plasma discharge, corona discharge or flame polishing).
This changes the surface in a chemical way and also by mechanical roughening. Polymer layers or primers with good adhesion to the substrate (e. g. by etching) and to the metal can be coated as bonding agent with a plasma technology.

The simplest and most common form of pre-treatment to improve adhesion is glowing in air with an argon-oxygen mixture. The negative self bias which builds up during gas discharge leads with insulating substrates to an ion bombardment from the gas discharge plasma. This removes adsorbed water. Moreover, polar groups arise (-OH, -COOH, -CO). The surface is "activated ", and is roughened by ion etching processes. This increases the interfacial surface tensions and improves adhesion.

The obtainable adhesion strength of metallic layers on plastics heavily depends on the chemical composition of the plastics, but also on production conditions of the parts to be coated in the injection moulding or forming processes. The optimum parameters (power, duration, working gas) depend on the kind of plastic material and should be determined by experiments in any case.

Tab. 6 includes recommendations for pre-treatment of plastic materials to improve adhesion.

Tab. 6: Pre-treatment of plastics

	Pre-treatment	Parameter
ABS,PA, PPD, PS	Glowing	Ar $5 \cdot 10^{-5}$ mbar, 300 mA, 3 to 5 min
PC, ABS/PC	Primer	EMVatrend special

Long storage times (influence of atmospheric conditions, other contamination) essentially reduces the surface activity which exists directly after injection moulding as a result of heating. Coating just on the day of injection moulding has an advantageous effect on adhesion strength.

1.3.2 Metallization of plastics for decorative purposes

Decorative coating improves color and gloss of commodity goods. As metallic layers with a thickness over 50 nm completely reflect visible light plastic articles can get a metallic appearance already with thin layers. If the roughness of the surface is low surfaces with metallic lustre are the result, whereas each roughing results in lustreless surfaces. Such surfaces arise in the injection moulding or swaging process of plastic parts due to the roughness of the forming surfaces of the injection die or too high temperature (recrystallization processes, partial damages) during the injection moulding process.

Coating of plastic surfaces with a lacquer which quickly dries in air, well adheres on the substrate and which is suited for following vacuum processes leads to surfaces with an outstanding optical quality and saves costs for surface refinement of the forming surfaces of injection dies or for electroplating leveling of substrate surfaces (e.g. by nickel plating). Moreover, the lacquer layers form a barrier for the gas permeation from inside of the substrate and may eliminate adhesion problems between starting material and layer material.

In the most cases aluminum (layer thickness 50 to 100 nm) is vaporized on the lacquer layer because it has a high light reflection, the material costs are low, and it is easy to evaporate. Metallic surfaces of high brilliance are the result. To protect them against mechanical damage and corrosive effects they are coated with a transparent protective lacquer which can also be colored. With the latter articles, preferably from plastics, can get a colored appearance with metallic lustre in a very efficient way. Common colors of metals (silver, gold, chromium, copper, bronze, etc.) can be imitated by appropriate selection, but also completely other colors and patterns can be obtained. In the end the layer structure shown in Figure 3.1 builds up on the substrate:

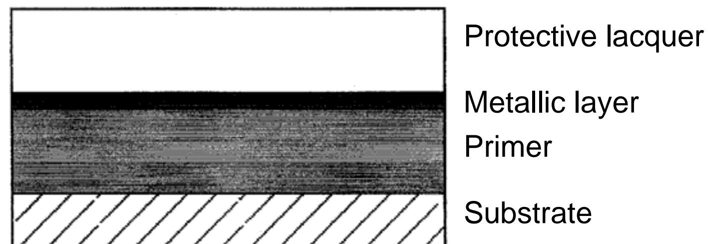

Fig. 3.1: Decorative coating with primer and transparent protective lacquer (protective layer)

Also glass-like layers which are coated by vaporization of silicon oxide, plasma polymerization of hexamethyldisiloxane (HMDSO), or by means of sol gel coating can be used as protective layers for vaporized metallic layers.

If the metallic layer is sufficiently resistant to scratches and corrosion it does without protective lacquer layer. This applies to hard material layers (transition metal nitrides such as TiN, ZrN, CrN, Borides, etc.), and also chromium or nickel chromium with certain reservations. But coating of decorative hard material layers on plastic materials

is difficult because of the high thermal stress. The vapor deposition plant CREAMET EMI is not intended for coating of hard materials.

1.4 Vapor deposition of metallic layers on plastics for shielding purposes

1.4.1 Objectives

Metallization of plastics for shielding purposes is a kind of functional coating. The aim of vacuum vapor deposition is the all-surface or partial coating of normally one side (that is the inner side of cases) with a long-term stabile and adhering metallic material. This material should be abrasion resisting at the contact points of case parts, preferably be suited for soldering, and it must ensure the required shielding of electric, magnetic and electromagnetic fields or waves. Decorative aspects such as color and gloss have no priority. But a pleasing coating is expected (that means even, free from speckings and with sharp contoures).

1.4.2 Physical basics of shielding efficiency

Shielding efficiency is understood as attenuation of electrical or magnetic fields and electromagnetic waves by a screen which is arranged between source (transmitter) and the measuring location (receiver), for example the metallic layer on a plastic case (Figure 4.1).

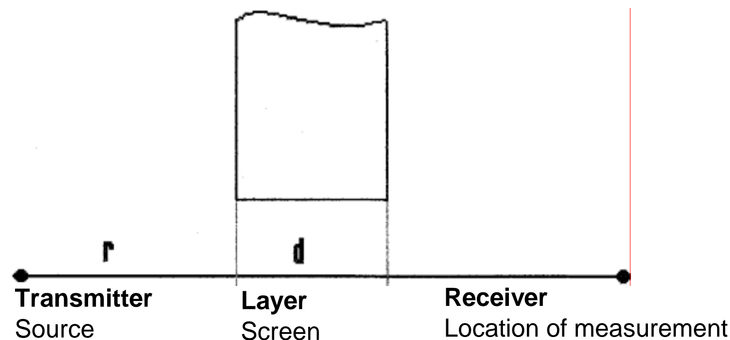

Figure 4.1: Measurement arrangement for shielding efficiency

Definition of shielding efficiency, SE; Figure 2):

$$SE = 20\ {}^{10}\log (F_o/F)\ dB \qquad (10)$$

F Field intensity at the measuring point
F_o Field intensity at the source location

Shielding efficiency depends on the frequency of the field, the shielding material (specific electrical resistance ρ , magnetic permeability μ_r), its thickness d and

geometrical shape, and in the near field on the distance r between source and shielding layer.

Alternating electric and magnetic fields are called *near fields* if r·f is < 48 MHz m; otherwise they are called *far field*, for example r > 5 cm and a frequency of 1 GHz is in the far field range of electromagnetic waves.

Figure 4.2 shows an example for the dependence of shielding efficiency on frequency and shielding thickness (shielding material: copper, r=10 cm).

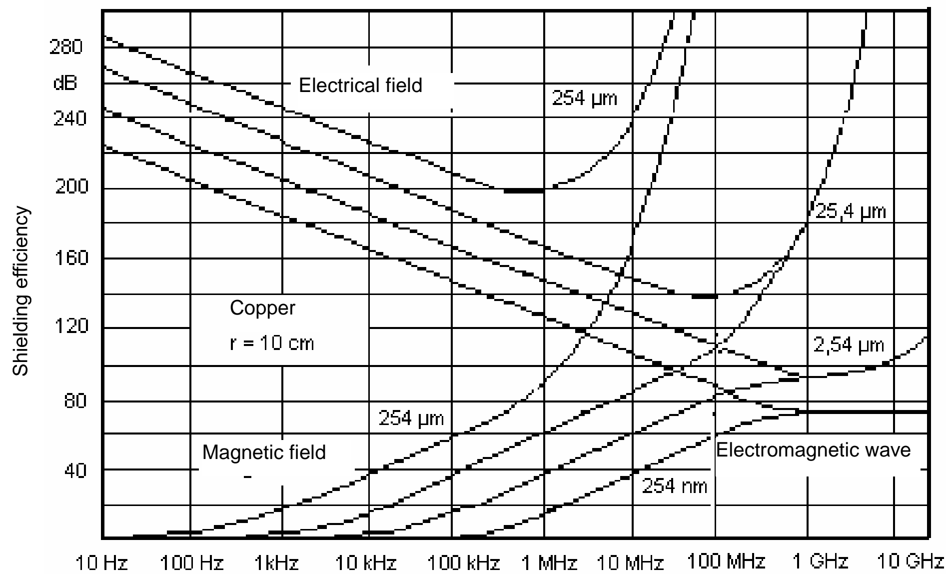

Figure 4.2: Shielding efficiency as function of frequency

Metallic shielding screens attenuate *alternating magnetic fields*, because the fields of the induced currents work against their cause. The lower the frequency the lower the shielding efficiency.

Alternating electric fields are attenuated by charge reversal within the conductor (electrostatic induction). It is true that the attenuation decreases with increasing frequency, but it is always at a high level.

Electromagnetic waves are attenuated by reflection and absorption.
There is electromagnetic radiation in the far field of the transmitter (Figure 4.3).

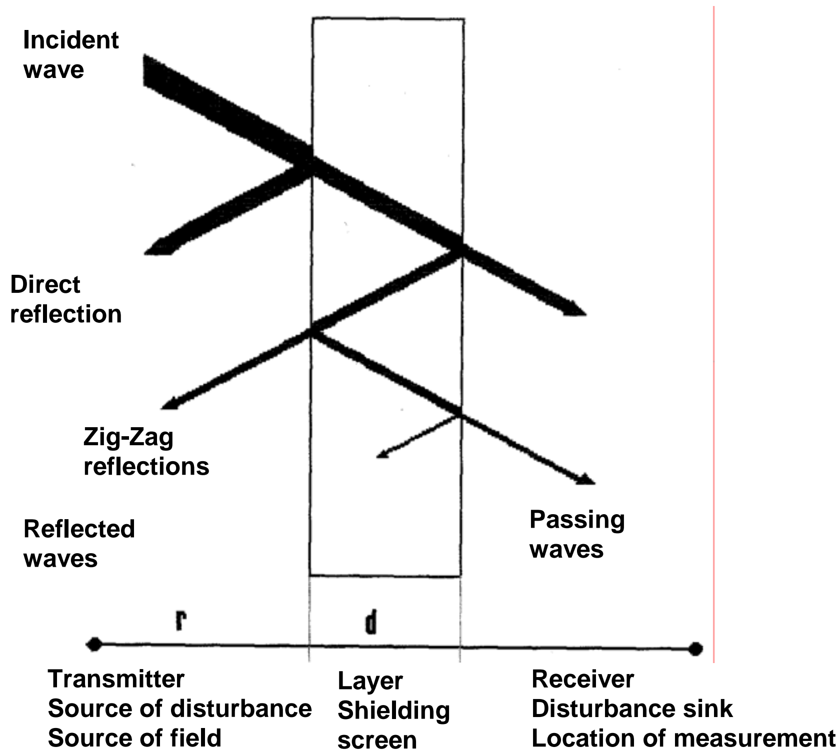

Abb. 4.3: Interaction between electromagnetic wave and shielding layer

Shielding screens from thin metallic layers (in this case copper) attenuate electromagnetic waves and electric fields in an efficient way.
The following applies to electromagnetic waves:

$$SE = 20\ {}^{10}\log\,(1 + Z_0/2R_F)\ \text{dB} \qquad (11)$$

with $Z_0 = 377\ \Omega$ and $R_F = \rho/d$. R_F is the sheet resistance (measured in Ω, often given as *Ohm per square*). This is the resistance between the opposed sides of an electrically conductive square layer element with the specific resistance ρ and the thickness d.
For $Z_0 \gg R_F$ results

$$SE = 20\ {}^{10}\log\,(Z_0/2R_F)\ \text{dB} \qquad (12)$$

A shielding efficiency of 60 to 80 dB requires a sheet resistance between 200 and 20 mΩ.

Shielding of magnetic fields is only hardly possible or even impossible with thin layers.

1.4.3 Requirements for the shielding layer

1.4.3.1 Layer material and thickness

As the layer thickness is only some micrometers due to technical and economic reasons materials with very low specific electrical resistance must be used (Table 2).

Tab. 2: Layer materials

	Specific electrical resistance µΩcm	Layer thickness µm
Silver	1,6	
Copper	1,7	2 ... 5
Gold	2,4	
Aluminum	2,7	3 10
Nickel	6,1	0,3 ... 1 *)
Nickel chromium	approx. 15	0,1 ... 0,3 *)

*) corrosion protection

Aluminum and copper are used because of economic reasons. Aluminum is coated by vacuum technology, copper by electroplating, but to a growing extent also by vacuum technology. Precious metals are only used in special cases.

The vacuum vapor deposition plant HTC10001-2H-EMI is preferably intended for the metallization of plastic cases with copper and with an anti-corrosion cover layer from NiCr.

1.4.3.2 Adhesion strength

Normally, only the inner surfaces of cases are provided with a shielding layer. Therefore, the risk for mechanical damages is limited to the contact points between assembled case parts and during assembly.

For shielding layers the traction-adhesive strength should be higher than 5 N/mm^2 and the peel strength higher than 0.4 N/mm. GF1 is still accepted as result of cross-cut adhesion test. But the layers must always stand the tape test. See also 2.3.

1.4.3.3 Long-time strength, UL 746 test

The adhesion of the metallic layer, the electrical resistance (sheet resistance), and the transition resistance between assembled case parts must not deteriorate to an unacceptable extent under the conditions of use (temperature, temperature changes, moisture). It is true that the oxide layer of passive metals such as aluminum prevents developing corrosion, but also increases the transition resistance at contact points of case parts. Copper layers require an anticorrosive cover layer.
Precious metals would be suited for this purpose, but they are only used in special cases. Nickel (0.3 to 1 µm, by electroplating), tin (approximately 1µm, by electroplating or vacuum technology), or nickel chromium (0.1 ... 0.3 µm, by vacuum technology) are coated in the most cases (Tab. 2).

For the evaluation of long-time strength the shielding layers must be in compliance with the UL 746 C test of the Underwriter Laboratories (USA) (Annex 1; version of 20. 5. 1991).
It consists of a spalling test, an aging test and the adhesion strength test according to ASTM D 3359-93 (see 2.3.3).

1.4.3.4 Measurement and evaluation of shielding efficiency

Shielding efficiency of flat surfaces is determined with an experiment according to Figure 1, for example, with a coaxial TEM measuring probe for the far field (electromagnetic waves) and with a dual-chamber measuring probe for the near field (alternating electric and magnetic fields). Table 7 contains the evaluation criteria.

Tab. 7: Evaluation of shielding efficiency

very good to outstanding shielding efficiency	80 dB and higher
good to very good shielding efficiency	60 to 80 dB
middle to good shielding efficiency	20 and 60 dB
insufficient shielding efficiency	under 20 dB

The sheet resistance of thin shielding layers is a measure for shielding efficiency. For good shielding efficiency it must be below 200 mΩ, and for very good shielding efficiency below 20 mΩ according to (12).

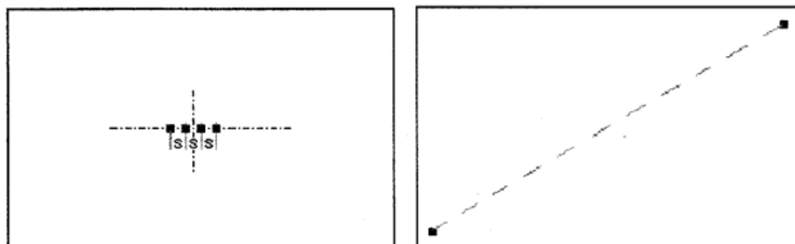

Fig. 4.4: To resistance measurement

The sheet resistance is measured with the four-point-method (Figure 4.4). The space between the points is the same (distance 1 to 3 mm). A current I is fed through the outer points, and the voltage U is wattlessly measured at the inner points. The sheet resistance results from:

$$R_F = F\,U/I, \qquad (12)$$

For thin layers the factor F depends on the dimensions of the surface which is measured. The measurement principle excludes the influence of transition resistance.

For quick quality control a two-point method is used for which the measurement distance must be always the same and selected large enough that transition resistance may be neglected (e. g. measurement across the complete diagonal of a surface).

1.4.4 Metallization of plastic cases by vapor deposition within high vacuum

1.4.4.1 Vapor deposition plant for the metallization of plastic cases

The high vacuum vaporization plant must meet both the peculiarities for the metallization of plastic materials and also economic aspects. As the use of plastic materials for cases in the first place results from economic aspects metallization in vacuum must not make the case more expensive as reasonably accepted, and in particular it must be cheaper than electroplating.

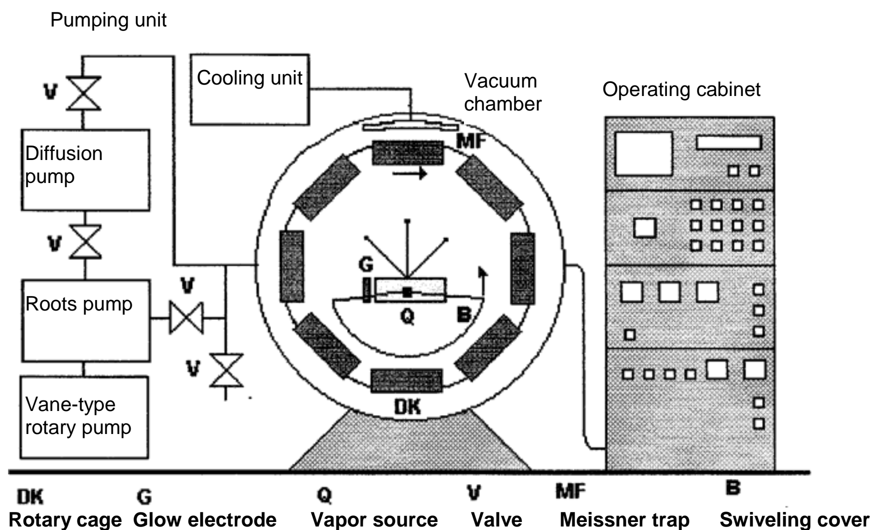

Fig. 4.5: Vapor deposition plant

The variety of possible plastic parts and also plastic cases (size, shape, material) requires an outstandingly flexible and easy-to-match plant. This can only be achieved by a batch plant (Fig. 4.5) which was developed for decorative coating of commodities. Such appropriately adapted plants are also used for the metallization of plastic cases and case parts for electric engineering and electronics.

The electrically parallel connected resistance evaporators and the glowing electrode are arranged in the axis of an cylindrical vacuum chamber. The rotary cage bears the substrates to be coated (cases) and rotates around the evaporators.

A swiveling cover serves for time limiting of vapor deposition and therefore it essentially limits the thermal stress for the substrates.

The pumping unit evacuates the vacuum chamber to the required operational pressure. It is connected with a cryogenic pump to increase the water vapor displacement capacity (Meissner trap with belonging cooling unit)

As the actual coating process takes only some few minutes (maximum 10 minutes for a multi-layer system) the evacuation process is the factor which limits efficiency. That means the evacuation and preparation process (glowing, see 1.3.1.3) up to the starting pressure for vaporization should only take 20 minutes for a cycle time of maximum 30 minutes.

Assuming a volume of 2.5 m ^{3} ***and an internal surface of 10 m*** ^{2} ***an effective displacement capacity for air of ... must be installed (uncharged vacuum chamber). Additional displacement capacity is necessary for the water vapor arisings if plastic parts are charged. A combination of a powerful diffusion pump (nominal displacement capacity ...) with a cold trap for water vapor (Meissner trap, machine cooled, figure 4.5) of 30 000 l/s makes reasonable economic cycle times possible.***

Growing layers on plant parts (e.g. chamber wall) increase their outgassing with increasing charge number. Therefore the rotary cage should be charged as tight as possible and other parts that are vaporized should be provided with replaceable covers, or it must be possible to remove such layers in an easy way.

The complete process (evacuation, glowing, vapor deposition, venting) is computer-controlled from the operating cabinet.

71.4.4 Evaporating of aluminum

For metallization with aluminum, layers with a thickness between 2.5 to 5 µm are vaporized.
Table 9 shows the mass calculated according to (7). This is the mass which must be vaporized per 10 cm evaporator length with an axially arranged row-shaped evaporator for a specified layer thickness on a cylinder with diameters of 50, 75, or 100 cm. A loss of 30% due to integrated parts (e. g. holders, current bars), gas scattering and alloy formation is considered.

Tab. 9: Mass to be evaporated per 10 cm length

Thickness	Mass in g per 10 cm for a diameter of								
	50 cm			75 cm			100 cm		
in µm	Al	Cu	NiCr	Al	Cu	NiCr	Al	Cu	NiCr
0.1	-	-	0.75	-	-	1.2	-	-	0.4
0.2	-	-	1.5	-	-	2.5	-	-	3.0
0.3	-	-	2.25			3.7	-	-	
1	0.6	2.0	-	0.9	2,8	-	1.2	3.9	
2.5	1.5	4.9	-	2.3	7	-	3	9.7	
5	3	9.8	-	4.5	14	-	6	19.5	
10	6	19.5	-	9	28	-	12	39	

Aluminum is evaporated from spiral-shaped coils from wolfram (Figure 2.2a) which are arranged on a straight row and are electrically parallel connected. The required uniformity of layer and the *mass carrying capacity* of the coils determine the number of coils. This is the mass which can be evaporated with one coil without dripping of liquid material. It is not more than 1.5 to 2 g from experiences. Already 3 to 4 coils per 20 cm must be arranged to coat a cylinder with a diameter of 50 cm with a 5 µm layer. It is also

clear that thicker layers (e. g. 10 µm) can not longer coated with coil evaporators. Directly heated TiB_2 boats with continuous aluminum charge are used for this purpose.

It is true that the intensive alloy formation between wolfram and aluminum ensures good wetting and therefore the mass carrying capacity of the coil on the one hand, but it limits the amount of aluminum that can be vaporized from the wolfram coil, that means the service life, on the other hand. Heavy deformation of the coil and wire breaks result. With a charge of 1.5 to 2 g a coil can only be used ...... times.

Purity, power consumption of a coil (current, voltage), thermal stress

1.4.5 Vapor deposition with copper

From Table 9 it becomes clear that for the same layer thickness the three-fold mass of copper must be evaporated compared with aluminum. To obtain a 5 µm thick copper layer on a cylinder with a diameter of 50 cm approximately 10 g per 10 cm evaporator length must evaporate. Funnel-shaped evaporators with a collecting pan from which up to 10 g copper can be evaporated (Figure 2.2c) are used for this purpose. As the copper hardly wets the wolfram wire the melted copper drops into the lower part of the evaporator onto the collecting pan (spoon). Evaporation occurs at the upper and hotter windings to which the copper rises due to the capillary effect. Intensive evaporation is characterized by the green lighting, thermally excited copper vapor within the basket.

To reach the described evaporation process the coils must be operated with sufficient high power. Otherwise the melted material is not sufficiently heated up and the evaporation process can not start or breaks down. The optimum electrical parameters heavily depend on the design of the funnel-shaped coil.

The funnel-shaped coils can be repeatedly used (10 to 15 times). This is limited by the deformation of the coils.

The thermal stress for the substrates (with the same layer thickness) is essentially higher because of the larger evaporated and condensed mass (compared with aluminum). Therefore it is difficult to coat plastics with low thermal strength especially in the case of thicker layers. Thermal optimization of the vapor deposition process only applies to the radiation stress. During the heating up and melting down phase of copper and during cooling down of the coils a water-cooled cover (Figure 4.2) interrupts the visual contact between substrate and source (cover closed). It is only opened if evaporation of copper starts. Then, a metallic layer quickly builds up which serves as IR reflector. The thermal stress for the plastic parts can be hold within acceptable limits in this way.

1.4.6 Evaporating of nickel chromium

For purpose of corrosion protection a NiCr20 alloy is vaporized. In this way 150 to 200 nm thick layers are enough instead of approximately 1 µm in the case of nickel plating. As known, the included nickel heavily tends to form alloys so that wolfram is perhaps the only evaporator material. The mass of the nickel chromium to be evaporated must be matched to the mass of wolfram with which the melted material is in direct contact. Therefore NiCr20 is evaporated in a straight-line evaporator according to Figure 2.2c., where two or three wolfram wires are twisted with a nickel chromium wire. The diameter of the wires and the lengths of the evaporators must be matched to each other in order to make sure that the evaporator remains mechanically stable and the material to be evaporated does not drop down. Because of the unavoidable alloy formation a part of the nickel can not be evaporated (70 to 80%)

The used evaporators according to Figure 2.2c which are already charged with NiCr20 makes it possible to vaporize layers with a thickness of up to 200 nm. They can only be used once.

1.4.7 Evaporating of precious metals

Precious metals do not or hardly wet the evaporator material. Therefore they can not be evaporated from coils, but from crucibles or boats. Boats from wolfram, molybdenum or tantalum are suited for relative thin layers (Figure 4.6).

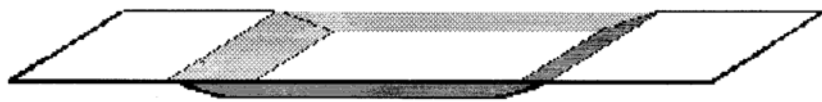

Fig. 4.6: Evaporator boats