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The uniformity control of a deposited layer in vacuum web metallising

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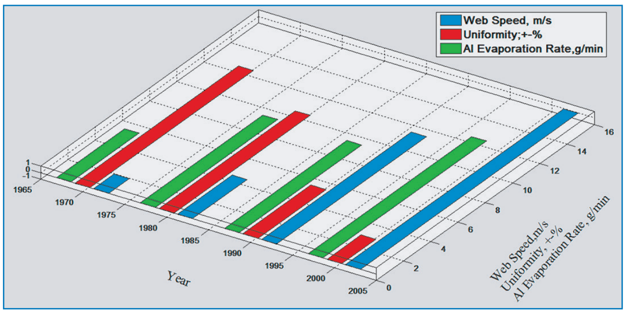
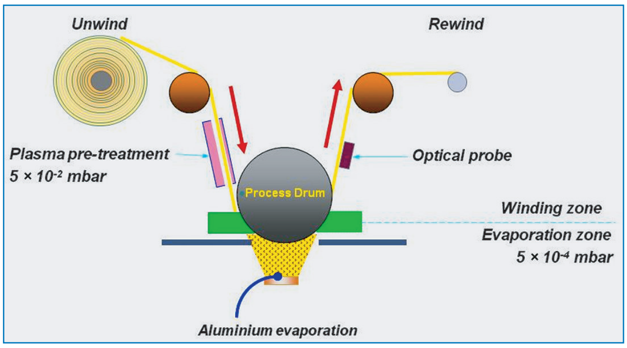
The demand for higher speed vacuum metallising coupled with higher Aluminium deposits has focused attention on improving the uniformity of the deposited layer across the width and along the length of a moving film web. Consequently, this has led to the modification of the design of standard vacuum web metallisers and, in particular, the modification of the evaporation source and the improvement of monitoring techniques with associated closed loop feedback systems. Inline optical density monitoring is now used to control the evaporation rate and line speed via a computer controller closed loop feed back system. A further addition to the standard metallising process is the use of plasma pre-treatment to improve substrate surface energy and hence, reduce problems of banding and non-uniformity. However, this depends on the type of gas mixture used, plasma energy and the nature of the substrate surface.

There is a growing demand for vacuum web metallisers with higher speeds and performance to metallise wide webs for flexible packaging and other applications. For example, the new generation of equipment for packaging applications requires a line speed of more than 10 m/s (33 fps) with coating thickness uniformity below ±5%[1]. For solar window film application the uniformity requirement is below ±2%. The increase in machine efficiency has focused attention on improving the uniformity of the deposited layer across the width and along the length of a moving film web. Uniformity is one of the most important characteristics reflecting machine performance with poor uniformity often leading to banding on metallised film. Uniformity is influenced by many parameters including film surface wettability (i.e surface energy), level of vacuum in the evaporation zone, the design of the evaporation source and control of the evaporation rate[2]. To improve uniformity across the web width the evaporation source arrangement has to be modified to accommodate wide-web film. Coating monitoring techniques with associated closed loop feedback systems have also been redesigned or altered to improve uniformity. Inline optical density monitoring using light sources such as lasers is now used to control the evaporation rate and line speed via a computer controlled closed loop feedback system[3a, b].

Figure 1 (top): Development of vacuum web metallisers over the last couple of decades.

Figure 2 (bottom): Schematic of a vacuum web metalliser.





Another addition to the standard metallising process is the use of a plasma pre-treatment source to improve substrate surface wettability and hence reduce problems of banding and non-uniformity. The interaction of plasma with the polymer surface removes contaminants and increases surface activation by cross-linking native film polymers[4]. This depends on the type of gas mixture used, plasma energy and the nature of the substrate surface.

This paper reviews the many parameters that can influence the uniformity of a deposited Aluminium layer onto a moving film web. Most of the metallising technologies discussed are relevant to product applications such as standard flexible packaging; hot stamping foils, holograms, industrial packaging and solar window films.

1 Fundamentals of web metallising

Over the past decades, there has been a tremendous growth in the use of web coaters for many applications. The early applications concentrated mainly on the capacitor industry to supply metallised Zinc and Aluminium on paper, Polyester and then Polypropylene films. Then the stamping foil industry became a large user of Aluminium metallised Polyester[5]. Later, new developments and applications accelerated throughout the 1980s and 1990s with continuous growth. This technology has been marked with the constant evolution of development between machine design and process requirements as shown in *figure 1*.

The concept of Aluminium web metallising is shown in *figure 2*. The process involves the use of unwind/rewind zones and a deposition zone. The vacuum chamber is evacuated using a combination of mechanical and oil diffusion pumps. The film moves from the unwind zone onto a process cooled drum to the deposition zone where the film is coated with Aluminium (or other materials) then moves to the rewind zone. The evaporation source is mounted underneath the cooled drum. The process chamber is optimised for each individual deposition technology which includes, size and cooled

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deposition drum, pre and post lead-in rollers, nip rollers, number and placement of load cells, pre and post chill drums, vacuum pumping and gas flow requirements.

1.1 Evaporation sources

The vacuum web metallising process involves the production of a vapour from a material, such as Aluminium, placed in a heated source inside a vacuum chamber. The source is generally heated either in a electrically driven boat or electron beam guns. The process is carried out in a vacuum chamber at a vacuum level of 1 x 10^{-4} to 5 x 10^{-4} torr to minimise any scattering or reaction with impurity gas atoms.

Because vacuum evaporation is a line-of-sight coating process the evaporation sources are spaced in a defined geometry to obtain uniform coating. There are three steps in the formation of a coating using a vacuum evaporation process. The first is to transfer the evaporated material from its solid or liquid nature into a vapour phase. The second is to transport the vapour to the substrate and the third is to condense the vapour onto the substrate to obtain the required coating[6]. Each step can be controlled independently to alter coating characteristics according to requirements, however, to deposit a certain coating at a particular thickness requires the selection of the correct evaporation source.

In most web metallisers intermetallic composite ceramic evaporator boats are used to evaporate Aluminium. The Aluminium wire is fed continuously to the heated boats via wire feeders to metallise large webs of plastic films on a semi-continuous basis. However, electron beam[7] and induction-heated sources are also used in some vacuum web metallisers. Newly developed electron beam sources are more efficient and reliable but still more expensive than a standard electrically resistance heated boat. The boat can provide long evaporation life, efficient evaporation rates, is simple to operate and inexpensive. Overall dimensions and cavity sizes can be machined according to requirements.

The electrical resistivity specified is normally within the range of 250–1200 micro ohm-cm and has been designed to be stable in a vacuum and corrosive environment. In order to coat a wide web, many boats are equally spaced in the evaporation source to provide a coating uniformity <±5%. The spacing depends on the geometry of the source, the width of individual boat and source-to-substrate distance.

2 Factors affecting uniformity in standard metallising

Banding or any other form of non-uniformity is undesirable mainly because it would affect the functional and visual properties of the metallised film. Elimination of banding is not straightforward and there are many theories as to the causes. Banding becomes more pronounced with fast machine speeds and heavy deposits. Some factors affecting uniformity are shown in *figure 3*. It is a well-observed fact that banding in the metallised film reduces as the run progresses in line with the normal drop in pressure that occurs. This will be explained in the next section. Increasing power to the boats will increase the temperature and evaporation pressure, but may also increase banding. A unique solution to the problem seems to be difficult and various compromises have been attempted by different manufacturers to try to minimise this effect. These include angling the boats to the normal machine direction, using two sources with boats on each source positioned at half pitch source to source[8], reducing the pitch distance between boats[9], feeding two wires to the same boat[10] and using staggered boats geometry[11]. The use of shorter boats may aggravate the problem.

2.1 Evaporation theory

Metallising efficiency is normally defined as the ratio of the mass of material deposited on the film to the total mass evaporated for a given geometry. The evaporation flux from the boat is affected by the vapour pressure. The evaporation flux can be calculated using the following formula[12]:

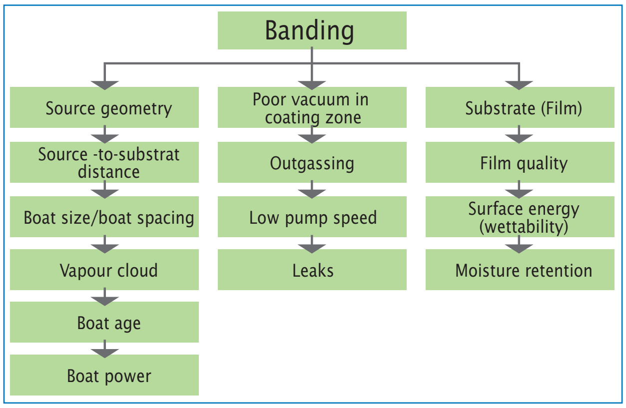


Figure 3: Factors affecting uniformity in standard metallising.

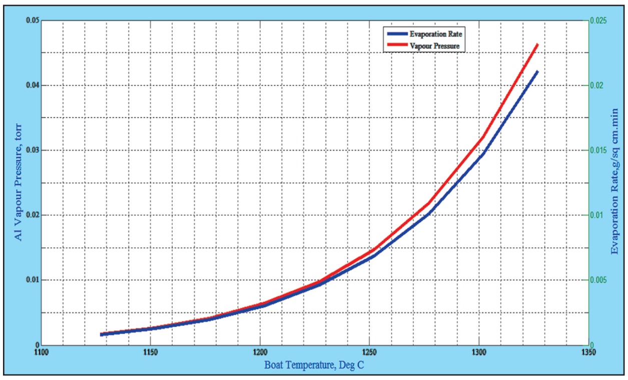


Figure 4: The dependence of Aluminium mass evaporation rate on boat temperature and vapour pressure.

$$\text{Ø}_e = \alpha N_A (P_v - P_h)/\sqrt{(2\pi MRT)}$$

Ø_e = evaporation flux;
α = evaporation coefficient ($0<\alpha<1$);
N_A = Avogadro's number;
P_v = vapour pressure;
P_h = ambient pressure.

Maximum flux is obtained when $\alpha = 1$ and $P_h = 0$. Therefore

$$\text{Ø}_e = 3.513 \times 10^{22}\, P_v/\sqrt{MT}$$

molecules/cm² sec

This can also be put in mass units by multiplying flux with the atomic mass. The mass evaporation rate close to the source is:

$$\eta_e = 5.84 \times 10^{-2} \sqrt{MP_v/T}$$

g/cm²sec

Figure 4 shows the mass evaporation rate of Aluminium for different boat temperatures and vapour pressures. This graph illustrates the dependence of mass evaporation rate on vapour pressure and boat temperature.

For Aluminium (M=27g), the vapour pressure is 10^{-4} torr at a boat temperature of 1000 °C (1832 °F). The Aluminium mass evaporation rate is 9.7 x 10^{-7} g/cm². When the boat temperature is increased to

1220 °C (2228 °F) the vapour pressure is 10^{-2} torr. In this case, the Aluminium mass evaporation rate becomes 8.7 x 10^{-5} g/cm²/sec. However, the mass evaporation rate near the source is different from the arrival rate of atoms to the substrate. The arrival rate can be calculated from the following equation:

$$R = \O_e A_c / 4\pi h^2$$

Where $\O_e$ is the evaporation flux as atom/cm² sec, A_c is the source area in cm² and h is the source to substrate distance in cm (*figure 5*).

For a standard boat with A_c area = 45 cm², T = 1220 °C (2228 °F); P_v = 10^{-2} torr, h = 15 cm, the arrival rate (R) of Aluminium atoms to the substrate (film) = 3 x 1016 atom/cm² sec. The growth rate of Aluminium on the film is 44 Å/min.

It is known that the vacuum chamber usually has a background of water vapour even if the chamber pressure is about 10^{-4} torr. If we assume that the vapour pressure in the chamber at room temperature is about 10^{-6} torr, then the arrival rate of water molecules to the substrate (film) would be 4.8 x 1014 molecule/cm² sec.

Although the arrival rate of Aluminium is higher than the arrival rate of water molecules the Aluminium coating will still be contaminated with oxygen. However, in practice, when boats are conditioned before the shutter is opened, evaporated Aluminium rapidly getters the residual oxygen and water vapour in the source trough and chamber. This will reduce the arrival rate of water and oxygen molecules to the substrate but the freshly deposited Aluminium coating will still has a thin oxide layer. In standard web metalising the boats temperature is usually above 1200 °C (2192 °F) and the vapour pressure above 10^{-2} torr. For an Aluminium wire feed speed of 1000 mm/min (39.4"/min), the evaporation rate of Aluminium will be about 5.4 g/min. Therefore, the arrival rate of Aluminium on the film would be several thousand Å/min.

For a web moving at a line speed of 800 m/min (2625 fpm) the deposited Aluminium thickness would be about 300 Å (0.03 micron). To obtain the required thickness of Aluminium (or optical density) at high line speeds, machine operators usually increase the boat's power (temperature) and wire feed speed. This will increase the vapour pressure in the region immediately above the boats thus creating a virtual source with a viscous flow regime. Operation within this regime can lead to condensation of the evaporated Aluminium into droplets. If these droplets travel to the surface of film and adhere, the coating can have poor surface morphology with open columns. Operation within this system can also affect the deposition uniformity because of the formation of a virtual source at some distance above the boat. To obtain the best uniformity, the evaporation rate must be optimised. This will be explained in detail in section 2.3a.

From the foregoing it can be seen that any change in the boat temperature or wire feed speed will result in a change of vapour pressure and the mass evaporation/arrival rates of the material. For a stack of many boats any fluctuation of temperature or any defects in any boat will affect the evaporation rate, hence uniformity. As a general rule, it is always recommended that Aluminium metallising is carried out at a chamber pressure considerably below 10^{-3} torr to achieve a consistent evaporation rate at a reasonable boat temperature. *Figure 6* illustrates Atomic Force Microscopy surface morphology pictures of BOPP films metallised at 3 x 10^{-4} torr and 5 x 10^{-3} torr resp. It is clear that the surface of the metallised film at a poor vacuum level has a columnar structure that can affect the property of the film. Film metallised at a good vacuum level of 3 x 10^{-4} torr has a denser structure.

2.2 Evaporation source geometry

This includes boat size, boat spacing, boat temperature, boat clamping, vapour plume, evaporation rate, source–to-substrate distance and the overlap of evaporation plumes from adjacent boats. Most vacuum metallisers use standard 150 x 30 x 10 mm (5.9" x 1.2" 0.4") intermetallic boats. However, others use slightly shorter boats. The evaporation boats are usually arranged in 100 mm (3.94") pitch intervals and an effective spring-loaded end clamping system is used to maintain a constant compressive stress on the boat for good electrical and thermal contact. Using this arrangement the evaporator electrical power is maintained to ensure a uniform evaporation rate and consequently a uniform vapour plume. As discussed previously, any small variation in boat temperature would result in a variation in vapour pressure and the shape of the vapour plume. The source-to-substrate distance is another factor affecting deposition uniformity. The distance has to be optimised to achieve good collection efficiency on the web and at the same time provide a good evaporation throw in the upward direction. As the rate of evaporation increases, dark and light bands may appear on the film. Dark bands usually appear over the evaporators and lighter bands appear in the interspaces between the evaporators. To solve this problem during the manufacturing stage of the metalliser, evaporator spacing and source-to-substrate distance have to be adjusted to achieve good uniformity with no band effects. Typically, with evaporators spaced at pitch intervals of 100 mm (3.94") and a source-to-substrate distance of 150 mm (5.9"), 45–50% of the evaporant is collected on the moving web with an overall uniformity of ±5–10%[10, 11, 12].

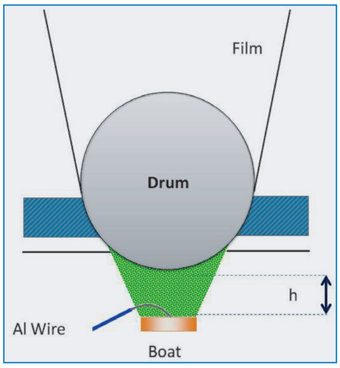
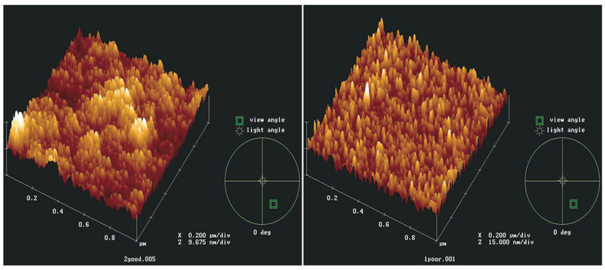


Figure 5:* *Source-to-Substrate distance h.



3x10^{-4} torr 5x10^{-3} torr

Figure 6:* *AFM pictures of BOPP films metallised at 3 x 10^{-4} torr and 5 x 10^{-3} torr.

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2.3 The vapour plume

Understanding the dynamics of the plume is important to the prediction of the distribution of the evaporant species in the chamber and, in turn, the prediction and control of the deposition rate and thickness uniformity across the width and length of flexible web.

The vapour flux usually follows cosn angular distribution geometry, where n is an index defining the source geometry. If the source, i.e. evaporation area, is small compared to its distance from the substrate (figure 5), then it acts as a point evaporation source. However, the aggregate flux arriving at any point on a substrate surface reflects the summation of the flux, from an array of 3-dimensional point sources, which model the molten surfaces and the evaporant plumes directly above the boat. The value of n may vary with angular displacement around the source (boat). Similarly changes in operating conditions, for example chamber pressure, can modify n. Hence, the performance of the source depends on source geometry, deposition rate and the operating conditions within the coating chamber[13].

The vapour deposition profile from a single evaporation boat can be estimated using the standard equation that describes physical vapour deposition profiles[14].

$$t/t_o = \frac{1}{[1+(r/h)^2]^{(n+3)/2}}$$

The thickness of the deposit directly above the boat is:

$$t_o = m/(4\pi\rho h^2)$$

Where t is the local coating thickness on a flat substrate (film), t_o is the coating thickness directly above the evaporation source, r is the distance from the coating surface midpoint to the point where t_o is measured, h is evaporation source-to-substrate distance, m is the mass evaporation rate, ρ is the evaporant density and n is an exponent used to characterise the relative focus of deposited vapour. In sputtering systems, this equation generates an exponent n = 1. In Electron Beam PVD systems, this equation generates an exponent n = 3,4,or 5. In vacuum metallising, where one single evaporation boat is used, n is found to be as high as 10. *Figure 7* illustrates a comparison between the calculated thickness distributions for n = 10 and the experimental thickness distribution measurement from a single boat. A stationary glass substrate was used for the thickness measurement. The Aluminium evaporation rate was 9 g/min and the sample was coated for 10s[15]. The deposition profile exhibits the classic bell shaped curve with a peak rate of deposition directly above the source.

The variation in the vapour plume, and hence n, depends on many parameters including the condition of the boat. Therefore, any fluctuation in the electrical current passing through the boat, wire feed rate or presence of cracks or defects on boat surface will affect the shape of the plume and leads to banding. *Figure 8* shows a thickness uniformity prediction of boats with stable and fluctuated evaporation temperature.

The experimentally measured shape of the vapour plume of a single boat is shown in *figure 9*. This was measured using a stationary glass substrate with an Aluminium evaporation rate of 9 g/min for a period of 10 sec[15 a, b] with h = 150 mm (5.9”). For comparison, this figure also illustrates a mathematical prediction of the vapour plume for a single boat. It is believed that the spread of the measured plume to the sides of the boat is due to the formation of a virtual source with a vapour pressure difference between the centre and sides of boat[11].

As more boats are added, vapour plumes start to interact and at high evaporation rates, the pressures are high enough to cause enough interaction to distort all plumes. *Figure 10* shows a comparison between experimental and simulated vapour plumes for seven boats[15]. The experimental measurement was done on a stationary glass substrate, which was metallised using Aluminium evaporation rate at 9 g/min for 10 sec with h = 150 mm (5.9”)[15 a, b].

It is evident from such results that by using more boats the interaction between vapour plumes increases and this results in improved uniformity across web width, provided that boat temperature, boat condition, material evaporation rates and chamber pressure remains stable. In practice, all boats should give the same evaporation rate for a high uniform deposition. However, it is possible to predict that some boats may behave in a highly focused manner due to higher evaporation rates, while others give a more dispersed distribution of the vapour flux due to lower evaporation rate. This can occur due to boat condition, fluctuation in boat temperature (power) or a fluctuation in wire feeder.

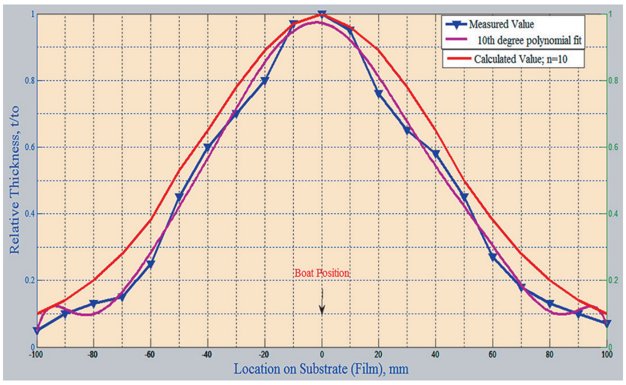


Figure 7: Comparison between calculated and experimental thickness distribution of Aluminium for a single boat.

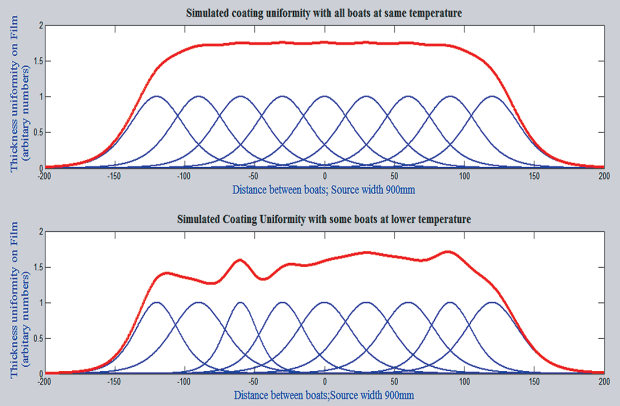
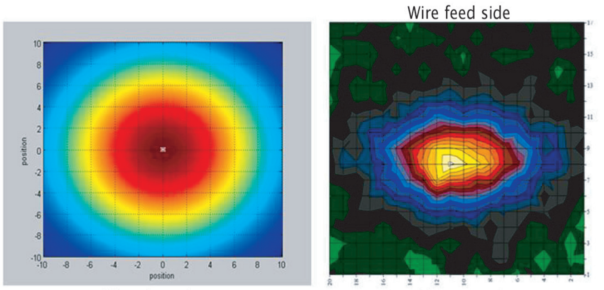


Figure 8: Simulation of thickness uniformity of boats with stable and fluctuated temperature.



Simulated

Measured

Figure 9: Comparison between experimental and predicted vapour plume shape.

2.3a The virtual source

The distortion in the vapour plume can be related to the formation of a virtual source above the real source. The two sources are different in area and location. It is from this virtual source that the vapour is then deposited onto the substrate. In general, the real source is defined as the area on the surface of the boat from which evaporation occurs. At low evaporation rates, free collisionless molecular flow conditions prevail. In this high vacuum regime the mean free path of these molecules is large and molecules travel in a straight line. The deposition distributions can be calculated using the conventional cosine distribution relationships. At higher deposition rates, important deviations occur since viscous flows start to prevail leading to the formation of a virtual source above the real source. In this regime, the molecules move in a near-compact manner thereby providing a flow and direction to the substrate. Thus, the physical effects deriving from the density of the evaporant molecules, such as dynamic viscosity, prevail. The flow of molecules is governed by the viscous forces and is constant over time. This high pressure virtual source extends some distance above the boat, with vapour flow assumed to be coming from this virtual source rather than the real one. The position of this virtual source varies with evaporation rates[16]. The virtual source is formed because of the relatively high local density of evaporant materials. Thus instead of the evaporant being beamed from the various points on the flat boat, they appear to be beamed from a region in the perimeter of the viscous plume. Relative to the substrate, they seem to be coming from a source located somewhere within the viscous plume at a distance h_v, rather than from the actual source at distance h (*figure 11*). The actual shape of the viscous plume is not known precisely, but it could be in the shape of ellipse[17]. The virtual or effective height, h_v, thus decreases with increasing evaporation rate at constant geometrical source-to-substrate distance, h. For multiple sources any change in the evaporation rate of a single boat will affect the virtual height, h_v, and therefore uniformity. At high evaporation rates the height of the virtual source from the top of the real source can be a couple of centimetres[17]. This is considerably larger and closer to the substrate than the real source. This data should be taken into account when calculating the vapour deposition distribution in a web metallising evaporation system at high evaporation rates. Clearly, assuming that the vapour originates from a single point on the surface of the real source will give significant errors in determining vapour deposition patterns.

2.4 Source to substrate distance

The other critical parameter that controls uniformity under multiple source evaporation conditions is the relative separation of the sources to the height of substrates above the plane of the sources (h). The source-to-substrate distance, h, and the separation between multiple sources are selected and fixed by the machine manufacture to give the required uniformity level. If a better uniformity is required, such as the case for solar window films, then the distance can be increased. However, the deposition rate will drop and the film speed has to be reduced to achieve the required thickness. Attempts to increase the evaporation rate by increasing wire feed speed may result in the formation of a dense viscous virtual source few centimetres above each boat, which will disturb uniformity as discussed in the previous section. *Figure 12* illustrates mathematical predicted results of the effect of changing the source-to-substrate distance on coating thickness uniformity at fixed evaporation rate. As the source-to-substrate distance increases coating uniformity improves.

For multiple sources, increasing the ratio of h/(distance between boats) to 2 gives a much more uniform deposition profile both directly above the source and obliquely (offset from the centreline). This approach allows much closer working distances, while still achieving uniform deposition, and permits greater throughput, better yields and more simple designs. In some vacuum metallisers, the source to substrate height, h, is 150 mm (5.9"), while the separation between boats is 100 mm (3.94"). Therefore, the ratio is 1.5, which is close enough to give a uniformity of about ±5–10%.

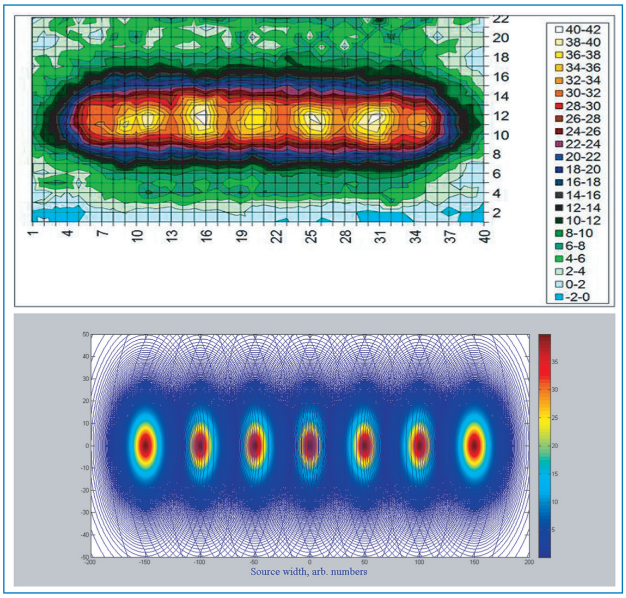


Figure 10 (above): *Comparison between predicted and experimental vapour plumes for seven boats (top: measured, bottom: predicted).*

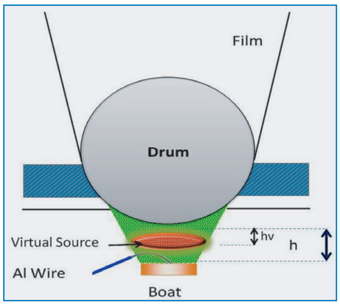
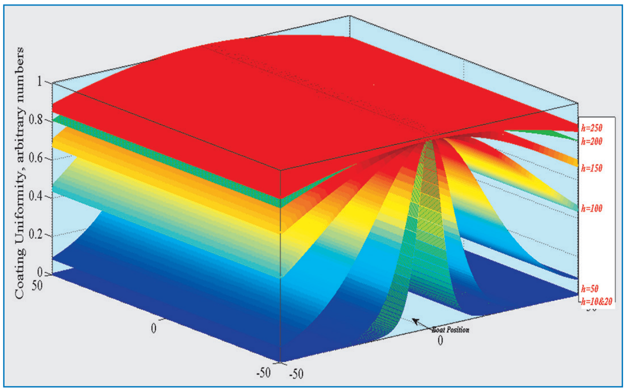


Figure 11 (left): *The formation of virtual source above real source.*

2.5 Moisture on flexible film and vacuum chamber

A high moisture content in film may affect the uniformity of a deposited coating due to outgassing. Effective separation of the winding and evaporation zones plays a crucial role in reducing outgas-

Figure 12: *Predicted coating uniformity vs source-to-substrate height, h (arbitrary numbers).*



sing. When the film is exposed to the radiant heat from the evaporation source, the outgassing rate can increase dramatically. Increasing the heat exchange between film and the chilled process drum reduces this. However, a high outgassing rate from film, or heavily oxidised evaporation trough, can produce banding during metallising. As discussed earlier, there is always an amount of adsorbed water vapour (moisture) even at a chamber pressure of 10^{-4} torr.

2.5a Sources of moisture during metallising

When a vacuum chamber is opened to the atmosphere, water condenses on the walls of the chamber at a rate of 1015 molecules/cm^2 of real surface area[18]. This water then diffuses into the passivated oxide layer of the chamber's wall. The amount of water trapped inside the walls depends on the surface condition and the humidity of atmosphere. On a humid summer day at 20 °C (68 °F), a 100% relative humidity (RH) means that one out of every 45 molecules of air is a water molecule, or that water has a partial pressure of 17 torr (760 torr x 1/45). Controlling the RH to 45% reduces the partial pressure of water to 8 torr[19].

The amount of free water vapour in a chamber can be calculated as follows:

Assume a chamber with 1000 atmospheric litre volume. At a pressure of 17 torr (partial pressure of water), the chamber would contain:

1000 litre x 17 torr(H_2O)/760 torr
= 22.4 atmospheric litre of water vapour.
1 mole of water (H_2O)
= 2 x 1+6 = 18 g
Density of water
= 1 g/cc
Volume = mass/density
= 18 cc of liquid water

Therefore, at RH=100%, there are 18 g of liquid water in the free water vapour state per 1000 litre of void volume.

The other source of water is the film. When a plastic film is metallised at high speeds the film releases a large amount of air which would also contain water vapour. As an example, 5% of the total volume of a web of Polyester material, 12.7 micron thick, is trapped air. A web 500 mm (19.7") in overall diameter by 1500 mm (59") in length will contain approximately 13 standard litres of trapped air. This will contain a large amount of trapped water vapour which should be pumped out in a separate zone to minimise contaminating the coating or metallising zone[20]. BOPP films usually have higher moisture levels than PET.

The other source of water vapour that can affect the overall vacuum level during metallising is virtual and real leaks in the vacuum system. Real leaks are caused by holes, O-rings and other seals in the system. Virtual leaks are caused by cracks in the chamber welds and other mechanical parts. Adsorbed water in film or chamber parts is more difficult to remove than atmospheric free water. In order to speed up the removal of water vapour from the system four basic methods can be used. These are:

1. Time,
2. Temperature,
3. UV radiation,
4. Momentum energy transfer exchange.

Pumping the vacuum system for a long time will eventually remove water but this may take days or weeks. Naturally, this is not acceptable in an industrial production environment. The rate of water removal can be enhanced by heating, thereby making the molecules more energetic to leave the surface. However, temperatures in the range of 200–300 °C (392–572 °F) have to be used for quick drying. The heating should be uniform otherwise the water will simply transfer to any cold surface and remains adsorbed[18]. In some applications where the chamber is water cooled, hot water is circulated around the chamber during pumping down to release trapped water. Hot water is also used during venting, loading and reloading to minimise water adsorption on the chamber walls. In other methods, the chamber is pumped down to about 100 torr then backfilled with dry nitrogen at atmospheric pressure for a few minutes before roughing again. Adsorbed water can also be removed by using ultraviolet radiation at a pressure of 0.1 torr and power density of 0.4-8 mW/cm^2. Water absorbs UV radiation at λ = 190–200 nm and the absorbed energy provides thermal energy to the water layer. However, UV lights should be shielded very well during coating cycle to allow for the continuous utilisation of the UV. Glow discharge can be used for the removal of water from a vacuum system. In this case anodes are used inside the grounded chamber in the presence of some gases such as Ar/O_2 mixture at a pressure of 7.5 x 10^{-3} torr. Ions generated in the plasma accelerate toward the chamber walls and the continuous bombardment releases water molecules and carries it to the pump. The problem with this approach is the possible contamination of the substrate due to the continuous sputtering of contaminants on the chamber walls.

However, the most efficient method for the removal of water from the vacuum system is the utilisation of refrigeration cooled panels or pipes. A typical panel with a surface area of one square meter at a temperature of –100 °C (–148 °F) will provide approximately 100,000 litres/second for the removal of water vapour at a chamber pressure of greater than 5 x 10^{-6} torr[20]. Another method of removing moisture from film is the use of a plasma treater. This will be discussed later.

2.6 Monitoring system

The demand for improved uniformity has led to the development of advanced monitoring systems and closed loop feedback to control individual deposition sources. Two systems are available to monitor and control the thickness of the deposited Aluminium layer. The first is a non-contact resistance monitoring system which measures the deposit on the substrate at 100 mm (3.94") intervals by measuring eddy current fluxes. A flux is produced from an RF coil, which links with the coated substrate[3a]. The resultant induced current in the substrate is measured and fed back to a controller/monitor unit which controls the wire feed to each individual evaporator based on the eddy current resistivity reading at the sensing coils. The controller constantly compensates the wire feed rate to

reduce the error between the reading and the actual set value. This function goes into a standby mode if the resistivity of any given position varies more than ±15% of the target specification. This is helpful in that the controller will not over compensate the wire feed rate for flaws, which may be unrelated[3a]. The second type of monitor is the optical monitor system[3b]. Light transmission is measured at numerous points across the web using light sources or lasers and the data is directly translated into OD readings. This system has the ability to measure very low OD, which is required for solar window films and clear barrier coating. For high OD, non-contact resistance monitors would be preferred.

3 Methods to improve uniformity

Throughout the history of vacuum metallisers, there have been many attempts to improve uniformity and reduce banding in metallised films. The following describes some methods which have been employed to minimise banding:

3.1 Source geometry

One of the methods used was to change the source-to-substrate distance and the separation between boats. It has been claimed that with a source-to-substrate distance of 250 mm (9.8”), banding was highly pronounced with high evaporation rate, in the range of 10 g/min, needed to maintain a deposit of 2.2 OD at a line speed of 500 m/min (1640 fpm)[9]. However, this could be due to the formation of a virtual source above the evaporation boats at a high evaporation rate. This would affect the vapour plume and uniformity as discussed previously. By reducing the rate of evaporation, changing the separation or arrangement of boats, improving surface energy of the film and operating at good vacuum levels, the metal collection efficiency can be improved dramatically. Angled or staggered boats is another geometry that has been deployed in an attempt to reduce banding by spreading the evaporant pool in a more traverse direction to the web[21]. In such a geometry the vapour plumes were offset, reducing the interaction between adjacent boat evaporator plumes thus reducing banding. The theory of staggered boats[21] suggests that the reduction of banding is due to a »honeycomb« arrangement of the vapour plume providing a reduced interaction of the boats and in effect reducing the vertical nature of the vapour plume with high evaporation rates. The uniformity was reported to be within ±3% at up to 14 m/s[8, 21]. The method of using wavy edge shields (cold fingers) near the drum was also used to reduce the amount of Al in centre of plume, thus reducing banding[9].

In addition to improving the evaporator geometry, improvements have also been made to the evaporator control. This includes the use of stepper motors to improve the response of individual wire feeders to feedback signals from inline deposition monitors and the automatic adjustment of boat power according to the corresponding wire feed rate[22, 23].

3.2 Slot sources

A further development to improve uniformity was to use a single linear slot source with a top baffle to direct the vapour stream towards the substrate. The source is heated directly or indirectly using special heaters, induction heating or electron beam gun. Such sources are already available for some materials such as Zinc, silicone monoxide, lithium and other materials[24]. There is growing development work to use a slot source for the Aluminium evaporation to achieve high line speeds with improved coating uniformity. In this respect, the vapour can be ejected through either a baffle or series of nozzles so that the substrate is presented with a uniform vapour stream. This work is still underway although there is equipment available on the market which uses a single crucible with electron beam evaporation[7].

3.3 Double row of sources

In this type of geometry, two rows of sources are used with double process drums or a single large drum to increase line speed and achieve good uniformity. The two rows are offset from each other so the two inline coatings overlap to reach the highest deposition rate. The rationale for this is the reduction of the vapour plume interference between adjacent boats[9].

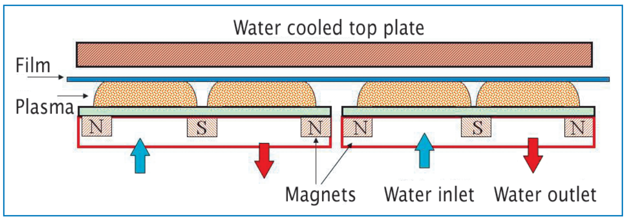


***Figure 13:* Schematic of plasma treatment source.**

3.4 Inline plasma pre-treatment

Most films for metallisation receive some form of pre-treatment to improve adhesion and uniformity and consequently barrier. This includes corona, flame and chemical web treatment. Such pre-treatment methods are carried out in a normal atmosphere with no control over treatment environment. Increasing demand for enhanced coating properties has led to the utilisation of inline plasma sources in vacuum to treat polymer films on a moving web. The interaction of plasma with the polymer surface removes contaminants and increases surface activation by cross-linking native film polymers and incorporating them onto the surface species from the plasma gas. This depends on the type of gas mixture used, plasma energy and the nature of the surface. Consequently, this promotes the interaction between depositing atoms and substrate surface, thus increasing surface energy and improving wettability, adhesion and uniformity[4, 25].

Plasma sources use pulsed DC, medium-frequency AC or RF generators to strike the discharge. Medium-frequency AC excitation sources may have either planar or tubular electrodes or electrode arrays to allow higher treatment powers with no arcing problems, that can sometimes plague DC discharges. Plasma sources use magnetic fields or hollow cathode discharges to produce intense and directed plasma at low gas pressures. *Figure 13* illustrates the typical arrangement of a plasma source. In some metallisers, plasma treatment sources with 5–20 kW, 40 kHz power supply are used to generate plasma[26, 27]. The plasma treatment is carried out using a gas mixture of argon and oxygen under constant pressure control at around 0.05 torr. The plasma source is installed in the unwind zone so that the film is treated before passing to the coating zone (figure 2).

Conclusions

Uniform coating has become more challenging because of the demand for higher speed machines and improved barrier properties. High uniformity levels at the highest line speed can be obtained by optimising the various parameters that can influence the spread of coating across film width and down the length. Uniformity can be improved by operating at a good vacuum level and by optimising source-to-substrate height, boats arrangement, evaporation rate and boat temperature. Plasma treatment has also been shown to reduce banding and increase adhesion. Plasma generating sources can be easily retrofitted into standard metallisers without interfering with its performance. ■

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