METALLIZING HIGH MOISTURE MATERIALS: industrial experience of paper and paperboard vacuum coating
By
Fabiano Rimediotti
Nordmeccanica NA Ltd. Vacuum Division - 250H Executive drive, 11717 Edgewood, NY
Ph.:+39 0523 596399   Fax : +39 0523 612051   e-mail : rimediotti@nordmeccanica.com

Introduction
Direct paper metallization is not a new process: the annual global production has been always growing, although at somehow moderate pace, in the last decade: according to a recent market study from AWA (“Vacuum Coated & Metallized Products Markets Global Review 2012), it represents 23% of the total metallized material, which exceeded, in 2011, one million Ton. Therefore, paper metallization establishes itself as a very important sector of the vacuum coating industry. A novel interest has grown, however, in recent years, mainly driven by definite development of new markets, such as the large tobacco packaging business in China, where the transition from foil laminate to direct metallized paper seems finally an established trend, after many years of expectations and uncertainty. The new metallization projects often require very large production volumes and the use of differentiated raw materials sources, preferably from domestic paper mills or from brands already approved for tobacco applications. These demands have been a challenge for the coating and metallizing machine manufacturers, more comfortable with using “metallization-grade speciality papers” of traditional suppliers, since the paper properties, in particular the surface finishing and the moisture content, represent a key factor in determining its ability of being metallized, let alone the final product quality. The principles for metallizing paper and, in general, substrate materials with high vapor and gas, imply coping with the vapor release into the vacuum chamber, which tends to affect the vacuum level required for aluminium deposition. The strategies consist of minimizing the natural moisture loss from the paper (mostly by paper coating, finishing and varnishing) and of continuously and efficiently removing the vapor released during the process. The separation of the vacuum chamber in different zones at different pressure, the “vacuum zoning”, is the method to “protect” the area where aluminium is evaporated, preventing the vapor migration from the winding zone where most of the moisture loss from paper occurs. Likewise, the consequent generation of differential pressure zone allows large mass of vapors removal from the higher pressure winding chamber, thus reducing the relevant volumetric amount. The combination of mechanical pumping and moisture condensation by cryogenic coil is another traditional feature of paper metallizers, which has required significant improvement to suit the latest more demanding specification. This presentation will discuss the application of the basic principles of vacuum coaters design for high outgassing materials to a recently implemented project of a large output paper and paperboard metallization line. From the data collected from industrial trials, it intends to propose solutions, which can further optimize the production process with the main objective of reducing production cost and increasing energy efficiency.
1- The process of paper metallization: the governing factors

a-Paper properties

Paper is, in its basic specification, unsuitable for metallization: its natural porosity represents a rough base for the condensation of aluminium vapor and the thin metallic layer (20-30 nanometers) would reproduce the surface peaks and valley and would be unable to create a continuous coverage. The result would be a dull gray color with no gloss and specular reflectance, useless in most circumstances. Moreover, the material fibrous nature absorbs moisture until reaching an equilibrium concentration with the storage relative humidity, to be desorbed when the humidity (i.e., the water partial pressure) decreases. At the metallizer vacuum chamber low pressure, the moisture loss always occurs: depending on the rate, this phenomenon can have a dramatic impact on the vacuum pumps capability of maintaining the minimum conditions for the metallization process. However, if properly prepared, paper becomes an important substrate for vacuum metallization. The metallizing-grade paper has, generally, a calendered or supercalendered finishing, a paper line mechanical treatment to compress the fibers and smooth the surface. Another paper mill treatment is the clay coating that is the application of a filler, calcium carbonate or titanium oxide, to improve the paper smoothness and reduce porosity. The final treatment is the “pre-metallization” coating that is the paper is varnished with an organic coating, typically a solvent or water base product, to further improve the surface smoothness and reduce the outgassing. The coater dryer can reduce the paper original moisture content but it is possible to do, usually, in a very limited amount, to avoid the negative dry paper effects such as, brittleness and curling. Moreover, in some cases, paper does not pass through thermal drying, since it is coated by means of energy cured processes, such as, uv or eb, with no vehicle release, which have no effect on the original substrate moisture content. The greatest impact factor on metallizing paper is the outgassing behavior during metallization cycle that is, how the material loses humidity when exposed to low pressure conditions of a vacuum coating process. The knowledge of a general humidity release mechanism would be of great help to set the conditions for a paper metallization process, but it is largely dependent from the composition and other factors, including storing and ambient condition, varnishing process etc. As resulting from experimental studies on multiple materials involved in vacuum coating processes, including selective paper cases, the rate of gas release from a material exposed to low pressure, consists of a time dependent phenomenon (approximately represented by a characteristic exponentially decay curve) with the parameters largely depending on the type of materials and conditions. For our present purpose, a few considerations resulting from industrial practice, summarizes the most relevant aspects:

- Paper and paperboard properties depend on the specific type of material; in particular, their outgassing rate is not directly and consistently correlated to any macroscopic parameter, including the original moisture content. There is, however, a practical linkage between the total moisture and the outgassing rate in vacuum.
- The moisture loss during a metallization cycle will vary from 0.2 to a maximum of 1% of paper weight that is 10 to 20% of the original moisture content (maximum 5%)
- Paper and paperboard with higher moisture content (6-7%) can be metallized if the material is double-side coated, thus reducing the moisture diffusing from the more porous backside.
b-Moisture removal techniques

As described in the previous paragraph, surface finishing, clay coating, varnishing and drying help to control the paper moisture content and the related outgassing rate. It represents, however, a significant load for the vacuum pumping system, as soon as a large paper roll starts the metallization process. For a rough appreciation of the quantitative impact, let us consider an “average” paper roll size of one Ton. If well stored in dry condition and properly treated, its moisture content can typically be close to 5% that is 50 Kg. When uncoiled inside the vacuum chamber for the metallization process, it tends to release both the air entrapped inside the roll and some moisture absorbed by the fibrous core… Considering 0.5% humidity loss (10% of the original content), the vacuum system would be loaded with 5 Kg water vapor, corresponding to more than 5 million cubic meters at the deposition pressure. This overwhelming amount of vapor load becomes more manageable if extracted from zones of the chamber with a significant higher pressure than the one required for metallization. In fact, all modern metallizers adopt the “vacuum zoning” design and large capacity vapor condensation.

“Vacuum zoning consists of dividing the vacuum chamber into two or more zones at different pressure, with the process zone maintained at the lowest level and the roll winding, where the largest vapor load is generated, ideally at the maximum pressure. They are separated, by means of low conductance, mechanical gaps and separate pumping system to balance the natural pressure equalization tendency due to the gas diffusion. The substantial advantage of this solution is the possibility of removing the moisture release into the chamber at an higher pressure level, that is hundreds and even thousand times less volume than it were if all the amount of water vapor ought to be extracted only from the process area at the lowest pressure.

The use of “low conductance” zone separation is one of the traditionally most used technics of the vacuum coating process: in many cases, for instance, in reactive sputtering processes, it is instrumental to avoid contamination from the gases used in a nearby chamber or process zone. In paper metallizers, they play a fundamental role in isolating and segregating the parts of the chamber where large amounts of vapors are released and their design is a key to efficiently remove large vapor loads. The picture of fig.1 below illustrate a schematic of the most classic zone separation of a roll-to-roll metallizer. The diagram represents the calculated conductance of a typical seal in vacuum, depending on pressure and gap: it is a quantitative indication of the flow of gas, which transits from the winding to the process zone for any given pressure. While it is apparent the advantage of keeping very tight tolerances to maximize zone isolation, in designing a vacuum coater, special engineering solutions must be implemented to reproduce an efficient sealing in spite of machine constrains, such as, web path geometry, space limitation, provisions of easy cleaning and maintenance due to debris accumulation.
An evolution of the classical two zones metallizer is the three zones design introduced in the so called “multi-chamber” machine as a solution to the high outgassing metallized materials of an high efficiency paper and board metallization line for tobacco packing application. The drawing of Fig.2 represents, schematically, the “multichamber” geometry with the different vacuum zones. Additional and separate winder chambers are sealed from the central two-zones process chamber by means of low conductance gap installed inside the connection tunnel. This “cascade” configuration allows a more efficient moisture removal and a more reliable protection of the coating chamber vacuum level from the paper outgassing, as it is demonstrated by the industrial trials results, which are described below.
2- Trials Results

The graph of Fig 3. represents the vacuum time for a three tons paper roll comparing a three and two zones (dotted lines) configuration in the same chamber geometry. It is apparent how the presence of an additional chamber, creates a lower pressure intermediate zone, thus reducing the gas transfer to the deposition zone. Likewise, during running, the implementation of a three zones design allowed high speed metallization (800 m/min) of an high outgassing paper roll (5% moisture content). A further design improvement of the “vacuum zoning” is the introduction of an “active” low conductance gap. This is an optimization of the separation sealing function and consists of the removal of the vapor flow passing the (“passive”) mechanical gap by means of a small vacuum pump or by cryogenic condensation, thus ideally eliminating any gas transfer from the two nearby zones.
Moisture condensation by means of cryogenic panels is a powerful method to maintaining the low pressure in the chamber especially when the outgassing is severe. Large cryocoil surfaces characterize, in fact, the high output paper metallizers. While for polymer metallizing, the use of cryo-generators dominates the industry, for paper metallization, cryopanels fed with liquid nitrogen are still the choice in the vast majority of cases. From cryogenic tanks, liquid nitrogen vaporizes at approximately -195°C, flowing through the coils inside the vacuum chamber and exits the machine as a cold gas to be vented in the atmosphere. The reason for this solution, usually more expensive than the modern cryopumps, is that the surface cooled by liquid nitrogen can sustain a larger moisture condensing heat. Moreover, nitrogen vaporizing temperature, much lower than commercial cryogenerators, guarantees a prolonged heat exchange efficiency even when the ice build up forms a thick insulating layer on the cold surface.

Vacuum zoning and cryogenic panels, complementing the vacuum pump sets are the most important design elements of a paper metallizer to guarantee an efficient moisture removal. The Fig. 4 below represents the result of a project aimed to metallize large paper rolls with high moisture content: using a multi-chamber geometry metallizer as represented above. The outgassing rate and distribution are calculated from the actual process and production parameters and represent the properties of a specific paper roll, but they are indicative of the system performance in controlling the moisture loss and keeping the vacuum condition.
3 - Optimization and improvement

The trend for implementing projects of paper and paperboard direct metallization characterized by high output and production efficiency will drive further system improvement. Decreasing production cost and optimizing energy efficiency seems a viable objective. In particular, reducing the liquid nitrogen consumption can be done by partially replacing or eliminating this consumable product with a new generation of more powerful cryogenerators. From the energetic point of view, moisture condensation and icing, with the subsequent heating for melting, although very efficient and practical, is, however, more energy-expensive than removing moisture from the gas phase through compression by vacuum pumps (3). Therefore, a different combination of moisture cryogenic condensation (in the low pressure zones) and mechanical pumping from winding zones could optimize energy distribution. A multi-chamber configuration with multiple vacuum zones will represent a further improvement basis.

References:
(1) C.A. Bishop “Moisture control-a vital aspect of paper Metallization” Converting Quaterly, 2013 Quarter 1
(3) F. Rimediotti “Vacuum Metallization of Paper and Outgassing Materials” AIMCAL 2006 Fall Technical Conference