Some aspects of system design for roll-to-roll vacuum coating machines.

Charles A Bishop.
C.A.Bishop Consulting Ltd., Long Meadows, Newby, Middlesbrough, N. Yorks. TS8 0AQ UK

Key Words: roll-to-roll system design; vacuum coating machine design; Holistic process design; Chemometrics

ABSTRACT

How many times have we heard the complaint that a production process was not the turnkey process that was hoped for? Often with the first few months or more of the life of a new production machine spent on re-establishing the process, losing valuable production and creating cashflow problems.

Why is this? Mostly it is because too many things get changed during the scale-up step between laboratory and production machines and with little or no knowledge as to how they will affect the process. Often it is also expected that the production machine will be a faster and hence a more efficient version of the development machines. This means that the production machine is aimed at being a bigger, better & faster machine but the process is, in effect, under developed. A third aspect that often occurs is that the cost of what was initially designed was too high and by compromising on the design a cheaper machine could be built. As the original design never gets built there can never be a comparison to evaluate the merits of these decisions.

In this paper I will highlight some of the common problems & show how making design compromises on a production machine can be an expensive decision.

INTRODUCTION

It is common for the research & development (R & D) work to be carried out on small box coating systems. There are not many facilities that have access to a small roll-to-roll coating system. These box coaters are workhorse vacuum systems that are modified as and when required to suit each new project.

The target of the R & D work will change throughout the project lifetime. Starting with 'proof of principle' experimentation to establish whether this process route is suitable for manufacture. Once this is established there will be a development phase where the main process parameters will be identified and optimised. Often it is during this phase that the process economics are included to revise the target to optimise the process at a particular cost, or less.

Single metal coatings are relatively easy to convert from a development box coater to a roll-to-roll coater. However as the number of layers increases and reactive deposition processes are required for some of the layers the risk of failing to easily transfer the process increases enormously. It is these more complex processes that I wish to concentrate on.

Once the proof of principle has been established and the optimisation stage is started it is not uncommon for an order for a production machine to be placed. As the production process is not optimised it must mean that assumptions are made in order to specify the production machine. Herein lies one of the large areas of risk.

There is the question of how much extrapolation of the process can be safely made to provide a cost effective production machine that is also optimised for manufacturing. At this point it is easier to include all the controls and monitoring everything that can be thought of on the basis of not knowing which it is safe to leave out.

Whatever the situation, it is unlikely that the R & D machine will be reproduced but on a larger scale. Typically there will be the change from a static deposition process to a dynamic roll-to-roll coating process. There is also likely to be the change from the discrete deposition of individual layers to a single pass process. As well as these there are also likely to be the process improvements to increase the productivity such as doubling up sources to increase the deposition rate.

All, or any, of these differences present a risk and the greater the number of differences the greater the risk that the process will not be a turnkey one.

Thus the target can change to become one of minimising risk.

43rd Annual Technical Conference Proceedings (2000) ISSN 0737-5921

REDUCING RISK

Better quality process information.

The question of how the risk in managed is not easy. It is no longer acceptable to wait until the last 'i' is dotted & the last 't' crossed before drawing up a production machine specification. The time to market for any product would be too long. Therefore as we have to place an order before we have all the information needed to be smarter about getting the best quality information from what little development time there is available.

Typically there is a lot of information recorded during development but there is only limited data processing to extract the maximum information that is available. In other cases information that is available is not recorded because it is not thought relevant.

Any process should be looked at holistically. Most processes have input materials, some will have webs that have been pre-treated or pre-coated. These are potential variables every bit as much as the deposition conditions and can affect the outgassing rate, the contaminant gas level, nucleation and growth characteristics and adhesion. Therefore details need to be recorded and ideally checked to determine if they are a critical factor in the process. This type of problem can be analysed using software tools for data analysis such as Chemometrics that will identify the critical process parameters, the interactions and the sensitivity [1].
Chemometrics is different to the 'Design of Experiments' technique in that it does not require specific experiments using high & low values to be made; the data collected from routine processing is sufficient for the analysis. Hence, those who are unconvinced about the time saving from filling in a 'Design of Experiment' matrix may feel happier that the Chemometrics does not reduce the development time on 'unnecessary' experiments.
This is not to say that the Chemometrics approach is foolproof. Where a multilayer coating is deposited as a series of discrete sequential deposition operations in a box coater, possibly even breaking vacuum between some layers, it is not possible to predict the effect of what might happen if some of the depositions have to, for instance, share the same deposition drum in a single pass production process. There is a possibility of interactions that would never be seen unless the box coater could be configured to run all the processes simultaneously. This is usually impractical and it is frequently deemed too expensive to build a pilot production machine to test these out.

A second way of minimising the risk is to develop an energy balance model of the whole process. This will at least suggest the amount of cooling required for the level of power input for any given process. When it then comes to the design the model can be used to verify that where sources are double up that the heat extraction is similarly improved.

Time spent at this stage to reduce the risk is well worth the effort. The time to identify and rectify a problem on a production machine will usually be greater and the costs will be considerable greater, both from lost production and from the cost of rework or retrofitting additional hardware. In some cases the production process may never achieve the envisaged performance with the concomitant reduction in profitability.

Mechanical design.

Most of us will design systems based upon experience. This tends to mean that each new system is very similar to the previous one with some minor modifications aimed at reducing the problems that the last machine had. This approach has some merit in that if every time we started with a blank sheet of paper and ignored all the good things about previous designs we would be repeating an assortment of mistakes.
However there are some aspects of design that I see repeatedly that are detrimental to the process which in many cases cannot be rectified without a complete system rebuild. The most common pair of problems, by far, is that for reactive processes most systems are
a) under-pumped and b) the pumping is not uniform.

Part of the advantage of roll-to-roll coating is that the web moving across the sources gives the opportunity for good coating uniformity in the down-the-web orientation. There is then a struggle to get similar uniformity of coating in the across-the-web orientation. Often there are elaborate shields and source designs made to aid across-the-web uniformity but little is done with respect to the pumping performance and uniformity. Let us now look at these two aspects the process.

Pumping

Consider the deposition of an oxide layer such as titania. The metal sputters at a rate almost twenty times faster than that of the oxide. Hence it might be expected that using a reactive process to sputter at the high metal rate and add the oxygen from the process gas would be the preferred process. Titanium, because its reactivity is very sensitive to the oxygen and the sputtering rate is affected by minute variations in the ratio of oxide to metal present upon the target. If there is insufficient pumping then this shows itself as a hysteresis loop where the target is quick to oxidise but slow to clean back to metal [2]. This does not need to be the case; the hysteresis loop is only evidence that the process zone is insufficiently pumped

[3,4,5]. Once the system exhibits a hysteresis loop it is this that then dominates the design and operation of the process. The development of some of the modern power supplies that allow pulsing was aimed at recovering some of the deposition speed lost because of operating with a system that exhibit a hysteresis loop [6].

Essentially the system needs to pump faster than the growing coating for no hysteresis loop to be produced. More pumping means a higher capital cost as well as a higher process gas throughput that increases the operating costs slightly. This trades off against more precise and faster, stable deposition. Set against systems that are currently built this could look as if the system has too much pumping. Consider the situation of the design and build of a production machine put out to tender. There is always likely to be some nervousness, on the part of the company submitting their design, that if they include sufficient pumping the system cost will look too expensive, which could lead to the loss of the order. It is easier to reduce the pumping to look more typical and to bring the price down to make it more competitive. The process can always be made to work to some extent irrespective of the design, however it will be far from optimised. The use of a more sophisticated power supply and the use of pumping shields [3] will compensate albeit at a reduced deposition rate.

High pumping also has other benefits. The high gas throughput means that the reactive gas partial pressure excess can be minimised. Also the high gas throughput means that the process zone is continuously being swept such that there is less build-up of contaminant gases and particles.

Non-Uniform pumping.

There is a continuing trend of ever increasing coating quality and uniformity. With roll-to-roll coaters having good down-the-web uniformity the focus has always been on improvements on across-the-web uniformity. The advent of linear sources of all types, rectangular magnetron sputtering sources, linear evaporation sources [7], linear ion guns [8] and sweeping e-beam linear sources, have all contributed towards improved coating uniformity. When using reactive processes this is only half the process and if the pumping and reactive gas feed is not as uniform as the deposition source then there can be no expectation of uniform deposition either in thickness or stoichiometry. This is shown schematically in Fig. 1.

I am sure all of us have seen systems where the pumps are hung off the end plate rather than distributed across the width of the system. There can be many reasons for this, such as keeping the system all at one operating level, or having more space on that end plate, or being able to use a more standard vessel design repeatedly are all possibilities.

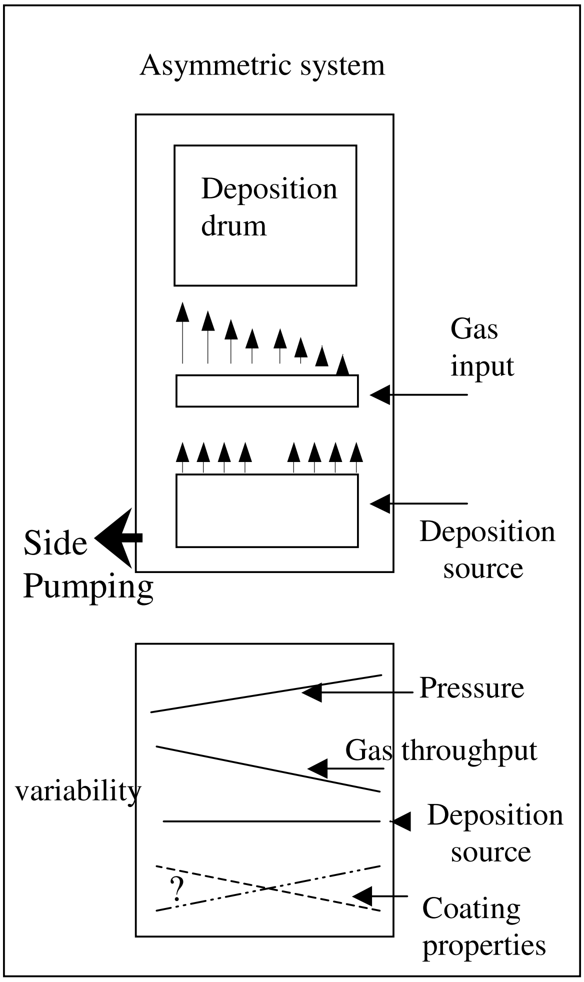

Figure 1. Schematic showing the effect of non-uniform pumping on the resulting deposited film variability.

On systems where some attempt has been made to distribute the pumping across the width either by use of a manifold or by a multiplicity of pumps it tends to be limited to the deposition zone. If there is not similar uniform pumping on all zones then within the vessel will be non-uniformity of conductance between zones. This too will create pressure and throughput differences. Similarly within any one zone there is a tendency to add components without regard to how they might disrupt the reactive deposition process [9]. Included in this would be the use of cryocoils. These are often mounted against

43rd Annual Technical Conference Proceedings (2000) ISSN 0737-5921

vessel walls without any consideration to the effect they might have on the pressure gradients generated across the vessel.
On other systems a skewed distribution of gas input is done as an attempt to balance the reactive gas against the non-uniform pumping. This only a fix and is usually difficult to optimize. Attacking the root cause by providing uniform pumping then enables uniform reactive gas input to be used making the optimization of the process easier, shown schematically in Fig. 2.

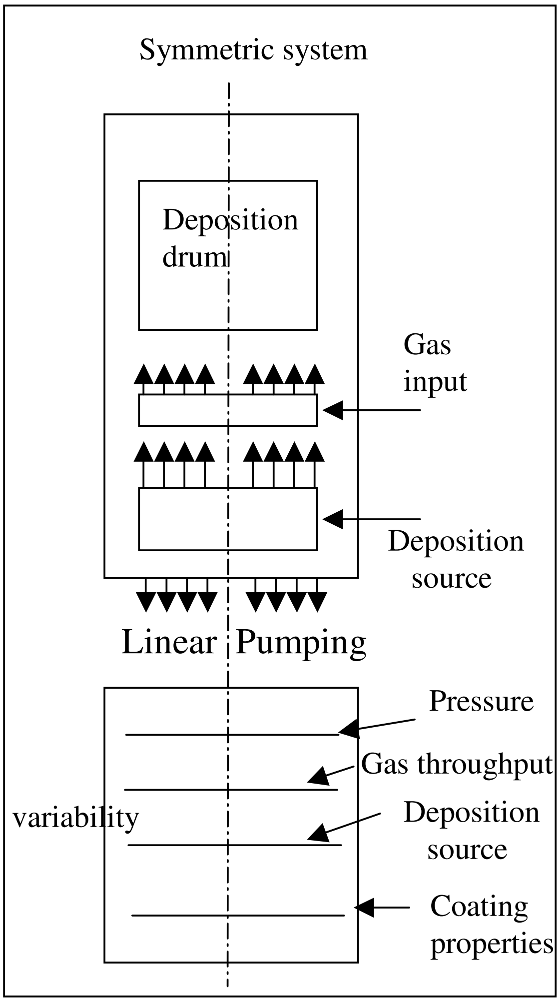

Figure 2. Schematic showing the effect of uniform pumping on the resulting deposited film with reduced variability.

It is worth comment that in 1976 Officine Galileo patented a linear diffusion pump [10]. The idea is simple. If you regard a linear magnetron sputtering cathode as being a circular cathode cut in half with a parallel section placed between the two halves. Then the same principle can be applied to the diffusion pump, as per Fig.3

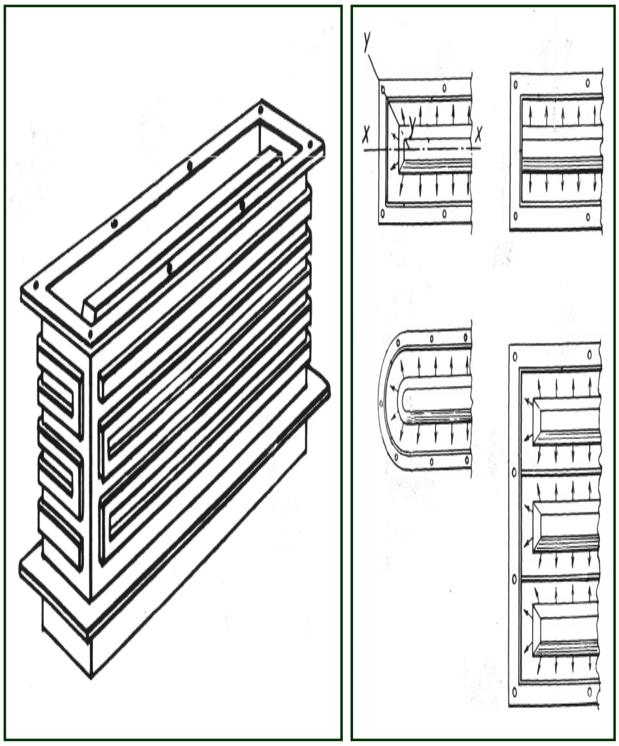

Figure 3. Diagrams taken from Officine Galileo Patent of linear diffusion pump design.

Thus there is no reason why roll-to-roll systems cannot be built with symmetry either side about a centerline down the web.

Oxide deposition is usually the rate limiting step in any multilayer deposition process. If all the layers are deposited in a single pass then all the other processes will be restricted to match that of the slowest. If we take titania as a desired coating. Sputtering titania from the oxide is as much as 20x slower than reactively sputtering from the metal. If we can work from the metal then we can speed up the whole process. Using all the techniques that have been developed such as a pulsed power supply, customized shielding, separated gas inputs, etc. will have already improved the deposition rate to be better than sputtering from an oxidized target. If, however, we eliminate the hysteresis loop we can still make a significant further improvement on the deposition rate.

If we consider the implication of an improvement on costs. Taking as a baseline if we have a roll length of 10,000m and a web speed of either 10m/min or 100m/min the deposition time will be 1000min or 100min respectively. If by using the extra pumping to eliminate the hysteresis loop we get a rate improvement of a factor of 2x the winding speed can be doubled and so the deposition time will be halved. The extra pumping will also mean a reduced pumping time down to the starting base pressure. Thus doubling the deposition rate will not quite give double the production output.

This is very simplistic but it can be seen that for a reactive deposition process, which is invariably the rate limiting step in any multilayer process, any increase in deposition rate must be worthy of consideration. As the pumping, typically, represents only a small fraction of the total machine build costs for a roll-to-roll coating system, doubling or tripling the pumping to speed up the reactive deposition process still likely to represent a worthwhile investment.

CONCLUSIONS.

In designing roll-to-roll deposition systems advantage should be taken to reduce the risks associated with scale-up by taking the following actions.

1. Use Chemometrics data processing tools to maximise the learning from the R & D phase. Thus identifying the critical interactions and where the critical control and monitoring is required.
2. Use an energy balance model as a 'sanity check' to confirm the heating and cooling processes are compatible.
3. Design the production machine with symmetry about a down-the-web centreline. This must include symmetry of pumping, deposition sources, gas inputs and all other system hardware.
4. Use sufficient pumping to eliminate the hysteresis loop in any/all reactive processes.

REFERENCES

1. M.J.McCann & C.A.Bishop, "Chemometrics – A holistic approach to troubleshooting" 42nd SVC Annual Technical Conference Proceedings; p487 (1999).

2. S.Schiller et al., "Advances in high rate sputtering with magnetron-plasmatron processing and instrumentation" Thin Solid Films 64, p455 (1979)

3. A.G.Spencer et al., "Pressure stability in reactive magnetron sputtering" Thin Solid Films 158, p141 (1988)

4. A.G.Spencer et al., "Design and use of a vacuum system for high rate deposition of TiO_2/TiN/TiO_2 solar control films." Solar Energy Materials 18 p87 (1988)

5. A.S.Penfold. "The influence of Pump size on the d.c. reactive sputtering systems", 29th SVC Annual Technical Conference Proceedings; p381 (1986)

6. G.Brauer et al, "New approaches for reactive sputtering of dielectric materials on large scale substrates" J. Non-Crystalline Solids 218 p19 (1997)

7. Evaporation source for vacuum web coating. European Patent EP 652303 (1995)

8. A.Shabalin et al., "Industrial ion sources and their application for DLC coating" 42nd SVC Annual Technical Conference Proceedings; p338 (1999)

9. D.W.Hoffman. "A sputtering wind" J.Vac.Sci.Technol. A.3 (3), p561 (1985)

10. French Patent FR 2310482 (1976)
German Patent DE 2619411 (1976)