Electron Beam Induced Bias for High Speed, High Quality Coating of Ultra Thin Capacitor Web

Dr. Stephan Küper
Leybold Optics GmbH
Siemensstrasse 88
63755 Alzenau
stephan.kueper@leyboldoptics.com

Introduction

In the capacitor film industry there is a continuous strive for metalizers producing with higher coating speed and better film quality. At the same time, the film thickness is continuously decreasing. In order to metalize film with higher coating speeds or with lower peak temperature, a key issue is to improve the cooling of the film during the metallization process. This paper compares the different cooling strategies, the physical forces at work and the effects on the thermal stress to the film. Numerical calculations were performed with the target of showing the differences of both systems and comparing their results semi quantitatively.

Competing Processes: Heating and Cooling

During the actual metallization (while traveling through the coating window) the film is exposed to drastic conditions. The radiated heat from the evaporator boats as well as the heat of metal condensation put a heavy thermal load onto the film.

During the phase of the film traveling though the coating window and in the absence of any cooling, we would expect an almost linear rate of heating with a film temperature $\mathbf{T_{F(t)}}$ at the time **t** of

$$T_{F(t)} = T_{F(t_0)} + \frac{P}{A} * \frac{1}{\rho_F d_F C_F} * (t - t_0)$$

Eq. 1

where **P** is the power of heating, **A** the area, $\mathbf{C_F}$ the specific heat of the film material, $\mathbf{d_F}$ the film thickness, $\boldsymbol{\rho_F}$ the density of the film and $\mathbf{t_0}$ the time at the point of entering the coating window. Without proper cooling, the heating of the film would within milliseconds lead to temperatures causing thermal destruction of the base material.

The competing process is the cooling of the film, which can be described by Newton´s law of cooling. In the absence of any heating this would lead to a temperature $\mathbf{T_{F(t)}}$ at the time **t** described by

$$T_{F(t)} = T_{CD} + (T_{F(t_0)} - T_{CD})\exp^{(-kt)}$$

Eq. 2

Here, $\mathbf{T_{CD}}$ is the temperature of the coating drum, **k** is the heat transfer coefficient. k is composed partly of contact conductance and conductance of a trapped gas layer between film and drum. For simplicity we assume that k is nearly proportional to the pressure between film and coating drum. As will be described later, the pressure (and hence the heat transfer coefficient k) is not constant during the time the film is in contact with the coating drum.

Bias

In order to maximize the cooling to the coating drum the drum temperature is lowered and strategies are employed to improve the contact (or pressure) between film and coating drum. Widely spread is to apply a bias voltage between the metalized layer and the coating drum. This makes use of the electrical force of a plate capacitor created by charge on the film and the coating drum. The pressure (**F/A**), with which the film is pressed against the coating drum is calculated by:

$$\frac{F}{A} = \frac{1}{2}\frac{\varepsilon_0 * \varepsilon_r}{d^2}U^2$$

Eq. 3

where **d** is the film thickness, **U** is the voltage of the plate capacitor and $\boldsymbol{\varepsilon_0}$ and $\boldsymbol{\varepsilon_r}$ are the respective field constants. Using a 2 µm PET film and a voltage of

250 V, a pressure of app. 1.5 bar can be generated between film and coating drum. Because the adhesion force is proportional to the square of the applied voltage the ability to utilize a higher voltage will boost the pressure between film and drum considerably and will thus raise the heat transfer coefficient k accordingly.

Static vs. Mobile Charge

Conventional bias is applied between the metalized layer and the coating drum. It is limited by the break through voltage of the film and the surrounding atmosphere. Since conventional bias is a mobile charge applied to the metalized film, it is generally limited to max. 250 - 300 V due to arcing. During an arc, the complete voltage is discharged to the drum or any other grounded part of the metalizer, leaving the film without any adhesion to the cooled surface.

On the contrary, static charge on the film surface is only limited by the break through voltage of the film and not by arcing. The charge is immobile on the film, and thus discharging (or local arcing) is limited to the immediate microscopic neighborhood of the arc, while the remaining surface stays charged and under high pressure to the coating drum. The break through voltage of a 2 µm PET film is app. 1160 V, which in turn leads to a theoretical pressure of 33 bars between film and drum which can be induced by static charging

The heat transfer coefficient k as a function of time

The time of the film in contact with the coating drum (at 10 m/s app. 100 ms) can be divided in three phases during which the electrical charge of the film (and thus the pressure and also the heat transfer coefficient k) assume different values:

Phase 1: The film is in contact with the coating drum, but not metalized yet

Phase 2: The film is traveling through the coating window, coating takes place

Phase 3: Coating is finished, but the film is still in contact with the drum.

In phase 1 and in case of conventional bias the contact of the film is mainly determined by the tension of the film. Since there is no conductive layer coupled to a bias voltage, no electrical force is at work. The pressure of the film against the drum (and thus k accordingly) is very low.

In case of electron beam bias, a high electrostatic charge is applied to the film immediately following the film touching the coating drum. The static charge is in the kV-range, thus causing a pressure of the film against the coating drum between 10 and 30 bars, which in turn causes a high heat transfer coefficient k.

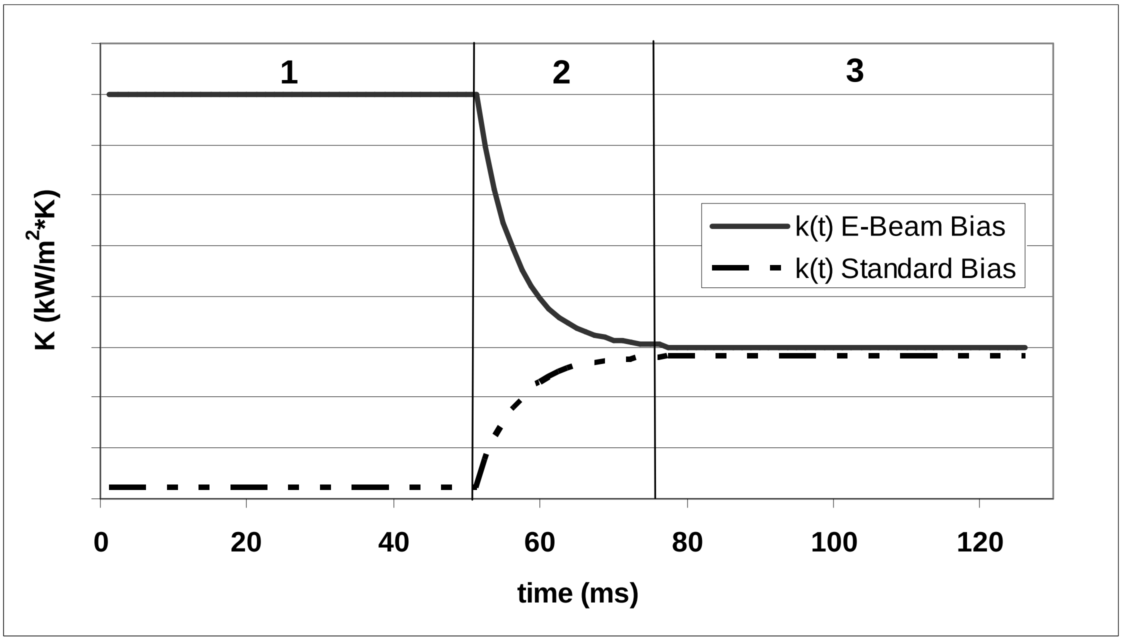

Fig. 1: Heat transfer coefficient k as a function of time.

During phase 2 the film is gradually coated with metal and suffers a large heat load. At this time a conductivity of the metal film to the following guide rollers is built rapidly (in the calculations an exponential rise is assumed). In case of conventional bias this leads to an exponential rise of the pressure of the film to a value determined by the bias voltage applied.

In case of electron beam bias the static charge becomes mobile in the aluminum layer and assumes a state similar to standard bias. As a consequence the pressure between film and coating drum is decreased to values comparable to standard bias (again we assume an exponential decrease).

In Phase 3 the film has left the coating window, but is still in contact with the coating drum. There is no heat load during this phase, and the film temperature follows a classical cooling process. The pressure between film and coating drum is moderate and constant, caused by the applied bias voltage in case of conventional bias and by the remaining charge in case of electron beam bias.

Calculation of film temperature

Taking into account the behaviour of the film pressure against the coating drum and thus of the heat transfer coefficient k, and assuming a constant rate of heating while the film is traveling through the coating window, it is possible to calculate the film temperature as a function of time numerically.
The result shows remarkable differences between electron beam and conventional bias.

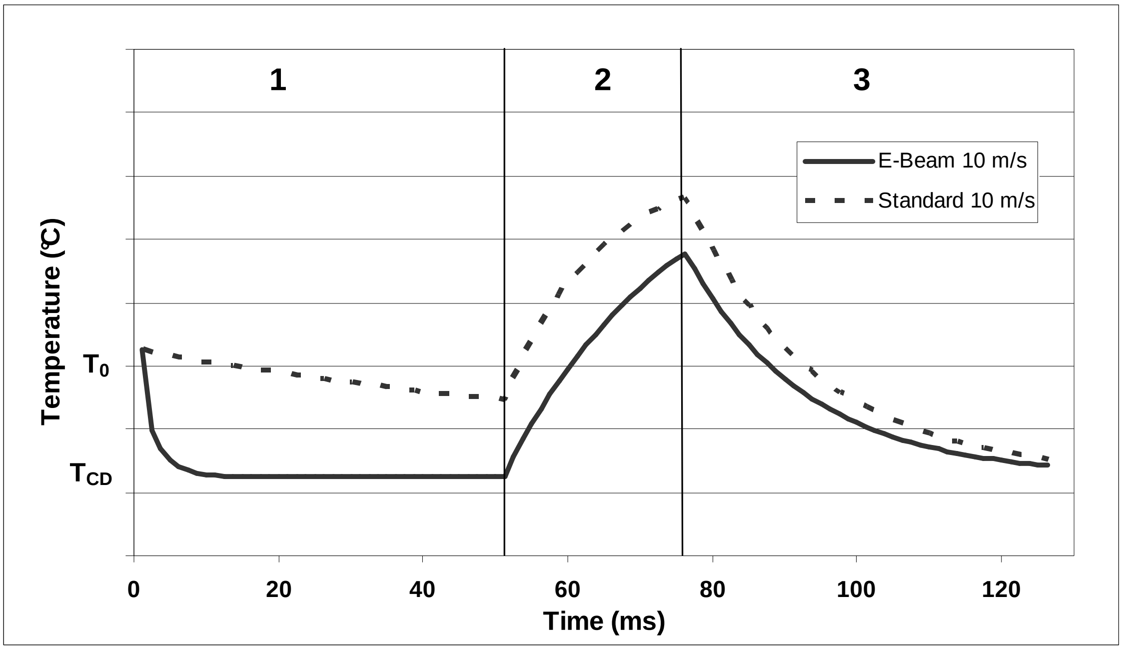

Fig. 2: Film temperature as a function of time during contact with the coating drum

While there is little cooling in phase 1 for conventional bias, electron beam bias has the most intensive cooling during this phase and rapidly lowers the film temperature to the temperature of the cooling drum. At the end of phase 1 there is app. a 30 ℃ difference between both systems. In phase 2 both cases show a rapid increase of temperature. Interestingly, in case of conventional bias, the film suffers a slightly smaller increase of temperature, even though the cooling is worse over most of the time. This is due to the fact that the temperature difference between film and coating drum is always larger than for the electron beam bias case. With electron beam bias the film starts from a lower level of temperature and reaches a lower peak temperature than with conventional bias. During phase 3 both systems follow a classical Newtonian cooling curve leading them to virtually identical temperature when leaving the coating drum. Electron beam bias keeps the film temperature lower than conventional bias for the whole time the film is in contact with the drum. As a consequence, the film coated with electron beam bias will have the better quality, as it had to suffer less thermal stress.

Increase of coating speed

In another calculation the coating speed was increased while maintaining the same thickness of metal to be coated. As a result the metal has to be deposited in a shorter time, which increases the rate of heating and in turn allows less time for cooling. The calculation again shows remarkable differences between the two cooling strategies.

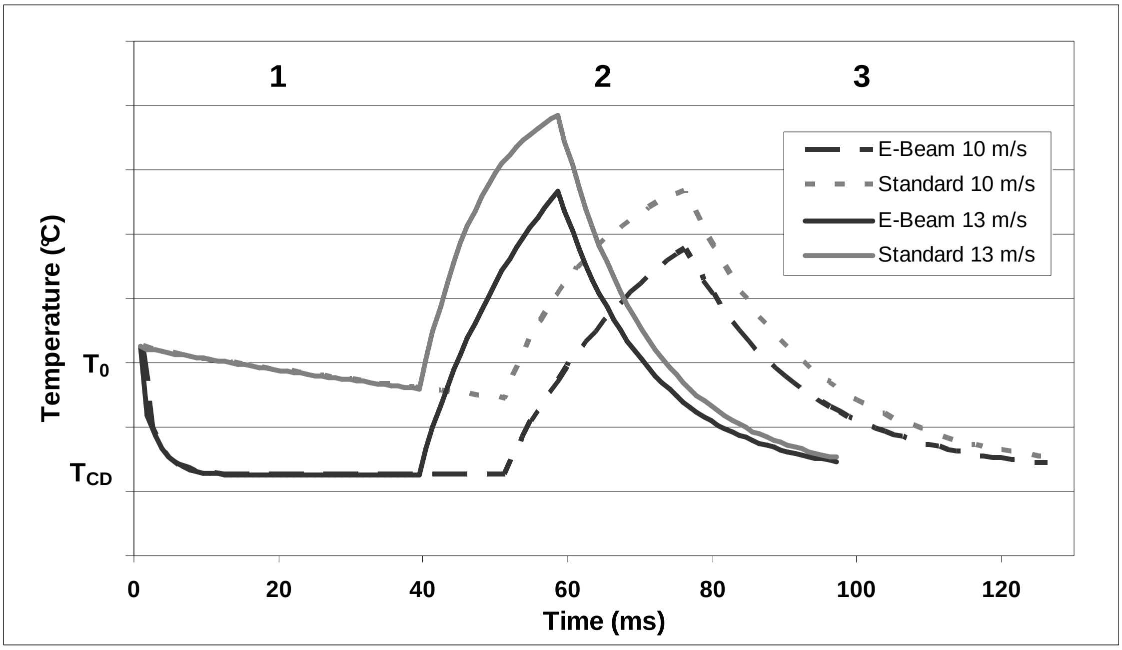

Fig. 3: Film temperature at 10 m/s and 13 m/s coating speed for conventional and electron beam bias.

In the calculation the coating speed was increased from 10 m/s to 13 m/sec. Both cooling systems display an increase in the maximum film temperature, the one for conventional bias is slightly higher than for the electron beam variant.

As a result, the maximum film temperature of the electron beam system at 13 m/s is approximately the same as for the conventional bias at 10 m/s. In the calculation all other variables were kept constant except for the speed and heating rate. The result shows that electron beam bias offers about 30 % advantage in terms of coating speed while maintaining the same film peak temperature, or alternatively allows lower peak temperatures at the same coating speed, resulting in better quality film.

Hardware realization

In order to use electron beam bias several changes have to be performed on the machine compared to the conventional bias system. First of all, a plasma pretreatment becomes mandatory to neutralize any existing static charge on the film before the electron beam charge is applied. This is necessary to provide a defined state before charging the film. At the same time, a surface activation of the film can take place by adding reactive gases to the plasma source. The charge is applied by an electron gun with deflection coil, capable to scan at a rate sufficient to cover the whole surface of the film homogeneously. Finally, after the metallization, the film is discharged at a plasma post treatment station after the coating drum, thus allowing a neutral film to be wound on the rewinder.

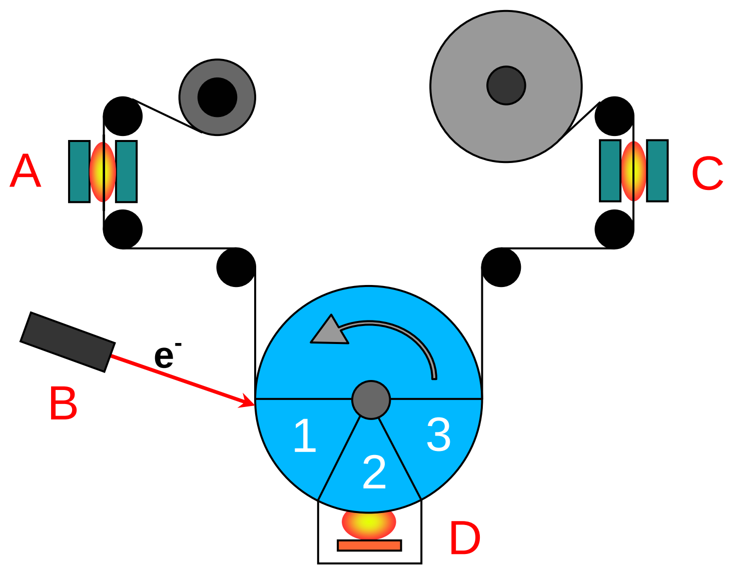

Fig. 4: Schematic of coating system with electron beam bias. A = plasma pretreatment, B = electron beam gun, C = plasma post treatment D = Al-evaporator.

Effect on pinholes

Pinholes induce a contact between metalized film and the coating drum, which is in turn followed by a more or less complete discharge of the bias voltage. For the time until the pinhole has left the coating drum and the bias voltage has recovered, the film looses virtually all pressure to the drum and thus the heat transfer is drastically reduced. As result the film can be thermally damaged, expands and can slip on the drum. This is visible as “jumping” of the film on the drum. The areas of thermal damage are large and the film quality can be reduced repeatedly, thus creating an inhomogeneous film quality. In case of electron beam bias the pinhole can only affect the adhesion after phase 1. As a consequence, the adhesion of the film can also be reduced after coating, but the uncoated film is still pinned to the drum providing initial cooling and adhesion. Therefore, the film cannot slip and the tensions remain intact keeping the film in contact with the drum. This is visible on electron beam systems when watching the film coming off the coating drum completely undisturbed with no jumping or slipping at all. In consequence, electron beam bias minimizes the impact of defects and pinholes on the quality of the film. The affected area per defect is much reduced.

Summary

Electron beam bias allows a higher charge of the film compared to conventional bias due to the immobile, static charge. The pressure of the coating drum (and accordingly the heat transfer coefficient) can be increased by one order of magnitude during the time before coating takes place. In addition, the cooling of electron beam bias is effective for the whole time the film is in contact with the coating drum. Before and after the coating drum the film is discharged by plasma treatment stations. Electron beam bias provides several advantages for the capacitor film metalizer:

- it improves the cooling of the film by increasing its pressure to the drum.
- cooling is effective during the whole time, when the film is in contact with the drum
- this reduces the peak temperature of the film during metallization and provides a better quality film. An increase in break through voltage of up to 100 % has been observed for thin films coated with high conductivity.
- alternatively, the film can be coated at some 30 % higher speeds with a peak temperature comparable to conventional bias

- the effect of defects is reduced due to the continuous adhesion of the film to the drum, which prevents slipping and jumping of the film upon pinhole generation.