Ensuring of high deposition rates by increasing of cooling efficiency

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Summary

Performance investigations of two equipments for the cooling of metal strips are presented in the paper. The so called “brush cooling equipment” enables heat transfer coefficients up to 150 W/m²K. The cooling intensity depends on adapted strip winding force. Partial roughening of the strip has to be considered as unwanted concomitant phenomenon. An optimum for high cooling performance and moderate roughening was detected.

Heat transfer coefficients of up to 600 W/m²K are demonstrated with the “gaseous cooling equipment”. The designed cooling drum ensures high gas pressure up to 100 mbar inside the contact zone of the metal strip and the drum. Partially evacuation prevents high gas pressure in the vacuum process chamber. The realized pressure separation of six orders of magnitude enables the combination of “gaseous cooling equipment” with high-rate sputtering or electron beam evaporation.

The demonstrated heat transfer coefficients describe a distinctive performance increase compared to known state of the art. Extensions concerning deposition rate or deposition of thick layers onto thin metal foils get feasible. In future should be checked whether the new developed equipments can be adapted for the cooling of plastic films as well.

1. Introduction

Vacuum coating processes are well established in many business fields. The aim from an economical point of view is to accomplish the deposition with high rates. Since deposition costs decrease approximately proportional to the square root of the rate, high-rate deposition processes are relevant at any time. Electron beam evaporation as a physical vapor deposition (PVD) technology offers the highest coating rates at a broad range of materials. By using axial beam guns the deposition rates are typically in the range between 0.1 and 2 µm/s. Thereof it can be estimated that the heat input to the substrate mounts up to a few watts per square centimeters caused only by the heat of condensation. Additional heat input from backscattered electrons and radiation heat from the evaporation crucible has to be added to the overall heat input. Depending on the material type, substrate thickness and layer thickness, which is proportional to the coating time, unwanted substrate overheating can occur. The highest acceptable temperature can be limited by the layer material or by the substrate itself.

Basically the possibilities for cooling metal substrates under vacuum conditions are limited. Basic heat emission processes like heat conduction, convection and radiation allow heat fluxes only below 1 W/cm² typically in vacuum at medium temperatures. Such heat emission is low compared to the
heat input and not sufficient for metal substrate cooling. Solid-solid heat contact under vacuum conditions is also limited because of the typical roughness of surfaces, which affects the total heat transfer.

The realization of polymer film cooling systems was essential for film coating processes, since polymer films often do not allow temperatures above 200°C. Polymer films cooling drums were installed in coating plants, as the mechanical properties of polymer films allow close contact with the drum. In addition, the increase in temperature during deposition processes causes the evaporation of water from the films and generates an increased pressure in the gap between foil and drum. Under these conditions – small gap, increased gas pressure – heat transfer coefficients (HTC) up to 500 W/m²K are achievable [1], [2].

However, when it comes to the cooling of metal strips and foils, no water is evaporated and gas pressure is negligible resulting in a much lower heat transfer coefficient. HTCs only up to 50 W/m²K could be verified on common cooling drums [3]. A couple of inventions have been published to overcome this deficiency [4], [5], [6]. It has been evaluated that these suggestions do not reach the needed cooling efficiency in order to be installed during high-rate electron beam evaporation. A promising suggestion was introduced by Yadin [7]. He reported HTC up to 120 W/m²K by using a gas supporting system inside a cooling drum.

In the present work two new methods for metal strip cooling in vacuum and their basic characterization will be presented.

2. Cooling Equipments and Experimental Methods

Brush Cooling Equipment

The basic idea for designing the so called “brush cooling equipment” [8] is to increase the number of contact points between cooling body and substrate to be cooled. The bristles of a brush are flexible and are able to adjust to the microscopic surface of its counterpart. The increased number of contacts provides the opportunity for a higher heat transfer coefficient compared to unmodified solid body contact under vacuum conditions.

A design model for brush cooling equipment is shown in Fig. 1. The cooling body was manufactured from steel and can be cooled by flowing liquid. The surface of the body has a contour according to the running strip and is equipped with metal bristles. The equipped area has a length of 300 mm and a width of 120 mm according to the strip width.

Fig. 1  Brush cooling equipment
Gaseous Cooling Equipment

The basic idea for designing the so-called “gaseous cooling equipment” is to realize a high gas pressure $p_a$ in the contact region between the cooling drum and the metal strip to be cooled and to minimize the gas flow into the vacuum chamber simultaneously [9]. The principle is demonstrated in Fig. 2. Gas is carried with a certain pressure $p_c$ to a central chamber (1) inside the cooling drum (2). The gas pressure $p_c$ is measured by a pressure control unit located outside the whole vacuum chamber. The drum is perforated and gas diffuses into the gap between the drum and the strip (3) in the central contact region. This region can be surrounded by separate chambers (4 and 5) which are pumped (6). Therefore gas can be partially evacuated and the amount of gas which is entering the process chamber (7) is reduced. Cooling liquid is fed into the drum body and removes the transferred heat from the equipment (not shown in Fig. 2). Fig. 3 illustrates the mounted gaseous cooling equipment inside the vacuum coating pilot plant MAXI at Fraunhofer FEP [10], [11]. The cooling drum has a diameter of 800 mm and a width of 260 mm. The contact zone with the metal strip has a length of about 270 mm.

Fig. 2  Scheme of gaseous cooling equipment

Fig. 3  Gaseous cooling equipment installed in the metal strip coating plant MAXI
Experiments and Analysis

For all experiments steel strips with a thickness of 0.1 mm were used. The temperature $T$ of the strip passing the cooling equipment is described by equation (1) and its solution for time dependence in equation (2).

$$\rho cd \dot{T} = -\alpha (T - T_C) + q_H$$  \hspace{1cm} (1)

$$T(t) = T_C + (T_0 - T_C) \cdot \exp\left(-\frac{\alpha t}{\rho cd}\right) + \left(\frac{q_H}{\alpha}\right) \cdot \left(1 - \exp\left(-\frac{\alpha t}{\rho cd}\right)\right)$$  \hspace{1cm} (2)

with $\rho$, $c$, $d$, $T$ = density, specific heat capacity, thickness and temperature of the strip, $\alpha$ = heat transfer coefficient (HTC), $T_C$ = base temperature of the cooling drum, $T_0$ = initial temperature of the strip entering the cooling zone and $q_H$ = heat flux density into strip of the radiation heater below the cooling drum.

Different experimental setups were realized. First, the cooling of preheated moving strips was tested. The preheating was realized by an electron beam gun in a pre-chamber (see Fig. 4).

![Fig. 4 Scheme of metal strip coating plant MAXI with components for strip cooling experiments](image)

Strip temperatures are measured with pyrometers before and after the cooling equipment. Pyrometers for measuring the temperatures $T_1$ and $T_2$ were located 1290 and 675 mm respectively in front of the cooling equipment. The pyrometer for measuring $T_3$ was located 1170 mm after the cooling equipment. Temperature changes between the measurement positions of the pyrometers and onset as well as the end of the cooling zone are considered in the analysis. The temperature change of the moving strip was quantified in several experiments. The HTC can be calculated from the simplified equation (2) by neglecting heat flux density $q_H$.

Secondly, the temperature of the strip passing the cooling drum was measured with an array of mounted thermocouples (not illustrated in Fig. 4). The HTC was calculated by an interpolation of the temperature profile according to equation (2). This second setup was used for parameter conditions achieving high HTC values. In this case the strip temperature is reduced to the base drum temperature within distances shorter than the total length of the contact zone.

At high HTC values of the cooling equipment an additional heat input from a radiation heater (Fig. 4) increases the strip temperature and keeps it measureable above the detection limit of the used pyrometer behind the cooling equipment. This setup with an additional heat input is a good model for real deposition, etching or any thermal treatment processes. The quantitative estimation of HTC is influenced by the uncertainty of the heat flux density. The heat flux density at metal strip was determined in pretests by strip warming without cooling. Alternatively it can be quantified from heat...
input flowing through cooling equipment into cooling liquid. This alternative type of analysis is entitled “type B” in later result discussion. Equation (2) could not be solved analytically for heat transfer coefficient ($\alpha$) at occurrence of an additional heat input. Therefore HTC is estimated numerically from equation (2) according to the measured temperatures and the additional heat input (expressed by heat flux density $q_H$).

3. Results and Discussion

3.1 Brush Cooling Equipment

In the experiments the dependency of HTC from the winding force was identified. The collected data are summarized in Fig. 5. The winding force is given dimensionless. It is a general machine parameter and not known in detail at the precise position of the cooling equipment. At low forces an increase of HTC with increasing winding force was detected. At the level above 100 W/m²K HTC values increase only lowly with increasing winding force.

In Fig. 5 the HTC values that were obtained with the second analysis method “B” as explained in section 2 are illustrated with a dashed line. In analysis method “B” the amount of heat removed from the strip was estimated from the heat input into the cooling liquid. HTC values from standard analysis (type “A”) and type “B” correspond well at low winding forces. At high winding forces “B”- results mount higher. It is assumed that the sliding of the strip over the brush causes friction and heat is produced. This amount of heat shifts the “B”-analyzed HTC to higher values. The standard analysis (type “A”) shifts in opposite the HTC to lower estimated data according to the increased strip temperature. In summary, friction and connected heat production has to be considered in detailed evaluations. The quantitative exact HTC values should lie in between the results according the two analyses “A” and “B”. So it is postulated that HTC of up to 150 W/m²K are representative for the brush cooling equipment.

![Fig. 5 Dependency of heat transfer coefficient from winding force (A and B represent different methods for HTC analysis)](image-url)

The mechanical contact of the strip with the brush during winding could cause some mechanical surface modifications of the steel strip. The influence of the winding force onto the roughness $R_s$ is demonstrated in Fig. 6. The initial roughness value $R_s$ of the steel strip is 50 nm. The roughness increases marginally at moderate winding forces. At a certain force level the slope is changing.
essentially and the measured roughness $R_a$ increases to above 200 nm.
From HTC and roughening measurements the following can be concluded. At low winding forces only
a small number of bristles are in close contact to the strip. With increasing force the number of local
contacts and HTC values increase. The Roughening of the strip shows only a weak dependence at low
winding forces. In this range the force is too low to scratch the steel strip. At selected winding force a
certain amount of bristles are in mechanical contact and HTC level above 100 W/m$^2$K is reached.
Further an increase of winding force yields to stronger roughening of the strip. HTCs increase only
moderately with increasing force in this range. This demonstrates that realization of a large number
of solid-solid contacts is the primary factor for maximizing heat transfer.
In our coating plant a relative winding force of 45 % gives a preliminary optimum between achievable
HTC and roughening of strip. Higher winding forces increase HTC only slightly but increase
roughening disproportionately.

![Graph showing dependency of strip roughening from winding force](image)

**Fig. 6** Dependency of strip roughening from winding force

The mechanical contact also causes wear at the brush side. The length of bristles was measured
before and after usage. The wear rate is below 9 µm per kilometer strip winding over the brush
cooling equipment. This is an average value for many experiments with different winding forces
during investigations. The wear rate for bristles is certainly reduced by constant applying of a
moderate winding force.

For every application it is necessary to decide if roughening of the strip and connected abrasion is
tolerable on the strip rear side and inside the strip coil. Because of this side effect the suggested
“brush cooling equipment” is not acceptable for several applications. But for a number of coating
techniques heat transfer coefficients with magnitude of 150 W/m$^2$K offer new opportunities to
overcome up to date thermal limitations.

### 3.2 Gaseous Cooling Equipment

The relation between the gas pressure $p_c$ in the central region of the gaseous cooling equipment and
the pressure in the recipient are shown for a moving strip in Fig. 7. For gas inlets up to 100 mbar no
pressure increase is observed in the process chamber. This demonstrates the tightness of the whole
equipment. However, for a higher inlet above 100 mbar the pressure in the vessel increases
distinctly. It is assumed that at high pressure the strip is lifted off and the gas leaks under the strip.
Fig. 7  Relation of pressure $p_c$ supporting the contact zone of cooling drum and pressure in recipient

For the gaseous cooling equipment the strip is cooled effectively within a few seconds. Therefore an estimation of the HTC was not possible by measuring only the temperature after complete passing of the cooling drum via pyrometers because of their detection limit. The strip temperature is almost reduced to base temperature of the cooling liquid upon passing the contact zone. A direct correlation of cooling down time of the strip respectively strip movement upon the drum and the resulting temperature is needed for analyzing HTC values. Finer temperature resolution in the contact zone was measured with an array of sliding thermocouples (not illustrated in Fig. 4). One example for a measured temperature profile is illustrated in Fig. 8. Within a distance of 100 mm the strip temperature is reduced from 100 to 40°C. According to the used strip speed of 100 mm/s in this experiment the cooling down time amounts only 1 sec. The interpolation according to equation (2) results in a HTC of 470 W/m$^2$K.

Fig. 8  Cooling down of running strip on cooling drum

HTC measurements were done at different pressure values $p_c$. The results for pressure variations are summarized in Fig. 9. The HTCs increase with pressure starting from 30 W/m$^2$K up to 600 W/m$^2$K. The pressure dependence of HTC corresponds to the pressure dependence of heat conductivity of gas in small gaps. The agreement of calculation with experimental data in Fig. 9 could only be achieved by using decided lower pressure values in the simulation. This is an indication that in the equipment a pressure difference between the gas inlet where pressure is measured and the contact zone of the
strip and the cooling drum occurs. Nevertheless the estimated HTC values are distinctly higher compared to an unmodified cooling drum.

![Heat transfer coefficients depending on the impressed pressure pC for contact zone of strip with cooling drum](image)

With the developed “gaseous cooling equipment” a large performance increase was realized. It opens new opportunities in the field of high-rate vacuum coating of metal strips. This should be illustrated with the following example. Assuming a heat flux density of 10 W/cm² and a heat transfer coefficient of 500 W/m²K a maximum calculated strip overheating of 200 K to reference temperature of cooling device will occur. Such a temperature is compatible for the handling of metal strips. The assumed heat flux density is an extreme high value. So the large potential of realized strip cooling methods under vacuum conditions can be illustrated. The example demonstrates that the developed “gaseous cooling equipment” is able to manage most demands of metal strip thermal management for high-rate PVD. This includes keeping the strip temperature constant or reducing it during ongoing deposition.

4. Conclusions

Two equipments for cooling of metal strips in vacuum were investigated. They differ in their technical efforts and achievable cooling effects. The measured heat transfer coefficients (HTC) of up to 600 W/m²K demonstrate a distinct increase in contrast to so far realized values for metal strip cooling. High HTCs offer new options for realizing depositions with very high-rates respectively high heat inputs and also for future depositions of thin strips with very thick layers. The cooling equipments provide a thermal management instantaneous during strip coating so that the strip temperature increase remains moderately and strip deformations are avoided.

The adaptation of the “brush equipment” will become especially interesting for the cooling of plastic films if the relative movement of the brush and the film will be avoided. Therefore a drum can be equipped with a brush cover.

The actual demonstrated HTC for the developed “gaseous cooling equipment” of about 500 W/m²K could prevent the temperature determined damaging of plastic films for usual coating processes. Because of the flatness of plastic films and the connected thin gap dimensions to the cooling drum they offer a large potential to realize high HTCs at medium working gas pressures.
As an outlook should be notified that the cooling equipment will still be optimized and the heat transfer coefficient will be further increased in our future developments.

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**Literature**


