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Temperature control of metal strip during high-rate vacuum coating

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ABSTRACT

Electron beam evaporation with deposition rates of hundreds of nanometer per second is predestined to fit large throughput. In a few cases, high-rate vacuum depositions demand effective cooling of the substrate to exploit their potential, otherwise substrate or layer temperature represents limiting factors. Therefore a new kind of cooling equipment for vacuum coating of metal strips was developed. As a result, the practical realized heat transfer coefficient (HTC) was increased from 50 W/m^2 K for common cooling drums up to 1000 W/m^2 K. The demonstrated heat transfer coefficients describe a distinctive performance increase compared to known state of the art. For the first time, a 10 μm aluminum high-rate deposition was realized without any alloying with steel strip. Extensions concerning the deposition rate or deposition of thick layers onto thin metal foils become feasible.

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 cost 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 for a broad range of materials. By using axial beam guns the deposition rates are feasible in the range between 100 nm/s and 10 μm/s [1]. It can be estimated from these rates 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 source have 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, undesired substrate overheating can occur. The highest acceptable temperature can be limited by the layer material or by the substrate itself. A high-rate aluminum deposition process (deposition rate of 400 nm/s and heat flux density of 4 W/cm^2 as example) leads to a temperature increase of 380 K for a 0.1 mm thick steel strip within 3.5 s which corresponds to an aluminum layer thickness of 1.4 μm. At such a temperature, steel strip begins to deform plastically and unwanted alloying of aluminum with iron occurs. This example will be extended graphically as a reference curve for comparison with new obtained data later again. In general it can be noted that for relatively high heat flux densities and thick layers or a combination of both, the deposition process is limited.

The possibilities for cooling of metal substrates under vacuum conditions are limited. Basic heat emission processes as heat conduction, convection and radiation allow heat fluxes only well below 1 W/cm^2 at medium temperatures. Such a heat emission is low compared to the heat input and not sufficient during high-rate coating. Solid–solid heat contact under vacuum conditions is also limited because of the typical roughness of surfaces, which affects the total heat transfer. The cooling of polymer films is essential for film coating processes, since polymer substrates often do not allow temperatures above 200 °C. Therefore cooling drums for polymer films are usually installed in coating plants, because 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 absorbed water from the polymer films and generates an increased pressure in the gap between foil and drum. Under these conditions — small gap and increased gas pressure — heat transfer coefficients (HTC) up to 500 W/m^2 K are achievable [2,3]. This amount of cooling effect is difficult to reuse in a multi stage process or to reproduce in practice steadily. However, at the cooling of metal strips and metal foils the evaporation of water from substrate and the rising gas pressure in the gap are negligible resulting in a much lower heat transfer coefficient. HTCs could be verified only up to 50 W/m^2 K on common cooling drums [4].

A couple of inventions have been published to overcome this deficiency [5–7]. It has been evaluated that these suggestions do not reach the needed cooling efficiency for the high-rate electron beam evaporation. A promising suggestion was introduced by Yadin [8]. He reported HTC up to 120 W/m^2 K by using a gas supporting system inside a cooling drum. In [9] a different technical solution for an enhanced mechanical contact is demonstrated, which offers HTC up to 150 W/m^2 K.

In the present work, a method and technical equipment for metal strip cooling in vacuum and its basic characterization will be presented

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and HTC up to 1000 W/m^2 K are shown during high-rate aluminum deposition.

2. Equipment and experimental methods

The basic idea for designing the so called “gas gap cooling equipment” is to realize a high gas pressure 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 [10]. The principle is demonstrated in the drawing in Fig. 1.

Argon is provided with a certain pressure to a static central chamber (1) inside the rotating cooling drum (2). The gas pressure is fixed by a pressure control unit located outside the whole vacuum chamber. The drum shell is perforated and gas flows 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. 1). The practical realized 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.

The temperature T of the steel strip passing the cooling equipment fulfills Eq. (1) and its corresponding solution for time dependence in Eq. (2).

$$\rho c d T = -\alpha(T - T_C) + \dot{q} \qquad (1)$$

$$T(t) = T_C + (T_0 - T_C) \cdot exp(-\alpha t/\rho c d) + (\dot{q}\ /\alpha) \cdot (1 - exp(-\alpha t/\rho c d)) \qquad (2)$$

with $\rho, c, d, T =$ density, specific heat capacity, thickness (0.1 mm in all experiments) 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 $\dot{q} =$ heat flux density into strip.

Different experimental setups for the estimation of the cooling efficiency were realized. Firstly, the cooling of preheated moving strips was tested. The preheating was realized by an electron beam gun. The temperature of the strip passing the cooling drum was measured with an array of mounted sliding thermocouples in setup 1. The HTC was calculated by an interpolation of the temperature profile according to the simplified Eq. (2) by neglecting the heat flux density $\dot{q}$.

Secondly, the heat transfer between the steel strip and the drum was measured by applying an additional radiation heater 150 mm below the central contact region of strip and cooling drum. This setup 2 with an additional heat input is a good model for real deposition, as well pre- and post-treatment processes. The heat flux density at a pure metal strip was determined in pretests by strip warming without the cooling equipment. Alternatively, it can be quantified from heat input flowing through cooling equipment into cooling liquid inside the drum. The strip temperature in front of and beyond the cooling drum was measured again with sliding thermocouples and pyrometers. The temperatures at the measuring positions were corrected to the beginning and end of contact zone. Eq. (2) could not be solved analytically for the heat transfer coefficient (α) at the occurrence of an additional heat input. Therefore, the HTC is estimated numerically from Eq. (2) according to the measured temperatures and the additional heat input (expressed by the heat flux density $\dot{q}$).

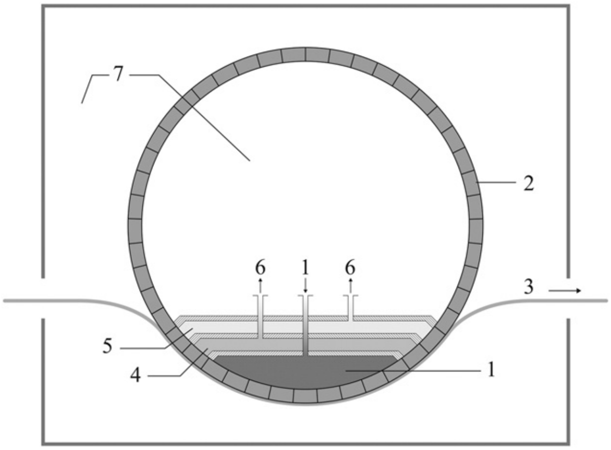

Fig. 1. Scheme of gas gap cooling equipment (see text for the description of the numbers).

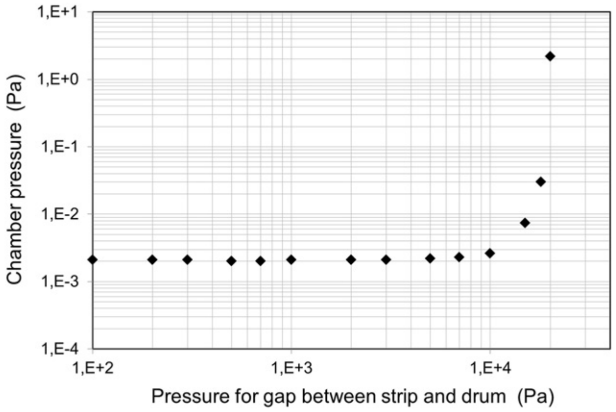

Fig. 2. Relation of gas pressure for the gap in the contact zone of the cooling drum and pressure in recipient.

In setup 3 the aluminum depositions by electron beam evaporation were realized, in which the steel strip was moved over the cooling drum. The drum was placed in a distance of 300 mm above a water cooled crucible. The electron beam source was operated with acceleration voltage of 40 kV and beam power up to 160 kW. The estimations of the heat flux density and temperatures and the analysis of the HTC were the same as described above.

3. Results and discussion

The relation between the gas pressure in the central region of the gaseous cooling equipment and the pressure in the recipient are shown for a moving strip in Fig. 2. For gas inlets up to 10 kPa no pressure

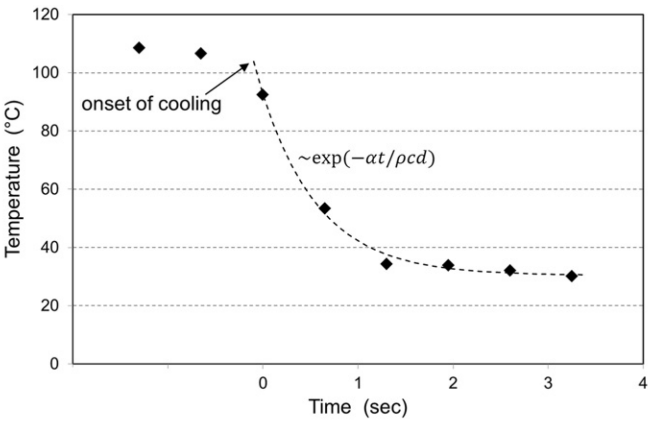

Fig. 3. Cooling down of moving 0.1 mm steel strip passing the gas gap cooling equipment.