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Original Research Article

Innovative technical solutions for evaporation of multilayer coatings by EB-PVD method

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ABSTRACT

The article presents problems concerning the use of the EB-PVD method (*electron beam physical vapour deposition*) for the evaporation of materials with different thermal properties including different coefficients of thermal conductivity, different melting points and evaporation temperatures. The evaporation process of material by electron beam was described and also the technical solutions for crucibles and devices that enable the production of composite coatings by EB-PVD were presented. The authors presented an innovative design of a multi-position modular crucible that provides different cooling intensity for materials with different thermal properties. This enables the efficient evaporation of various materials in the same technological process, which is essential for composing compound coatings, i.e. multi-component, composite and multi-layer.

1. Introduction

The development of technological evaluations in the field of surface engineering in particular the development of hybrid technologies [1,2], which consist in combining different methods of surface treatment in one technological process has created new possibilities in the production of compound coatings materials. A special role in this area plays the evaporation of materials by electron beam – EBPVD (*electron beam physical vapour deposition*) [3]. The fundamental phenomenon that occurs in the EB-PVD method is bringing the material placed in the crucible to evaporation state by high-energy electron beam bombardment. Focusing the electron beam on a small area of material enables obtaining high temperatures in the bombardment area and as a result the evaporation of the infusible materials including metals (W, Mo) and ceramic materials (Al_2O_3). It is these capabilities that make the EB-PVD method being increasingly used in hybrid surface treatment processes for the production of functional coatings [4–5] composed on the basis of ceramic materials such as thermal barrier coatings, friction wear resistant coatings and erosion wear resistant coatings.

2. Evaporation of materials by electron beam

The phenomena resulting from the interaction of beam-focused electrons with the solid are very complex. Their nature and intensity is strongly dependent both on the beam parameters, i.e. the electron energy and their incidence angle and the parameters of the solid including the atomic number of the component elements and density. The temperature distribution in the electron beam incident area was shown schematically in Fig. 1.

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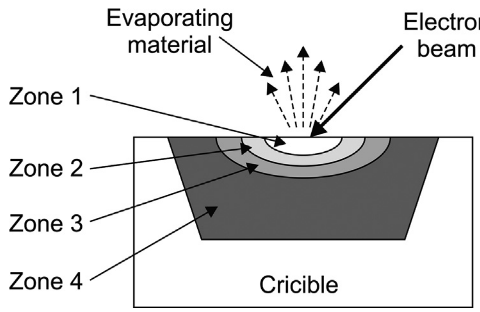

Fig. 1 – Schematic temperature distribution in the electron beam incident area.

The highest temperature prevails in the zone where the electrons directly penetrate the material (zone 1). In this zone the most intense evaporation occurs and the sublimation of the bombarded material is possible. Directly behind zone l there is an overheated material zone (zone 2) in which the temperature exceeds the material evaporation temperature but the evaporation intensity is much lower than in zone 1 and decreases along with the distance from the beam incident area. Zone 2 goes smoothly into zone 3, so-called liquid zone in which the temperature of the bombarded material is still higher than melting point but lower than evaporation temperature. Between the liquid zone and the wall of the crucible there is a zone of intense cooling (zone 4) in which the temperature is lower than melting point.

3. Influence of materials properties on the course of electron beam evaporation process

The size of interaction zones of each electron beam with the bombarded material depends on both the beam energy and the properties of the bombarded material including density, specific heat, phase transition temperature and thermal conductivity. The penetration depth of the electrons into the material increases along with the acceleration voltage increase and decreases along with the bombarded material density increase [6]. For the materials with high thermal conductivity, such as Al, Cu a special crucible providing low-intensity heat dissipation is needed. If the water-cooled copper crucible to evaporate the materials is used the additional thermal insulation to separate the crucible walls from the heated charge is required. Fig. 2a and b shows the Al and Cu charges evaporated from a water-cooled copper crucible with ceramic insulation. Materials with low thermal conductivity and also high melting and boiling point, such as Ti, Gd, Ni, $A1_2O_3$ can be successfully evaporated in water-cooled copper crucibles. The heat transfer intensity through the walls of the crucible is low enough to allow carrying out long-term evaporation processes by adjusting the power of the beam without the threat of overheating the walls of the crucible. Sample charges of Ti and $A1_2O_3$ after the evaporation process conducted directly in water-cooled copper crucible are shown in Fig. 2c and d.

Refractory materials with high melting and boiling point, high thermal conductivity and high density such as W, Mo require low-intensity heat dissipation during the evaporation process and high-power electron beam. Materials such as Cr, Mg are special type materials that undergo sublimation during the electron beam bombardment process. To obtain high-efficient evaporation process for both groups of materials mentioned above a special treatment technology involving the movement of the beam relative to the evaporated material is required. Sample charges of tungsten as refractory material and Cr as sublimating material after the evaporation process conducted directly in water-cooled copper crucible are shown in Fig. 2e and f.

After the analysis of the electron beam evaporation processes of various materials the evaporated materials can be divided into four different groups, depending on their properties i.e. high thermal conductivity materials, low thermal conductivity materials, refractory materials and sublimating materials. Also requirements for the crucibles properties, which provide the most appropriate cooling dynamics for the materials from the given group can be indicated. As far as materials with high coefficient of thermal conductivity are concerned, in order to ensure the high-duty electron beam evaporation process, it is advisable to use crucibles with low thermal conductivity. However, as far as materials with low coefficient of thermal conductivity are concerned, it is desirable to ensure rapid heat dissipation from the heated charge through the walls of the crucible to prevent them from overheating. Evaporation of infusible materials, in turn, requires the use of crucibles providing both low-intensity cooling and high heat resistance. Evaporation of sublimating materials requires the use of the crucible design allowing for the continuous change of electron beam operation area, e.g. by introduction of charge movement or electron beam movement.

4. Technical solutions for the production of complex coatings by EB-PVD

The possibility of complex coating deposition, including composite and multi-layer coatings is determined by the construction of EB-PVD devices, which have to allow for the evaporation of different materials in one technological process. In practice, there are two different design solutions used for this purpose. The first one is the device equipped with larger number of electron guns and larger number of crucibles [7] (Fig. 3a) and the second one is the device with a single electron gun equipped with specially designed multi-position crucible [8] (Fig. 3b). The main advantage of the devices equipped with several electron guns is the capability of controlling individual parameters of the electron beam for each evaporated material. Various materials are evaporated from separate crucibles with individual cooling systems. The disadvantage of this solution, in turn, is very high cost of equipment and construction difficulties resulting from the necessity of eliminating the interaction of deflection systems of each electron gun and also the necessity of creating a sophisticated system to control the operation of each electron gun and X-ray radiation security system.

To eliminate the necessity of using several electron guns a multi-crucible was designed. There are two variants of the