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Mechanical strength and wear resistance of protective coatings applied by fluidized bed (FB)

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Abstract

This study deals with the interrelation between the thermo-rheological behaviour of an epoxy-based powder coating system and its mechanical strength and wear endurance.

Matte-finish protective polymeric films deposited by electrostatic fluidized bed (EFB) and conventional hot dipping fluidized bed (CHDFB) on metal substrates were examined. First, the analysis of thermo-rheological behaviour of the epoxy-based powder coating system was detailed. Secondly, the adhesion strength and wear endurance of polymeric films was related to the thermo-rheological behaviour of the starting material formulation. Finally, based on the experimental data, generalized scratch and wear map, in which the overall mechanical performance of the matte-finish polymeric films at different curing levels is reported, was usefully provided.

The experimental findings lead to further advances in the understanding of the mechanisms involved in the establishment of the overall mechanical performances of fluidized bed (FB) deposited polymeric films. They also provide important indications for the settings of curing parameters or preheating temperatures in FB coating processes as well as for the development of new powder coating formulations.

Keywords: Powder coatings; Film morphology; Scratch adhesion; Wear endurance

1. Introduction

1.1. Premise

Powder coatings can be generated from a pulverized solid formulation (i.e., thermosetting powders) that is, mostly, electrostatically deposited on a substrate, usually a metal. Upon baking, the thermosetting powders fuse to a continuous film, and they are said to be crosslinked [1].

Powder coatings possess advantages over conventional coatings in that no polluting solvent loss occurs on application, and owing to the use of electrostatic [2,3] or hot dipping [4] deposition techniques, little material is lost. These aspects make powder coatings one of the fastest growing segments in the coating industry, with manufacturers involved in continuous improvements in powders formulation, application and process economics [5]. On the other hand, poor visual appearance can often affect powder coatings. Surface defects (i.e., orange peel, voids, pin holes, ...) due to incomplete particle sintering or coalescence as well as to 'back ionization' phenomena in electrostatic application are quite common issues [6]. Yet, problems of wrinkling and poor levelling can macroscopically influence the aesthetic aspect of powder coatings in the form of large surface undulations, even if powder particles coalesce completely [3,7,8]. In addition to visual appearance, basic coating functions, such as wear and scratch resistance, are critical to retain for example, in general industrial paints, furniture as well as in domestic appliances [5]. What is more, detecting reduced surface aesthetics and functionality due to wear or scratches and establishing a relationship between coating structure, coating properties and scratch or wear conditions can be definitely complicated [8–10].

1.2. State of art

Appearance qualities and functionality of powder coatings do strictly depend on the rheology of starting material formulations [11,12]. Melting, flowing, gelation and cure are

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the main steps in the development of both the paint aesthetic and protective properties. The duration of each step is influenced by the material formulation (i.e., binder, crosslinker, pigments, catalyst, fillers and additives) and, above all, by curing reactions and/or application techniques [11] and, in turn, determines the fundamental coating characteristics such as surface finish, mechanical strength, resistance to indentation and scratching, wear endurance, gloss, chemical inertness and exterior durability [12–16]. In this sense, the rheology of powder coatings has always been modelled by semi-empirical equations that join thermally activated viscous softening with the effects of thermally activated crosslinking [17]. Accordingly, a low viscosity polymer melt with a high surface tension should be the perfect choice to promote levelling and proper polymer crosslinking. However, if the viscosity is too low, then the polymer melt could sag and flow off the substrate edge during curing. To the contrary, if the surface tension is too high, then the polymer melt could dewet the substrate [18]. The challenge facing scientists is therefore satisfying this combination of conflicting needs, which require to study each particular powder coating system to customize the material formulation, application techniques and curing conditions.

In this regard, the correlation of mechanical properties and visual appearance of polymeric films with material formulations, curing and application techniques has been widely approached in the pertinent literature [19–24]. Since early nineties, dynamic mechanical analysis was used for the characterization of ‘free standing’ films upon curing. The related experimental findings permitted to deduce fundamental information on films glass transition temperature T_g and, above all, on their storage and loss modulus at different stages of curing process [19,20]. Later on, further analysis has detailed polymeric films internal stresses, Young’s modulus, wear endurance, impact resistance and mechanical strength for different material formulations [21–24]. In 1999, Bouchet et al. focused their attention to the determination of residual stress, Young’s modulus and practical adhesion of organic layers with different thickness, made of DGEBA epoxy resin and IPD hardener [21]. Later on, Francis et al. reviewed stress development mechanisms and stress measurement techniques during the drying and curing of polymer coatings, drawing many examples from previous stress measurement studies [22]. In 2001, Trezona et al. proposed a novel technique to determine the resistance of paint coatings to multiple solid particle impact, displaying a two-stage response to erosion of two acrylic automotive topcoats [23]. Next, Ramsteiner et al. measured the scratch resistance of hard coatings on polymeric substrates, giving rise to a failure map [24]. Hult et al. detailed an extensive use of multiple parameter tests to characterize the overall response of two ductile polymer coatings of commercial grade tailored for pre-painted steel applications to real contact conditions. The experimental results provided important information on the physical state, yield and break behaviour of the examined coatings [25]. Recently, Barletta et al. tried to define a more systematic approach for powder coatings, in which the evolution of main film properties (visual appearance, mechanical properties, durability, adhesion and wear resistance ...) could be studied at the different steps of curing process, underlining the mechanisms involved in polymeric films formation from the status of uncured film to the status of fully cured one [9]. This way, the best choice of application and baking procedure could be definitely pursued for each different powder coating system.

1.3. Aim of the work

A very large share of thermosetting powder coatings class is still today represented by protective and electrical insulating coatings [1]. They are mostly based on bisphenol-A (BPA) epoxy powders suitable for FB application with n values range up to 8, dicyandiamide crosslinkers and 2-methylimidazole catalyst [26]. The widespread fields of applications of such coatings, which include the finishing of pipes, rebars, electrical equipments, primers and automotive underbody parts, have pushed the authors to analyze the correlation of the scratch adhesion and wear endurance of EFB and CHDFB coatings on standard and preheated metal substrates, respectively, with the thermo-rheological properties of the starting material formulation at the different stages of the curing process.

Thermo-rheological characterization of the epoxy-based powders was so first carried out. The trends of cure conversion and viscosity of the epoxy powders versus time and temperature were deduced. Cure kinetic and complex viscosity of the epoxy powders were modelled by using the available experimental data and related analytical models were built on. Levelling and flowing capabilities of the polymeric films were analyzed by using an environmental scanning electron microscope (ESEM), which allows to follow, in real-time and at high resolution, the surface flattening of the epoxy films under strictly monitored time-temperature programs.

Electrostatic fluidized bed (EFB) and conventional hot dipping fluidized bed (CHDFB) were, then, used to apply the epoxy-based powder coatings onto standard and preheated metal substrates, respectively. Baking time and temperature as well as preheating temperature were set to cover a wide field of possible curing conditions. The resulting films were characterized at all the different stages of the curing process by standard tribological and advanced micromechanical tests (i.e., micro-scratch). Scanning electron microscope (SEM) and standard inductive gauge profilometry were used to determine the polymeric films scratch adhesion and wear endurance.

The experimental findings showed consistent trends of the epoxy films mechanical strength and wear endurance produced by scratch and pin-on-disk tests according to baking time and temperature for EFB coated samples and to pre-heating temperature for CHDFB coated samples. This way, indications on how the properties of the epoxy-based coatings are progressively established with curing time and temperature and on how to best set application and, above all, baking conditions can be usefully deduced.