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Stone-impact damage of automotive coatings: A laboratory single-impact tester

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Abstract

Coating damage due to stone impact remains one of the major concerns of the automotive industry. The development of new environmental-friendly paint systems prompts the paint manufacturers to pay more attention to the issue of reliable test methods that also approximate actual service conditions. This paper describes a single-stone impact tester developed at Delft University of Technology. The apparatus uses compressed air to launch a shaped projectile into a painted specimen. It allows to vary the velocity of the projectile, the angle of impact incidence and the testing temperature over wide ranges. The single impact test technique (methodology) is successfully applied to a set of automotive coating systems designed on water-base technology resulting in good reproducibility. Results are presented of a preliminary study on the influence of the primer crosslinker content on the stone impact resistance of the paint system.

Keywords: Water-borne paint; Single-impact tester; Chip resistance; Polyester/melamine primer

1. Introduction

Recently, new regulation that limits the volatile organic compound content of commercial paint products has led to the development of new formulations of water-borne coatings. The growing market for these new coating systems and an increasing demand for an improved chip resistance in the automotive industry have created the necessity for appropriate evaluation methods with a proven reliability.

The chip resistance of automotive paint can be defined as the ability of a multi-layered coating systems applied onto a substrate to withstand impact of foreign particles without damage. Moving automobiles are often subjected to impact by lofted stones. The velocity at which the stone hits the automobile is approximately the same as the velocity of the vehicle, i.e. 40–140 km/h. Stone impact onto a painted automobile body can result in paint removal or delamination at the substrate–paint interface, ultimately leading to corrosion of the metal substrate. Damage of paint due to stone impact is a complex phenomenon and depends on projectile, paint and substrate properties, and on the ambient conditions.

In literature several mechanisms of coating failure are listed [1–14]. Impact loading of coatings is characterized by the very short period of time involved and the high stresses that are induced at the site of impact. Multi-layer coating designs offer more possibilities for obtaining chip resistant systems. In a multi-layer configuration adhesive and/or cohesive failure can occur. Adhesive failure occurs when the adhesive strength between two layers is exceeded, resulting in delamination and flaking or peeling. Cohesive failure occurs by crack initiation and propagation within a layer or across the entire multi-layer coating. An important factor, which should be taken into account here, is the local temperature rise during impact, which will have an effect on the paint failure behaviour. This problem was discussed in [15,16].

There are several theories about the stresses involved in paint failure during the impact event. According to Ramamurthy et al. [8], for impact normal to the surface a compressive stress wave propagates through the paint layers and the impacting particle at approximately the acoustic wave speed in the respective media. The peak shock stresses can reach up to 400 MPa. These waves reflect in tension from free surfaces of both the target and the particle. When the tensile wave reaches the impact interface the

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projectile and target separate and further wave reflections occur. As stress waves propagate through the paint layers, local stresses may far exceed the interface and layer strengths, resulting in fracture, delamination, and spallation.

Papini and Spelt [12] assumed that coating removal mechanisms predominantly are quasi-static and not dynamic. They show that coating removal is due to interfacial shear stresses. The authors indicated that delamination typical occurs at the coating layer having the weakest interfacial strength. Layers with good adhesive properties fail by mechanical erosion mechanisms: plowing or two types of cutting [13]. In Ref. [14] coating damage is characterized as the result of three subsequent phenomena:

- initiation of delamination at the onset of impact due to large shear stresses at the interface;
- buckling of the paint film due to large radial compressive stresses in the film, which come from particle penetration in the coating;
- delamination of coatings in mixed mode, i.e. through a combination of modes I and II failure.

The existing test methods to quantify chip resistance can be classified as multiple-impact or single-impact tests. Ramamurthy et al. [7] gave a comprehensive review on this subject. In multiple-impact testing a painted plate is subjected to the impact of a stream of stones of a particular mass. The main drawbacks of these methods are the poor reproducibility of the results and lack of control of the variables that affect the impact phenomenon. Therefore, the multiple-impact technique has been used more as a rapid laboratory evaluation (ranking) method, rather than as a tool to design paint systems.

Single impact tests provide better control over the projectile velocity and the impact angle and give more reproducible results. The method can be successfully applied to study the mechanism of paint failure. There are several standardised single-impact test methods. However, very often they show limited possibilities to set important variables and to fully resemble the service conditions of stone-impacted automotive coatings. The use of inappropriate projectiles and/or the lack of the ability to vary impact temperature are the most common shortcomings.

This paper presents an experimental technique to study the stone impact response of automotive paints. The results of preliminary tests on two different coating systems are discussed.

2. Single-impact stone chip tester

The single-impact stone chip tester was designed at Delft University of Technology in cooperation with “A&M materiaaladvies” consultancy bureau in Delft. A schematic diagram of the test apparatus is presented in Fig. 1. The tester is constructed to launch cylindrical projectiles of 3.15 mm diameter and a length of up to 10 mm by means of compressed air. The launching takes place by applying a constant pressure to the projectile, thereby accelerating it in a tube of 3.2 mm diameter over a certain length. Calculations were done to determine the required tube length at a given pressure needed to achieve a maximum projectile velocity of 40 m/s. These calculations resulted in a tube length of 600 mm.

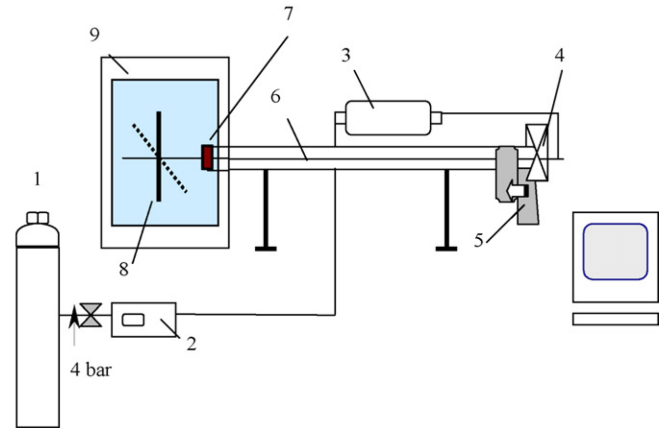

Fig. 1. Schematic diagram of the single-impact stone chip tester. (1) Air supply; (2) digital pressure controller; (3) air reservoir; (4) high-speed opening valve; (5) loading unit; (6) launching tube; (7) velocity sensors; (8) specimen holder; (9) temperature chamber.

An accurate digital pressure controller and a high-speed opening valve are used to apply the pressure needed to accelerate the projectile in the launching tube. The air reservoir located before the valve provides a sufficiently constant pressure during launching. The small difference between the inner tube diameter and the outer projectile diameter also contributes to a minimum pressure loss during launching.

The launching tube is fixed in a stiff housing to avoid vibrations of the free end of the tube. Such vibrations are found to cause tilting of the projectile after leaving the tube exit. To ensure a straight trajectory of the projectile, the distance between the tube exit and the specimen was set to only 20 mm. According to Chevallier et al. [17] the air velocity is uniform and equal to the air flow in the tube over a distance of approximately 6.2d, where d is the diameter of the tube. The straightness of the trajectory of the projectile over a distance of 20 mm from the tube end was confirmed by high-speed camera recordings (see Fig. 2).

The test specimen for the stone chip tester is a square panel of automotive steel plate with a side of 100 mm. The specimen is clamped at its four corners on a specimen holder, which can be displaced in horizontal and vertical directions, controlled by two stepping motors.

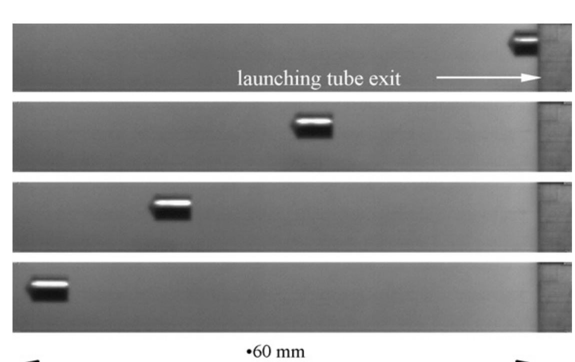

Fig. 2. Photographic records of the projectile trajectory.