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Out of die ultraviolet cured pultrusion for automotive crash structures

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ABSTRACT

In this paper the out of die ultraviolet (UV) cured pultrusion for manufacturing impact automotive energy absorbing parts has been analysed. Aspects such as the UV source, pultrusion process variables and final mechanical and physical properties of the pultruted parts have been studied. The measured maximum pulling force in the die was approximately 80 N. The parts cured with high intensity UV LED sources present low void concentration and almost no expansion at the exit of the die. The parts cured with the traditional UV arc lamp have an expansion of 20% of the expected thickness and hence, high void concentration. The less expansion at the exit of the die is translated into an improvement of 26% in the interlaminar properties and in 8% in the energy absorbing capability of the UV LED cured parts.

1. Introduction

Energy efficiency, in both fuel and electric cars, is one of the most important priorities of the automotive industry. Greenhouse gas, air pollutant and noise emissions of the internal combustion engines are a main source of pressure on the environment. For electric vehicles improving the range is the main driver. Consequently, lightweight materials, such as aluminium, magnesium and fibre reinforced polymer composite, are in the strategic agenda of all OEMs [1]. The future challenge for lightweight designs is even bigger, since urban traffic, where cars are often accelerating and braking, is increasing. Moreover, the recent concerns about road safety have led to increase the importance of the crashworthiness, demanding new materials and structures with higher impact energy absorption capabilities and damage tolerance.

It has been already proved that polymer matrix composites exhibit higher specific energy absorption (*SEA*) properties in crash situations comparing with metallic materials [2–11]. Toksoy [5] analysed the *SEA* of real metallic crash boxes. It was showed that *SEA* values of steel structures were between 5 and 10 kJ/kg, while aluminium crash structures *SEA* were higher, between 15 and 20 kJ/kg. On the other hand, many researchers have demonstrated that *SEA* values of composites are above 30 kJ/kg, depending the geometry and materials used [2–4]. The most used geometry in real applications is square sectioned tubular crash structure due to assembly and element integration feasibility. However, Palanivelu et al. [8–11] showed that constant circular tubes have the highest *SEA* values within tubes with constant section, axially corrugated and conical structures.

However, the limited productivity of some composite manufacturing processes is an obstacle for utilisation of composites in high-volume automotive applications. Moreover, the high productivity requirements referred to automotive industry make essential the automation of the manufacturing processes. In this way, Bader [12] compared different composite manufacturing processes based on a defined composite part. The study concluded that one of the processes with less influence of the labour cost is pultrusion, which indicates a high automation level of the process. Indeed, those conclusions make the pultrusion a suitable applicant for the manufacturing of automotive energy absorbing parts. Even though the traditional pultrusion process requires low energy and it permits a relatively high production rate, the use of this process in automotive industry is limited. As the curing takes place inside the die, this limitation is mainly due to [13]: the high initial investment needed in machinery due to the high pulling forces, the high cost of the pultrusion dies, process incidences, the production rate is not fast enough in some cases and the limitation to manufacture linear profiles. Hence, if the composite is cured out of the die, the limitations of the use of the traditional pultrusion in the automotive industry can be overcome. Therefore, an alternative fast-curing method is needed.

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On the other hand, in recent years considerable effort has been made to develop alternative fast-curing routes for manufacturing composite materials [12]. One of these alternative curing methods is the ultraviolet (UV) curing [14–17]. Resins such as vinylester [15], epoxy [16] and polyester [17], when formulated with a proper photoinitiator, can be cured quickly under exposure to UV light. In addition, UV curing presents other advantages such as a reduction of the emission of volatile organic compounds and reduction in the energy consumption compared with the thermal curing [15,18].

Hence, the out of die UV cured pultrusion can overcome the main limitations of the use of the traditional pultrusion: the productivity can be increased, and curing out of the die, non-linear profiles can be produced. In this way, the study carried out by Lackey et al. [19] shows that a dual thermal/photo cure strategy has the potential to increase line speeds that can be achieved while producing well-cured composites. Another study work carried out by Britnell and co-workers [13] demonstrates the capacity of the process to produce non-linear profiles. Anyway, aspects related to the process as the effect of the UV source and formulation, die design, force estimation, pulling speed, path design, process simulation and monitoring techniques, final mechanical properties, and so on, are not studied yet.

Analysing the curing process, the trough-thickness cure is an essential factor in the out of die UV cured pultrusion. The composite has to be cured as fast as possible at the exit of the die, in order to obtain the desired geometrical tolerances and mechanical properties. This leads to the problem of the photo-polymerisation of thick system, which is relatively difficult due to issues associated with the light absorbance through the material [14]. However, an efficient photo-polymerisation of thick polymers is possible if the emitting spectrum and photoinitiator systems absorbing spectrum are properly matched [20]. In addition, the penetration capacity of the different UV sources depends on the emitting intensity and the emitting spectrum of the source [14]. Therefore, the trough-thickness cure speed will largely depend on the penetration capacity of the UV source.

In this way, this paper analyses the effect of the UV source on the out of die ultraviolet (UV) cured pultrusion for manufacturing impact automotive energy absorbing parts. Aspects such as the UV cured pultrusion process variables and final mechanical and physical properties of the pultruded part have been characterised.

2. Experimental

2.1. Materials and light sources

The composite used in this study is a glass/UV cured polyester composite. The reinforcement consists of 300 g/m^2 and 75 mm width quasi unidirectional E-glass ribbon. The reinforcement is described as quasi unidirectional because of 9% of fibres are oriented at 90° to maintain the cohesion of the unidirectional fibres. Furthermore, these fibres are interwoven with the longitudinal fibres. The resin is UV curable unsaturated polyester supplied by Irurena S.A., whose commercial name is FPC-7621 NA. Two different lamps were used in this study: a traditional flood type UV arc lamp with metal halide 400 W bulb provided by Dymax with an intensity of 1 W/cm^2 and an emitting window of 200 × 200 mm^2; and high intensity Phoseon FireFlex UV LED curing system with a maximum intensity of 8 W/cm^2 and an emitting window of 75 × 50 mm^2. Hence, as two different light sources were used, two different photoinitiator systems had to be selected [21]: the first one (AHK-BAPO) is a mixture of α-Hydroxyketone (AHK) and Bis (2,4,6-trimethylbenzoyl)-phenylphosphine oxide (BAPO); the second one (BAPO - α aminoketone) is a combination of the same BAPO and 2-Dimethylamino-2-(4-methylbenzyl)-1-(4-morpholin-4-yl-phenyl)-butan-1-one (α aminoketone). The (AHK-BAPO) mixture was formulated for the UV arc lamp, whereas for the UV LED the (BAPO − α aminoketone) mixture was formulated. As can be seen in Fig. 1, the absorption spectrums of the photoinitiators match properly with the emitting spectrums of the different UV sources.

Referred to the emitting spectrums of the selected UV sources, the differences are not only in the total emitting intensity of the UV sources. Analysing the UV arc lamp it has to be remarked that a significant portion of the emission spectrum does not contribute to the curing process. This reduces the total intensity used for the photopolymerisation. However, the presence of short wavelengths favours the surface cure. For the UV LED source, it has to be remarked that the match between spectrums is significantly better, and the entire emission spectrum is used for the curing process. Thus, the total emitting intensity can be used for the photopolymerisation. The presence of high intensity at long wavelengths makes this type of sources especially suitable for trough-thickness cure. Those significant differences between the emitting spectrums of the UV sources may contribute differently to the final properties of the pultruded profiles.

2.2. Pultrusion processing

The pultrusion line has been developed entirely by the research group at Mondragon University. The selected pulling speed was 0.65 m/min, being between traditional thermal pultrusion [22] and hybrid thermal/photo initiated pultrusion pulling speed [19] found in literature. The impregnation was done by an open resin bath system and the pull system is a roller system developed specifically for the pultrusion line and the profile section. It has to be remarked that the profile is only irradiated with one UV source (Fig. 2a). To ensure that all the specimens reach the same degree of cure, all the specimens have been post-cured in an oven for 2 h with a temperature ramp rate of 2 °C/min from room temperature to a maximum temperature of 220 °C.

The assembling of semi-hexagonal profiles (honeycomb concept) allows designing and manufacturing composite crash structures for vehicles which have different energy absorption requirements in crash situations. In this way, the same semi-hexagonal profile can be used as a modular geometry to fulfil the crashworthiness requirements. Thus, the die was designed to manufacture continuous semi-hexagonal sectioned profiles. The die length is 100 mm and it is designed to permit pulling force measurements. Fig. 2a illustrates how the pulling force is measured. The die is placed in a linear guide that is fixed to the machine. This linear guide permits only the movement in the pulling direction, so that the pulling force in the die is measured by a 4.45 kN load cell.

In the Fig. 2b the open sectioned semi-hexagonal specimens used in the present study is shown. The length of the specimens is 60 mm and the thickness is 2 mm (8 fibre layers). A 45° chamfer type trigger is machined in the upper side of each specimen in order to control the collapse initiation that will ensure a progressive collapse of the specimen during the compression test, maximizing the energy absorption capability of the composite structure [23].

2.3. Inspection and characterisation techniques

The physical characterisation was carried out determining the density of the composite according to ASTM D792-08; and the glass fibre volume fraction and void content following the procedure described in ASTM D3171-09. The samples taken from manufactured specimens were also examined using a JEOL JSM-5600LV scanning electron microscope.