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Experimental evaluation of a fully recyclable thermoplastic composite

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ABSTRACT

For several years the application of composite materials with continuous fiber were limited to those with thermosetting matrix. Indeed, in recent years, there is a growing interest in composites with thermoplastic matrix thanks to the considerable advantages in terms of recyclability, and the reduction in weight and in production costs. In the automotive sector, increasingly stringent requirements for reduced emissions of CO_2, the maximum return on capital investment and the increase in plastic recycling and reuse, are some of the most important problems that directly influence the development of new materials. The thermoplastic composites appear to be the right alternative to the materials currently used for vehicles. They can replace not only the not structural parts (such as the interiors), but also the structural components located in areas potentially subject to impacts.

This paper presents the results of an experimental campaign made on a full thermoplastic composite, where both the reinforcement and the matrix are made in thermoplastic. The target is to know the mechanical properties in order to design an energy absorber with this new material. Initially, tensile, compression, bending and shear tests were made according to standards to obtain the mechanical characteristics. Subsequently, static and dynamic tests on thin-walled cylindrical tubes subjected to axial load were made in order to assess the energy absorption capacity varying the project parameters. The data were recorded and analyzed in terms of load–displacement curves, specific energy absorption (SEA), crush force efficiency (CFE), stroke efficiency (SE) and crushing stress. Comparing the new material to a common thermosets composite, different values of SEA are evident; fully thermoplastic composites are 3/4 times lower in energy absorption capacity. Nevertheless, taking into account the other favorable characteristic (such as full recyclability and shorter processing times) this fully thermoplastic material continues to be interesting for lightweight design. From the point of view of the energy absorption its spring back behavior offers some advantages respect to thermoset and conventional materials that tend to shatter and to buckle in the event of impact, respectively.

1. Introduction

Currently carbon fiber reinforced polymers (CFRP) are used in several industries with individual technological and economical challenges. Nevertheless, the material utilization for an optimized lightweight structure and cost efficient manufacturing processes are cross-industrial requirements to enable the breakthrough of CFRP in high volume structural applications [1]. Composites in general have been used in the aerospace sector for decades due to lightweight design requirements for increased flight performance, as well as reduced operating costs that usually balance the upfront investment in more expensive material and process technologies. Since the material performance is the key factor, mainly high-end woven prepreg systems are being used respect to continuous or discontinuous filament composites [2]. The comparative situation for automotive applications is slightly different. Key drivers for lightweight design are much more the upcoming government regulations and society needs, which require more efficient cars for the near future, with reduced fuel consumption and emissions [3–5]. So far, composite technology has only been established for niche cars and the step to high-volume automotive applications is very high. Low-cost material systems have to be developed as well as specific structural concepts for car bodies and automated manufacturing technologies. Repair and recycling are other important topics to be considered. As a first step towards high-volume production of a composite cars, BMW started with the production of the model i3 and i8 and other manufactures like Audi and Daimler will follow soon. While BMW is using a full

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composite concept for the life module, others will focus on hybrid structures at the body-in-white or component level. During the design of a car, next to the concept of lightness and recyclability, the safety aspect must not be forgotten. Composite materials are able to fulfill such requirements, if properly designed and implemented [6–8]. Conventional CFRP use thermosetting resin, which hardens when heated during the cure. Generally this material requires some minutes and sometimes tenth of minutes to mold in the desired shape, depending on the selected manufacturing technology, in these conditions it may result not suitable as a material for mass-produced automobiles. Highly stressed load-bearing structures and crash components made of composites are designed to buckle on impact in order to absorb the energy of the impact and consequently to protect the vehicle's occupants in the event of a collision. However, these materials tend to chip into sharp-edged splinters during an impact. It is therefore necessary to find a way for the automotive industry to mass-produce a particularly class of lightweight materials that can absorb the energy in a collision without splintering. Moreover, the currently used composites made with a thermoset matrix, brings to components that cannot be easily recycled at the end of life. Therefore, significant steps forward are needed for efficiency improvements along the whole process chain and the material and process costs have to be cut down significantly.

A possible solution to these problems can be the development of a new class of materials designed for large-scale use in vehicle construction, such as composite materials where both the fiber and the matrix are made in thermoplastic. Not only they can be shredded, melted down and reused to produce high quality parts, but they have been found also to perform significantly well in crash tests [9,10]. When reinforced with textile structures they can absorb the energy of a collision through viscoelastic deformation of the matrix material, without splintering. While thermosetting composites involve several stages of processing, thermoplastic ones requires just two steps (press molding and demolding). For these reasons, the thermoplastic composite enables highly efficient production. Moreover, the cost of the thermoplastic matrix material and the cost of its processing are up to 50% lower than the equivalent costs for thermoset structures. Compared with traditional metals, plastics and thermoset composites, the fiber reinforced thermoplastic composites may result lighter, tougher and stiffer, with reference to weight rated values, as well as more sustainable, because they can be easily recycled and repaired. Finally they can be produced in high volumes with low costs.

In this overview, the paper presents the results of an experimental analysis conducted on a new thermoplastic composite in order to evaluate its energy absorption capacity. In particular, a plain thermoplastic weave combined with a thermoplastic matrix is considered. Firstly, an experimental test campaign is carried out, in order to define the mechanical properties of this innovative material under different load conditions. In particular tensile, compression, bending and shear tests have been done in quasi static conditions. The results of these tests and the consequently obtained mechanical properties are presented and discussed. Starting from the information obtained in the first experimental tests, the energy absorption capacity of simple impact attenuators with circular section made with thermoplastic composite is analyzed. As regards to the geometry, symmetrical axial tubes have been used to carry out much of the experimental work on the energy absorption of composite materials because they are easy to fabricate and close to the geometry of the actual crashworthy structures. Moreover such composite tubes can be easily designed for stable crushing, absorbing impact energy in a controlled manner. For this reason, the crushing sensitivity of thin-walled circular tubes to the wall thickness and to the resistant section under quasi-static and dynamic loading conditions are presented and discussed. The data were recorded and analyzed in terms of load–displacement curves, specific energy absorption (SEA), crush force efficiency (CFE), stroke efficiency (SE) and crushing stress. The results obtained with the thermoplastic specimens were compared with those typical of a traditional thermoset material. The failure mechanisms, obtained varying the geometric parameters and the boundary conditions, will be also presented and discussed.

2. Material

The material studied in this work is a sealable, co-extruded triple layer polypropylene (PP) tape. It was provided by Lankhorst Pure Composites [11]. It was produced via the patented PURE technology. The PURE tapes are co-extruded and consist of a highly oriented, high strength and high modulus core and a specially formulated skin on both sides. The core and the two skins are welded together in a compaction process using a hot-press or continuous belt press. The Fig. 1 shows schematically the processing step of PURE. This process of co-extrusion and tape welding has enormous advantages over conventional sealing processes because of the large sealing windows (130–180 °C) without loss of material properties. PURE material has a high stiffness and low density; the combination of these two properties makes PURE an interesting option for automotive products. Moreover, PURE material has good properties in impact resistance showing a "soft" (safe) crash behavior. In impact situation PURE does not splinter, but fails in a more ductile manner. PURE tapes were used for weaving into thermoformable plain fabric processes, using PP fibers embedded in the same PP matrix, thus achieving a mono material concept that is fully recyclable. Table 1 reports the main mechanical properties for tape and sheet configuration according to the PURE technical data sheet.

In the present work, the PURE fabrics were consolidated using 53 layers into a 600 × 1200 mm sheet reaching a thickness of about 6.9 mm. The flat specimens, used for mechanical characterization, were obtained from this sheet with a waterjet cut. Such PP material exhibits only minimal water absorption and permeability. For this reason the waterjet cutter seems the best option to obtain the desired tolerance. As regards to the geometry, symmetrical axial tubes have been used to carry out much of the experimental work on the energy absorption of composite materials because they are easy to fabricate and close to the geometry of the actual crashworthy structures. Moreover such composite tubes can be easily designed for stable crushing, absorbing impact energy in a controlled manner [12]. The production of cylindrical specimens was done by Von Roll Deutschland GmbH, thanks to its experience with the production of tubes out of PURE.

3. Quasi-static tests for mechanical characterization

Initially standard coupon tests were performed in tension, compression, three points bending and shear according to ASTM Standards D3039, D3410, D790 and D5379, respectively. The tests

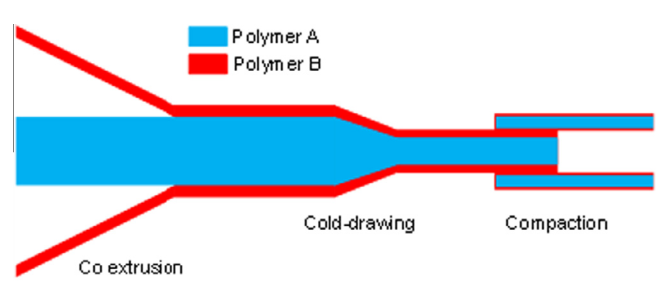

Fig. 1. Schematic processing step of PURE.