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An additive manufacturing solution to produce big green parts from tires and recycled plastics

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Abstract

Recycling is crucial for the conservation and improvement of the environment. The reduction of natural resource exploration and recovery of waste are examples of actions to contribute to a sustainable development. Waste from end-of-life tires and undifferentiated plastics represents an environmental problem due to the very high number of tons of used tires and plastics produced, but with a high economic potential because their incorporation into high value-added products is an issue of utmost importance. The manufacturing technologies oriented to the increase in quality levels, functional advantages, structural and financial gains of the produced products are currently a hot topic in industry. Similarly, the use of additive manufacturing technologies, instead of conventional techniques, e.g. moulding to process materials obtained from waste recovery, is a great industrial challenge.

In order to promote greater environmental responsibility and to present innovative solutions for the management and sustainable destination of used waste recovery from tires and undifferentiated plastics, a composite made from the blend of 60% of tire waste granulate and 40% of polypropylene (PP) recycled was tested with the final purpose of generating components with added value. Both waste recovery materials were used in the micronized state. The thermal and mechanical behaviours of the synthesized composite were studied through DSC/TGA analysis and tensile testing. The implementation of additive manufacturing methodologies to process the blends between used tires granulated with a high incorporation of wastes from undifferentiated plastics was also explored in this work in order to produce big green parts without mould needed, such as urban furniture.

Keywords: Additive manufacturing; Recycled tires; Recycled plastics; Green parts

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1. Introduction

The dramatic growth in the number of used tires around the globe became an issue for society due to their properties, which aren't commercially appealing. At the end of life, the tires can be used in different applications as represented in Fig.1 [1]. Undoubtedly, recycling is the best way to dispose of tires. Tires are shredded in crumbs and used in rubber or plastic industries to manufacture products such as playground surface, athletic tracks, and can also be used with asphalt. Since they contain more than 90% of organic materials with a high heat value, tires are a good source of energy [2]. Concerning energy recovery, tires are used as a source of energy to promote pyrolises. Furthermore, the cement industry is one of the greatest consumers of waste tires. The ash and the steel cord are permanently bound to the clinker and it's considered as environmentally safe [3]. Landfills were the earliest ways of tire disposal. It is the most undesirable of the methods for disposing used tires because they cause severe environmental problems and public health issues. The tire concave shape and its impermeability allow it to hold water for a long period of time, which provides good conditions for mosquitoes and larvae that can hold serious diseases, such as dengue and malaria. Another environmental issue is related to the inflammable properties of the tires, which can lead to dangerous fires, especially during the hot summers, causing toxic smoke to the atmosphere, representing an eminent threat to the environment [4]. Currently, 100% of used tires are collected and their fate may be recycled, retreated and reused [5]. However, given the very high number of tons of used tires produced, the relevance of their incorporation into high value-added products is of utmost importance.

The processes commonly used for recycling tires are the mechanical processes and the cryogenic processes. In the case of mechanical processes, the recycling of tires is performed by industrial processes to yield as final products the various elements and members of individual tires: rubber (in the form of powder or granule), steel (in small portions) and textile fibres. These mechanical processes consist of the grinding of the tires, where the separation of the steel is made using magnetic forces; the textile is separated from the rubber by density difference. At the end of the process the separation of the rubber is made according to its granulometry. However, this material type differentiation process still has associated with it substantial costs [6]. In the cryogenic process, initially the tire undergoes a small grinding that is done mechanically and after this grinding the rubber goes into a cryogenic tunnel where liquid nitrogen is used to freeze the rubber up to -160ºC, thus allowing the rubber to fragment. This process is generally used when it is desired to obtain a very fine granulate. After passage through the tunnel, the separation between the steel, the textile and the rubber is then made through a magnetic separation [7].

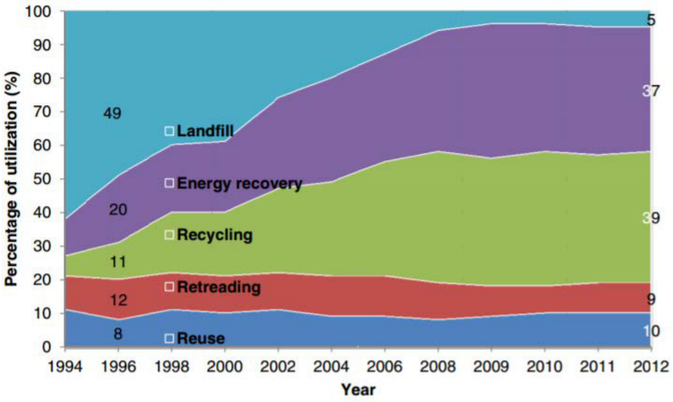

Fig.1. Breakdown of waste tire utilization in EU from 1994 to 2012 [1].

With the growth of world population a major concern of the plastics industry, both production and processing lies in the recycling of waste. The waste plastics are recoverable resources that can give rise to products of commercial value. The plastic, when it becomes waste, can be valued so that it can become useful again. In this regard, the polymer can also be considered an environmentally friendly material because it encourages the use/recovery of waste that, in addition to the environmental advantages in economic terms, can aid in the production of lower cost materials by reducing the cost of construction. Furthermore, plastic products also aim at sustainability as they have a long shelf life, high wear resistance and continue working at the end of their life cycle, either through recycling or energy recovery [8, 9]. The usual processes of plastic recycling are chemical, mechanical and energy recycling. Chemical recycling retrieves the individual chemical components to reuse them as chemicals or the production of new plastics. Mechanical recycling is the conversion of post-industrial or post-consumer plastics in granules that can be reused in the production of other products. Finally, the energy recycling recover the energy contained in the plastic by thermal processes.

In this work polymeric matrices from recyclable polypropylene (PP) are blended with tire wastes. A composite made of 60% of tire waste granulate and 40% of PP recycled (PP/Tires) was processed using a twin-screw extruder (Werner & Pfleiderer ZSK 25P 8,2E). Both waste recovery materials were used in the micronized state. With the final purpose of generating components with added value, i.e. great parts with the free desired shapes and sizes, the 3D printing additive manufacturing process was selected to produce those parts from the synthesized composite. For that a prototype of a 3D printing equipment was developed and it is presented here. The conventional manufacturing processes applied to these kinds of materials impose limitations on the complexity of the geometry and shape of the parts to be produced, which in turn greatly restricts the creativity of designers and consequently, the characteristics of differentiation and innovation presented by new products on the market. Additive Manufacturing (AM) techniques, such as 3D printing, allow for the rapid, automated and fully flexible manufacturing of products from templates generated by CAD (Computer Aided Design) in a fast, automated and fully flexible manner. The absence of tools translates into an almost total freedom in the generation of complex geometries, which offers a versatility which is non-existent with current productive systems. This allows designers to create physical forms of immeasurable complexity from the generation and optimization of three-dimensional digital models (3D) [10, 11].

In this work a complete solution for the additive manufacturing of big green parts from materials that result from a large incorporation of wastes from used tires and undifferentiated plastics, PP in this particular case, is presented. The new manufacturing strategy proposed here can contribute to the products generation that represent an effective contribution for the global reduction on the environmental impact as well as added value for the recovery wastes from tire and undifferentiated plastics.

2. 3D Printing Equipment Prototype

Additive Manufacturing (AM) processes produce physical objects from digital information piece-by-piece, line-by-line, surface-by-surface or layer-by-layer [12, 13].The evolution of AM over the past three decades has been nothing less than extraordinary. The AM has experienced double-digit growth for 18 of the past 27 years, taking it from a promising set of uncommercialized technologies in the early 1980s to a market that was worth over $4 billion in 2014. The AM market is expected to grow to more than $21 billion by 2020 [14, 15].

The AM technologies allow for the processing of a large range of materials. Commercial AM machines can process polymers, metals, and ceramic materials [16]. Sheet lamination processes are compatible with paper, wood, cork, foam, and rubber [17]. Leveraging the geometric and material freedoms of AM for end use parts creates a world of opportunity.

The Fused Deposition Modeling (FDM) 3D printing works on an "additive" principle by laying down material in layers; a plastic filament is unwound from a coil to produce a part. The technology was developed by Scott Crump in the late 1980s. The model is produced by extruding thermoplastic material to form layers as the material hardens after extrusion from the nozzle. [18] The FDM is one of the most widely used AM techniques which is therefore used to assist various production processes [19]. Furthermore, the FDM printing technology is very flexible, and it can handle small overhangs on the lower layers. However, the FDM has also some restrictions, e.g. it cannot produce undercuts without support material, and it is a very versatile technique in what concerns the type of material that can be used. Many materials are available, such as ABS and PLA among many others, with different trade-offs between strength and temperature properties. Considering the printing quality and the level of difficulty of the building process, the type of the material and the cost to produce such big parts, this work was developed based on the this AM technique, which it is the most advantageous technology among the 3D printing methods [20].

Usually the type of equipment used in additive manufacturing has a relatively small construction volume. Any equipment in order to present high dimensional accuracy, meaning high resolution of production, must be equipped with robust mechanical elements, mainly in its axes, which are normally expensive, because this is one of the factors for the small volume of construction. The scale up of this equipment, in order to have bigger construction volume, maintaining the print quality and resolution, has high costs, thus a reason why there are very few solutions available. The weight of the extruder when used with a conventional system of axes requires very low working speeds. The inertia caused by extruder weight when the direction changes during the printing process causes defective parts. Replacing the conventional axes system, a robot with six degrees of freedom was used. This system offers robustness and deposition speed associated with a large volume of construction.

The equipment used in this work was the Robot Yaskawa Motoman HP20F. The robot specifications are shown in Table 1. Also, the print heads of conventional equipment use wire as the raw material. In order to make the deposition of the recycled material, it was necessary to develop an extruder with suitable dimension and with the capacity to process pellets instead of wire. The deposition system consists of a feed zone at 45º to promote the flow of the pellets, a heating zone to keep the material at favourable processing conditions and a screw with the feeding, compression and metering zones with the desirable dimensions. The extruder is controlled directly by the robot so that the process is done automatically.

Table 1. Robot Specifications.

Axes	Specifications HP20F					
	Maximum motion range [º]	Maximum Speed [º/sec]	Allowable moment [Nm]	Allowable moment of inercia [kg.m^2]	Controlled axes	6
					Max. Payload [kg]	20
S	+/- 180	197	-	-	Repeat pos. Accuracy [mm]	+/- 0.06
L	+155 / -110	175	-	-	Max. Working range [mm]	1717
U	+255 / -165	187	-	-	Temperature [ºC]	0 to +45
R	+/- 200	400	39.2	1.05	Humidity [%]	20-80
B	+230 / -50	400	39.2	1.05	Weight [kg]	268
T	+/- 360	600	19.6	0.75	Power supply, average [KVA]	2

Fig. 2 illustrates the first version of the 3D printer prototype for big parts printing made of wastes from tires and plastics composites. This equipment is composed of a robotic arm, a modified extruder and a heated platform. After acquiring the essential equipment to build the equipment, it was necessary to make some changes, adaptations and to add some features to the equipment in order to print the parts. The robotic arm was coupled to a base of 600 mm which is fixed to the ground for greater amplitude of the arm. Moreover, other components such as an additional axis was developed and integrated into the robot. In addition, changes were made in the extruder in order to control the extruder through the robotic arm allowing for the control of the temperature with the same controller.

There will be many more improvements to make on the prototype presented mainly concerning the base platform, which is relatively small to produce parts with the required dimensions. Furthermore, modifications concerning the extruder itself, due to the lack of precision obtained with the present nozzle, and the building of an oven that covers the prototype for outside environment parameters control, which is one of the most important features to add to this prototype, must be done.

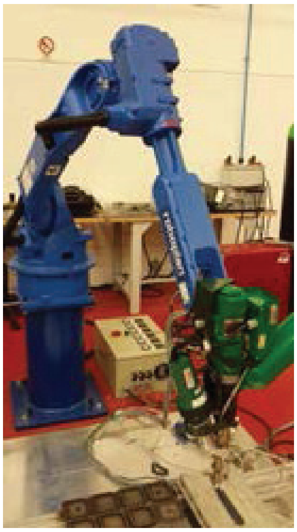

Fig.2. Prototype of the 3D printing equipment developed to produce big green parts.

3. Characterization of 3D Printing processed composite

Six specimens of PP/Tires with 6 mm of thickness, 150 mm of length and 10 mm of width were printed and submitted to tensile and thermal tests to evaluate their mechanical and physical properties. The parameters used to extrude the mixture of PP and tire in the developed equipment were: a layer thickness of 10 mm, a deposition velocity of 10 mm/s, an extrusion flow rate of 3 kg/h, the temperature of the printing base of 120°C and the extrusion nozzle temperature of 198°C.

3.1. Tensile Tests

Tensile tests were conducted using a universal test machine Instron 4505, as shown in Fig. 3, and done in accordance with the standard ISO 527-4. The assays were carried out using a load cell with maximum capacity of 100 kN and a crosshead speed of 2 mm/min.

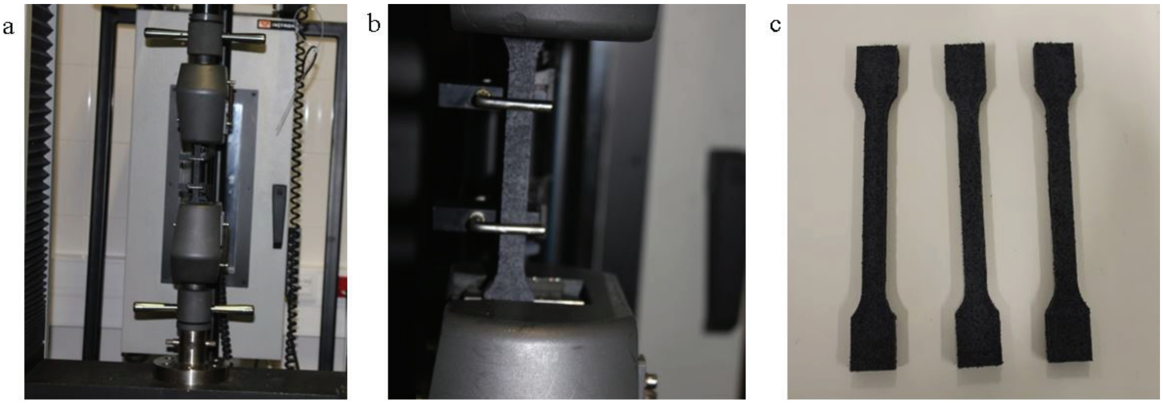

Fig.3. (a) tensile machine; (b) tensile test; (c) tensile samples configuration.

Fig. 4 illustrates the average curve of stress versus strain obtained from the set of tensile tests performed for the PP/Tires composite. It can be concluded that a maximum load of 214 N, corresponding to maximum stress around 6 MPa, leads to a deformation of 0,03.

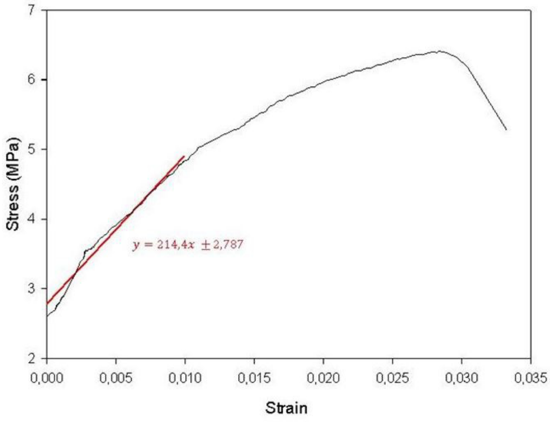

Fig.4. Average curve of the tensile test set performed for the PP/Tire composite.

3.2. Thermal Analysis

A STA 6000 (Perkin Elmer®) was used for thermal analysis of the materials. Samples of 6 mg were placed in alumina pans, and empty pans were used as reference. All samples were first heated at a range of 30-250°C at a heating rate of 10°C/min and held isothermally for 1 min to mitigate any prior thermal history. Following, the samples were cooled to 30°C at 10°C/min and then reheated to 250°C at the same rate. After each test, the melting point region from the thermograph was analysed to determine the heat of fusion (ΔHm) and the melting temperature (Tm); the crystallization region was analysed to determine the crystallization temperature (Tc) of all samples. The flow rate of nitrogen was 20 ml/min during all the runs. Fig. 5 shows the DSC/TGA results for both the PP and for the PP/Tires composite.

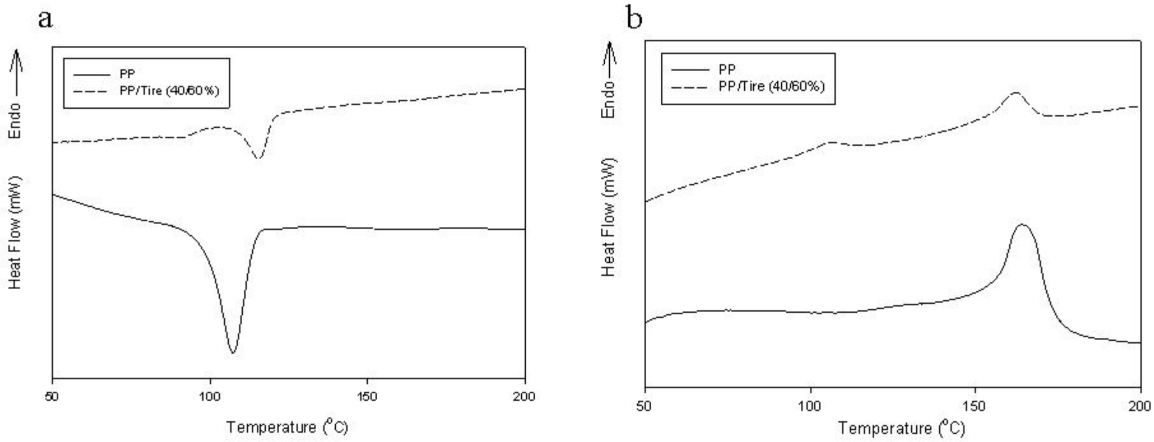

Fig.5. DSC/TGA results: a) crystallization temperature; b) melting temperature.

From Fig. 5a) it can be observed that the PP cristalization temperature (Tc value of 107ºC) is lower than the verified (Tc value of 116ºC) for the PP/Tires composite, which means that the tire waste presence leads to the increase of cristalization temperature. The knowledge of melting point is very important, mainly to optimize the printing process parameters. Fig. 5b) shows the melting temperatures for the materials under study. The PP/Tires composite shows a slightly larger melting point when compared to those reached for the PP. A melting temperature of 161ºC is registered for the PP/Tires composite and of 157ºC for the PP. In short, from Fig.5 it can be concluded that there are two peaks of temperature: the first is related to the beginning of the melting of one of the constituents of the tire and occurs at a lower temperature, and the other one causes the polymer fusion and occurs at a higher temperature. This means that in terms of process parameters, when compared to PP, more energy is needed to reach the PP/Tire composite melting point.

4. **Conclusions**

It was demonstrated that it is possible to do 3D printing of large parts made of from a blend between tires and undifferentiated plastics wastes. An exhaustive characterization is however necessary to optimize the relationship between the amount of tire residue and plastics, as well as optimize the processing parameters. Furthermore, the 3D printing prototype presented needs to be improved mainly in what concerns nozzle dimensions and geometry, construction platform and outside environment parameters control. As future work it is intended to use curable resins as a binder material for wastes from tires and undifferentiated plastics to develop a controlled printing chamber to introduce UV lights to promote stronger bonds between both materials.

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