



Original article

Use of 3D printing PLA and ABS materials for fine art. Analysis of composition and long-term behaviour of raw filament and printed parts



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ABSTRACT

3D printing is an additive manufacturing technique which involves the physical fabrication of an object from a digital model, by binding thin successive layers to build up the final shape. It was originated in the 1980s and currently is widely available for its use in contemporary sculpture. Fused Deposition Modelling (FDM) is one of the most accessible techniques for artists to carry out their work, turning ABS and PLA into the most commonly thermoplastics used in FDM machines. From an art conservation standpoint, it is essential to know the properties of these materials, as well as the different degradation processes that these polymers may undergo due to the action of the environment.

For this reason, this work aims to characterize samples of ABS and PLA materials, in order to study their initial properties and check whether any chemical, morphological or colorimetric changes have been produced after an accelerated artificial ageing process. Samples were prepared in two forms (filament and printed pieces) and two types of ageing tests were carried out, one under controlled conditions of UV radiation and another one exposed to the action of temperature (T). All samples suffered variations in their properties although no difference was ascertained between the filament and printed forms. The results showed that ABS samples experienced alterations in all analysed properties due to the action of UV and temperature, while PLA samples experienced fewer changes in their properties, resulting in the differences more significant after temperature ageing.

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1. Introduction

3D printing as expressed nowadays is an umbrella term which comprises numerous technologies and a miscellany of frequently confusing acronyms and terminology: SFF, FDM, FFF, SLA, SLS, LOM, etc. [1]. All of these have their own intrinsic development and historical justification [2], but perhaps a more general term would be that of *Additive Manufacturing* (AM from here on out) [3]. The word additive suggests that the parts are produced by binding material together, in contrast to the traditional machining methods of

Subtractive Manufacturing, where the material is gradually removed from an initial solid block [4].

We may consider the origin of modern AM in the mid-1980s with the development of stereo-lithography (SLA), although the genesis and introduction of this field can be traced back too much earlier. In a report by the JTEC/WTEC, Joseph J. Beaman highlights the areas of topography and photo-sculpture as early precursors to the field with relevant developments appearing around 1860 and extending all the way into the mid-1900s [5]. All in all, a few years before in 1974, chemist David E. H. Jones musingly describes a process in which UV lasers polymerize liquid monomers to manufacture 3D solid objects [6]. All of this, is summarized before the SLA patents developed in the 1980s.

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In any case, there was already a desire in the 1960s of sending the output of computer-aided design programs to the *Automatic Machine Tools* already present in the factory floor [7]. Naturally, the idea was to make use of the technology to increase productivity. Undoubtedly, this notion of efficiency induced the term *Rapid-Prototyping (RP)*, which collects many of those first AM efforts. *RP* enabled engineers and designers to quickly fabricate models and working prototypes to test their ideas and make further changes. The whole iteration process would take hours or days compared to weeks with the previous production means.

However, *RP* has evolved since its infant years and the industry has grown to incorporate *Rapid Manufacturing* or *Rapid Tooling* technologies in their workflow. Now, the produced parts are not just demonstration models or pieces to be cast in another material, but rather directly fabricated end-use components with similar characteristics to those produced by traditional methods.

Such is the ongoing development of this field that current AM offers a significant array of matured and specialized processes. Stereo-lithography (SLA), Selective Laser Sintering (SLS), Direct Laser Metal Sintering (DLMS), Laminated Object Manufacturing (LOM) or Fused Deposition Modelling (FDM) are just a few of the main key players in a field that keeps on evolving [8,9].

Even though the bulk of the research and techniques of AM were developed for industrial applications, it must be emphasized the fact that the fabrication capabilities of AM have quickly exceeded beyond strictly industrial uses [10]. Many different areas benefit today from the advances made in the realm of AM: tailored medical implants, custom fashion-ware, architecture, archaeology, innovative education proposals, cultural preservation, and, of course, fine-art and design [11,12]. In essence, anywhere and everywhere that the physical materialization from digital computer models may be desired, 3D printing has found its place [13]. Thus, it could be remarked that this technology has evolved from a state of *Rapid-Prototyping* to *Digital Fabrication*, or even *Digital Craftsmanship*, in an art and design context. As these tools and techniques become more widely adopted (and adapted) to other subjects, an increasing necessity of gaining intimate understanding of the materials and processes has appeared. Many pioneering artists are exploring the possibilities of these AM technologies, and incorporating them to their repertoire of tools (Fig. 1) [14]. Occasionally, it has even become the foundation of their practice and discourse [15,16].

New York's Museum of Art and Design (MAD) explores many of these issues in its 2013 exhibition 'Out of Hand: Materializing the Postdigital'. Through the efforts of a varied group of artists, designers, and architects, curator Ron Labaco shows how 3D printing, CNC and digital fabrication technology are generally being employed in the art world [17].

Even in the specific field of cultural heritage, 3D printing and surrounding technologies have a wide scope of applications. Many museums and cultural institutions use these technologies in the reproduction, restoration, and conservation of the cultural heritage artifacts preserved in their collections [18,19]. Applications may range from volumetric reconstruction of a damaged piece, from previously captured data, to the design and construction of mounting structures for restoration, display, documentation, etc. [12,20–23].

Factum ARTE, a private institution born in Madrid, is a pioneering example in such preservation endeavours. Concerning the development and implementation of tools for the digital conservation of art, they have produced a number of high-fidelity facsimiles of world-importance sites, such as the tomb of Seti I in Egypt, The Wedding of Cana by Veronese and many others. Furthermore, they collaborate with contemporary artists in the ma-



Fig. 1. PLA sculpture by Gabriel Jiménez S. Tirado.

terial and technological achievement of their works. Dedicated to digital mediation, they have successfully constructed a bridge between new fabrication and digitization technologies and traditional craftsmanship.

On the subject of materials, AM covers a wide spectrum including polymer plastics, metal alloys, and ceramics among others. Although SLA and other photo-polymerization based techniques may change soon the landscape of AM, this study is focused specifically in FDM, as it still remains the most accessible and ubiquitous form of 3D printing at the consumer level. FDM is a thermoplastic extrusion-based technology [24]. The range of polymers suitable for this form of process is fairly broad and includes, among others, Acrylonitrile Butadiene Styrene (ABS), Polylactic Acid (PLA), Polyethylene Terephthalate Glycol (PETG), Nylon (PA), Polycarbonate (PC) and Thermoplastic Elastomers (TPEs), such as Thermoplastic Polyurethane (TPU) and Thermoplastic Copolyester (TPC) [25,26]. From a commercially point of view, they can be found in the form of 1.75 mm and 2.85 mm diameter filaments, in a wide range of different colours.

Nevertheless, several questions arise, concerning the mechanical properties, long-term stability and durability of artworks produced by means of AM processes and materials [27,28]. In this regard, proprietary formulations and the protection of intellectual property often complicate the matter. Additionally, a deep research on the state of the art of already published information concerning the suitability of 3D printing plastic filaments for their application in the Cultural landscape revealed a lack of knowledge in this regard. Aura-Castro et al. [29] have recently analysed a selection of FDM materials and other authors [14,28] have also highlighted this concern. Therefore, the compatibility of these materials with existing and established methods in art production and conservation is an unanswered matter. Conservators and restorers, as practicing artists alike, would invariably wish to integrate these emerging technologies with the traditional tools and practices of their particular domain.

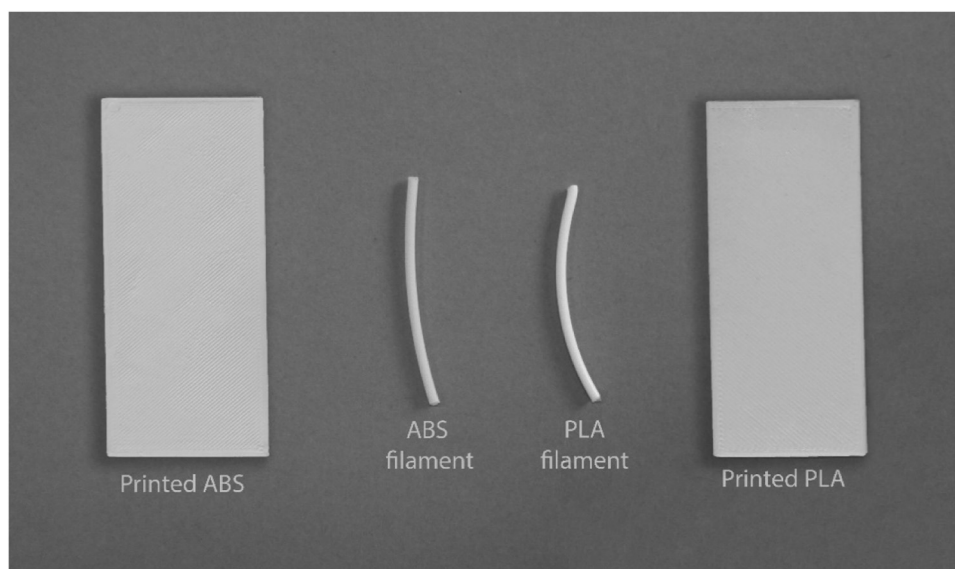


Fig. 2. Filaments and printed samples of ABS and PLA.

2. Research aim

As a result, this research is focused on ABS and PLA based 3D printing filaments, considered the most widespread FDM materials [30]. Some studies already exist on thermal degradation of PLA and ABS [31,32], indicating, specifically, the ageing temperature of ABS between 80 – 120 °C [33,34] and the value for PLA usually under 100 °C [35,36].

On the other side, UV radiation may have an enhancing effect on the degradation of PLA plastic films. Previous studies of UV degradation of ABS can be consulted in Güzel, (2009) [37]. Likewise, Copinet et al., (2003) and Ho et al., (1999) [38,39] represent similar studies of PLA exposed to UV radiation (315 nm).

For these reasons, this study proposes an in-depth analysis of the composition of PLA and ABS filaments (polymer matrix, fillers, and additives) as well as perform ageing tests under controlled temperature and light conditions.

3. Materials and methods

For this study, two test samples of PLA (commercialized by BQ) and ABS (commercialized by MakerBot) white filaments were prepared in two forms: segments of 1.75 mm diameter and rectangular printed parts of 80 × 30 × 3.75 mm (Fig. 2). The equipment used to produce the printed samples was a *Crealty Ender 3* 3D printer configured with the following parameters: 0.25 mm layer height, 100% infill, 230 °C nozzle extrusion temperature for ABS and 200 °C for PLA. Additionally, a heated bed at 80 °C was used during the printing step of the ABS samples.

Initially, these samples were analysed in order to determine their original chemical composition, morphology and colorimetric characteristics.

Next, they were exposed to different accelerated artificial ageing processes under controlled conditions of UV radiation and temperature. Specifically, a total of 500 h of exposure were divided in two steps of 250 h with a continuous temperature of 110 °C. After each cycle, the samples were analysed again so as to identify any change in the original characteristics.

Two different chambers were used for the ageing process: a UV chamber equipped with TL40W/12RS Ultraviolet-B fluorescent tubes with an emission range from 260 to 400 nm and a peak

emission value at 309 nm, in compliance with UNE 53–104–86 certification.; and a drying and sterilization by natural convection oven (model Conterm type Poupinel, P-Selecta brand) with temperature regulating thermostat from 40 °C to 250 °C.

For the chemical characterization of the samples and the evaluation of their long-term behaviour, the following techniques were employed: Fourier-transform infrared spectroscopy in ATR mode (ATR-FTIR) and gas chromatography-mass spectrometry-pyrolysis (Py-GC-MS) were used to identify the polymer matrix and the nature of the additives; scanning electron microscopy in energy dispersive X-ray mode (SEM-EDX) was performed to study the morphology and elemental composition; colorimetric measures were collected to quantify the colour changes in the materials surface. In addition, thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC) were applied to clarify the thermal properties of the polymers. This multi-analytical approach has proved to be effective for the study of plastic materials and their long-term behaviour [40–46]. Next, the technical specifications of the equipment used in our analyses are detailed:

ATR-FTIR spectroscopy: Thermo Nicolet 380 spectrometer with a DTGS/KBr detector in the range of 400–4000 nm. Spectral acquisition: absorbance mode from 64 scans at 4 cm⁻¹.

Py-GC/MS: pyrolyzer Pyroprobe CDS 5250 with a GC Agilent Technologies 7890A and a MS Agilent Technologies 5975C.

Pyrolyzer: Initial Temperature = 300 °C during 1 s. Then, heat was ramped 10 °C/s until it reached a Final Temperature of 750 °C, maintained during 15 s.

Once the pyrolysis process was finished, the chamber reached a temperature of 1000 °C during 5 s for internal cleaning and then it cooled and dried the interior at 80 °C for 1 s – GC Transfer line $T = 290$ °C and oven valve at 280 °C; carrier gas was Helium (He) and a capillary non-polar HP-5MS 5% Phenyl Methyl Silox (30 m x 250 µm x 0.25 µm) chromatographic column was employed. The injector worked in split mode (75:1) with 112.5 ml/min injection flow.

The GC oven was programmed with an Initial T of 40 °C during 2 min. Subsequently, heat ramped 6 °C/min reaching 295 °C. This final temperature was maintained during 15 min.

Mass Spectrometer: Detector Temperature of 300 °C.

TGA: Mettler Toledo TGA/DCS1 with a LF 1100 oven, DTA temperature sensor and MX weighing scales. Range from 40 to 800 °C, with N₂ inert gas at 100 ml/min flow.

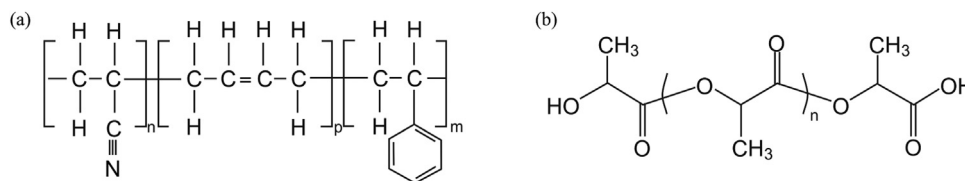


Fig. 3. Structure of ABS (a) and PLA (b) polymers.

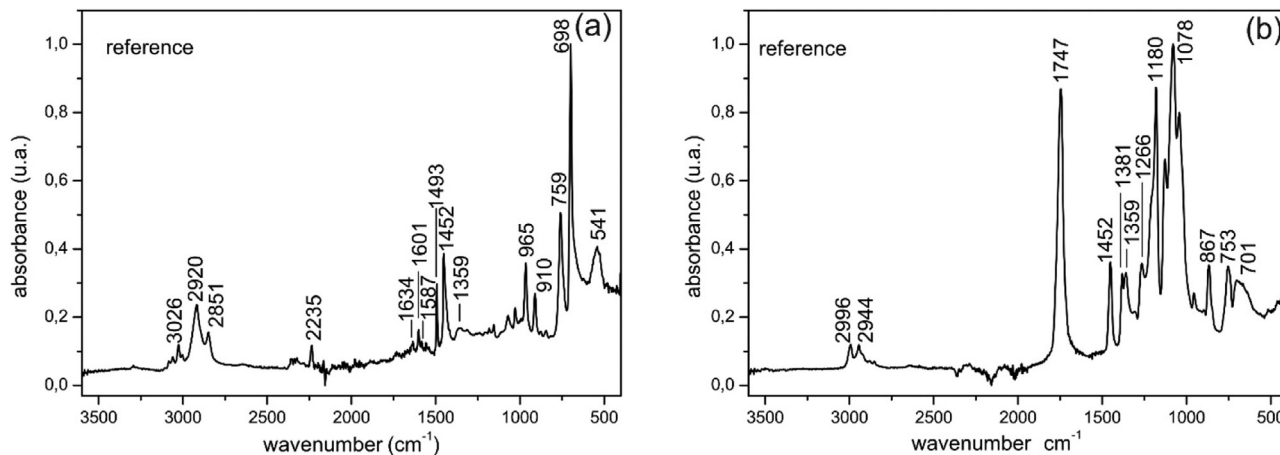


Fig. 4. Reference FTIR spectrum of ABS (a) and PLA (b).

DSC: Mettler high sensitivity DSC 822E. Range from -70 to 250 °C with N_2 inert gas with $30 \text{ ml} \cdot \text{min}^{-1}$ flow.

Spectrocolorimeter: Konica Minolta CM2600d spectrophotometer with 3 mm measurement spot. SCE mode, CIELAB space, range from 360 to 740 nm , step size of 10 nm , light source D65 and standard observer 10° .

SEM-EDX: JEOL JSM 6400 scanning electron microscope with a tungsten source and secondary electrons detector with image resolution at 15 kV to 3.5 nm (8 mm working distance) and to 10.0 nm (39 mm working distance). It incorporates a LINK eXL energy dispersion spectrometer, with a resolution of 138 eV at 5.39 KeV .

4. Results and discussion

4.1. Prior analysis. Material identification

First of all, before analysing the structural changes produced by the ageing tests, the original formulation of the ABS and PLA filaments (Fig. 3) was defined.

The polymer matrix and the additives present in the ABS and PLA samples were determined by ATR-FTIR spectroscopy and Py-GC/MS. In the ATR-FTIR spectrum corresponding to ABS (Fig. 4a), the characteristic bands of the compounds associated to the tri-polymer (Fig. 3) were identified: acrylonitrile (ν_{CN} ca. 2235 cm^{-1}), butadiene [$(\nu_{\text{CH}}$ ca. 3026 cm^{-1}), $(\nu_{\text{C}=\text{C}}$ ca. 1634 cm^{-1}), $(\delta_{\text{CH}}$ ca. 965 and 910 cm^{-1})] and styrene [$(\nu_{\text{C}=\text{Car}}$ ca. 1601 , 1587 and 1493 cm^{-1}), $(\delta_{\text{CH}}$ and CHar ca. 759 and 698 cm^{-1}) and $(\delta_{\text{C}=\text{Car}}$ ca. 541 cm^{-1})]. Other bands were also detected: [$(\nu_{\text{CH}}$ ca. 2920 and 2851 cm^{-1}), $(\delta_{\text{CH}_2}$ ca. 1452 cm^{-1}) and $(\delta_{\text{CH}}$ ca. 1359 cm^{-1})]. Regarding the ATR-FTIR spectrum corresponding to PLA (Fig. 4b), the following polymer characteristic bands were identified: [$(\nu_{\text{CH}_3}$ ca. 2996 and 2944 cm^{-1}), $(\nu_{\text{C}=\text{O}}$ ca. 1747 cm^{-1}), $(\delta_{\text{CH}_3}$ ca. 1452 and 1359 cm^{-1}), $(\delta_{\text{CH}}$ ca. 1381 cm^{-1}), $(\nu_{\text{CO}}$ ca. 1266 cm^{-1}), $(\nu_{\text{COC}}$ ca. 1180 and 1078 cm^{-1})]. Other bands linked to the presence of an amorphous phase (ca. 867 cm^{-1}) and a crystalline phase (ca. 753 and 701 cm^{-1}) were also distinguished [47,48]. The results described were similar for each polymer either in the filament form or the

printed shape. No bands belonging to additives were detected in any case.

Since, in general, the identification of additives proves to be difficult through the use of ATR-FTIR, samples were also analysed by Py-GC-MS. Table 1 show some of the compounds identified along with their retention time (min) and their mass to charge ratio values (m/z). In the case of ABS, monomers and other fragments associated to the polymeric matrix were identified. However, no fragments attributed to additives have been detected.

Concerning PLA, the nature of the polymer matrix composition and the L form (poly (L-lactic acid)) were confirmed [49]. Other fragments attributed to organic additives, specifically plasticizers and lubricants, were also detected. These plasticizers belong to the group of phthalates: diethyl phthalate (DEP), dibutyl phthalate (DBP), bis (2-ethylhexyl) phthalate (DEHP) and dinonyl phthalate (DNP). Related to lubricants, two types of fatty acids were detected, palmitic and stearic acid. In both polymers the results described were similar in filament and printed samples forms.

An elementary microanalysis has been performed using SEM-EDX to study the morphology of the samples. Carbon and traces of calcium (Ca) were detected in ABS. This Ca can be associated with CaCO_3 , an inorganic natural additive widely employed in the plastics industry. In the case of PLA, carbon and traces of titanium (Ti) were detected, associated to the presence of titanium white (TiO_2), another inorganic additive. These results were the same for filament and printed samples.

Equation 1: Crystallinity degree of a polymer

$$X_c = \frac{\Delta H_m - \Delta H_{cc}}{\Delta H} \times 100$$

Before the ageing process, a thermal analysis of the filament samples was also carried out by TGA and DSC techniques, calculating the degree of crystallinity (X_c). To obtain the X_c we have used the equation 1, where ΔH° corresponds to the theoretical value of the fusion enthalpy of a 100% crystalline PLA, ΔH_m to the fusion enthalpy, and ΔH_{cc} to the cold crystallization enthalpy (estimated at 93 J/g , -23.53 J/g and 22.85 J/g respectively in this case).

Table 1

Main compounds found in the pyrogram of ABS (acrylonitrile: butadiene: styrene) and PLA (polylactic acid).

ABS		
Compound	Retention time (min)	(m/z)
Butadiene:	1729	29, 39 , 54
Acrylonitrile:	1866	38, 41, 53
Styrene:	4324	39, 51, 63, 78, 104
Acrylonitrile; styrene:	13,995	39, 51, 77, 91 , 104, 128, 145, 157
Styrene; acrylonitrile:	15,862	39, 51, 91, 103, 115 , 128, 142, 157
Styrene; styrene:	21,21	39, 51, 91 , 104, 130, 180, 193, 208
Acrylonitrile; styrene; acrylonitrile:	23,411	39, 51, 91, 104, 128, 144 , 182, 210
Acrylonitrile; styrene; styrene:	27,481	39, 51, 91 , 117, 156, 169, 195, 261
Styrene; acrylonitrile; styrene:	28,45	39, 51, 91 , 118, 142, 170, 246, 261
PLA		
Compound	Retention time (min)	(m/z)
Acetaldehyde:	1717	29, 44
2,3-pentadione:	2204	29, 43 , 57, 74, 100
Acrylic acid:	2603	29, 45, 55, 72
Dioxane derivate meso form:	9514	29, 43, 56 , 83, 126
Dioxane derivate DL form:	10,862	29, 45, 56 , 70, 99, 144
DEP:	19,031	43, 55, 77, 105, 149 , 177, 222
DBP:	25,289	43, 55, 77, 105, 149 , 167, 222
Palmitic acid:	25,584	43, 55, 73 , 97, 129, 213, 256
Stearic acid:	28,438	43, 60, 73 , 97, 129, 185, 241, 284
DEHP:	33,442	45, 57, 104, 128, 149 , 267, 279
DNP:	35,656	43, 57, 85, 127, 149 , 167, 293

DEP: Diethyl phthalate; DBP: dibutyl phthalate; DEHP: bis (2-ethylhexyl) phthalate; DNP: dinonyl phthalate.

Through TGA, the thermal decomposition of PLA was confirmed to occur in only one stage, at $T_{\text{decomposition}} = 356\text{ }^{\circ}\text{C}$, with a weight loss of around 99.8%. Otherwise, the DSC diagram showed the semi-crystalline structure of PLA polymer with three thermal transitions: glass temperature ($T_g = 63\text{ }^{\circ}\text{C}$), crystallization temperature ($T_c = 113\text{ }^{\circ}\text{C}$) and melting temperature ($T_m = 151\text{ }^{\circ}\text{C}$), with a crystallinity percentage of 49.87%, according to equation 1.

On the other side, the main results for the ABS sample (again, through TGA), demonstrated a thermal decomposition stage at $T_{\text{decomposition}} = 412\text{ }^{\circ}\text{C}$ with a weight loss of around 99.7%. The DSC diagram proved the amorphous structure of ABS polymer with only one thermal transition corresponding to glass temperature ($T_g = 106\text{ }^{\circ}\text{C}$).

Additionally, morphological analysis of the surface of the samples was performed by SEM (SE) and a study of its colorimetric properties was completed by spectrophotometry. These results are presented in the following section.

4.2. Ageing process. Analytic results

Samples were exposed to two different artificial ageing processes: some of them to controlled conditions of UV radiation and others to controlled temperature. Both processes were applied in two steps of ageing, a first one of 250 and another of 500 h. ATR-FTIR measures were carried out at each step. The behaviour of the samples was similar independent of their form (filament or printed part).

Fig. 5(a) shows the ATR-FTIR spectrum of ABS before and after the UV ageing. Significant changes can be appreciated relative to the appearance of three new bands at 3276, 1718 and 1176 cm^{-1} which may correspond to the vibrations ν_{OH} , $\nu_{\text{C}=\text{O}}$ and ν_{CO} respectively. These bands point out a photo-oxidation process which affects the butadiene structure. Also, the two others significant bands of butadiene (965 and 910 cm^{-1}) are gradually weakened along with the increase of irradiation time, indicating the disappearance of the butadiene units. However, the behaviour of this polymer was different when subjected to temperature ageing.

In contrast, Fig. 5(b), associated to temperature ageing, evidenced less pronounced changes produced in new bands of hy-

droxyl and carbonyl groups. The butadiene band at 1634 cm^{-1} increased while the other bands (965 and 910 cm^{-1}) remained intact. Therefore, ABS behaves differently and experiences diverse chemical changes depending on the type of ageing factor (UV or T), considering the UV radiation one the most harmful parameter when preserving the structure of the material.

On the other hand, a considerable difference in behaviour between ABS and PLA (Fig. 6) could be noticed. While ABS exhibits several changes in the infrared spectrum, the variations in the case of PLA are greatly less pronounced. PLA samples showed no significant changes in absorption bands after UV radiation ageing (Fig. 6a). Nevertheless, Fig. 6b shows the spectra after temperature ageing where a noticeable difference with respect to the other UV ageing is observed. A new strong band at 674 and 650 cm^{-1} and another new weak band at 922 cm^{-1} appeared.

It is common to consider that these chemical changes are associated to variations in the morphological characteristics of the materials surface and their colour.

With a first preliminary visual inspection exam several discernible changes could be observed in the samples after ageing. For ABS, a significant alteration of its colour due to the exposure to UV and increased temperature was observed since the first ageing cycle. This colour modification was produced on the surface, as the core of the sample maintained the original hue. Filament and printed samples became warped and the rigidity and fragility of the material increased. PLA, on the other hand, barely changed its colour after UV ageing as well as after temperature exposure. The samples became slightly warped compared to those of ABS. Likewise, the rigidity and fragility of the material increased similarly to the ABS samples.

Furthermore, a detailed study about the evolution of the morphology of the samples with a SEM (SE) equipment was carried out.

Fig. 7 shows the variation in the morphology of an ABS sample after 500 h of ageing. After UV exposure (Fig. 7b) cracks covered the surface completely while in the case of T ageing (Fig. 7c) no variation in morphology was observed. Fig. 7 shows the images of a PLA reference sample (Fig. 7d), after the ageing process by means of UV radiation (Fig. 7e) and temperature (Fig. 7f). As a result, no

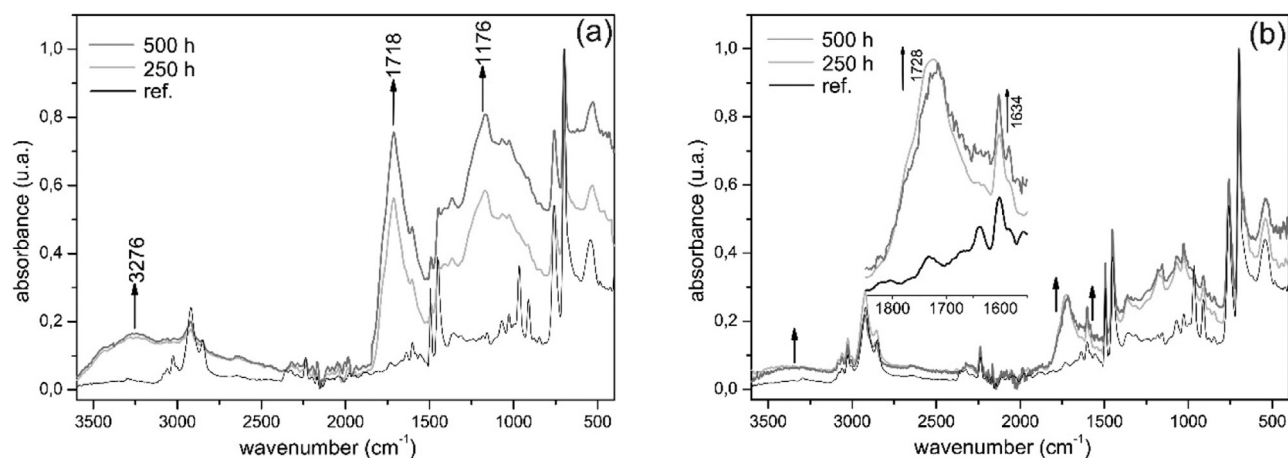


Fig. 5. FTIR spectrum of ABS after each ageing cycle with UV radiation (a) and after the ageing with temperature (b).

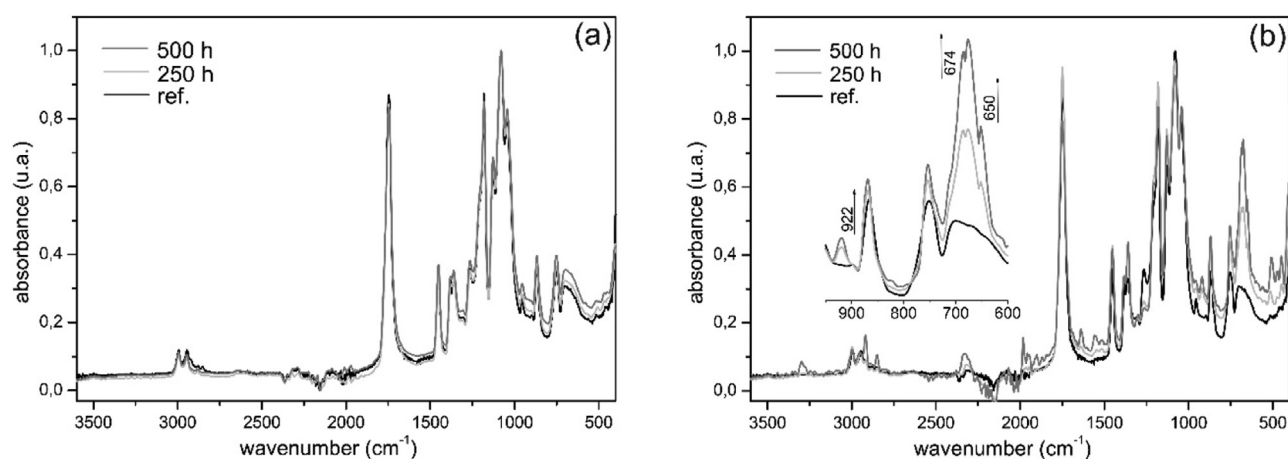


Fig. 6. FTIR spectrum of PLA after each ageing cycle with UV radiation (a) and after the ageing with temperature (b).

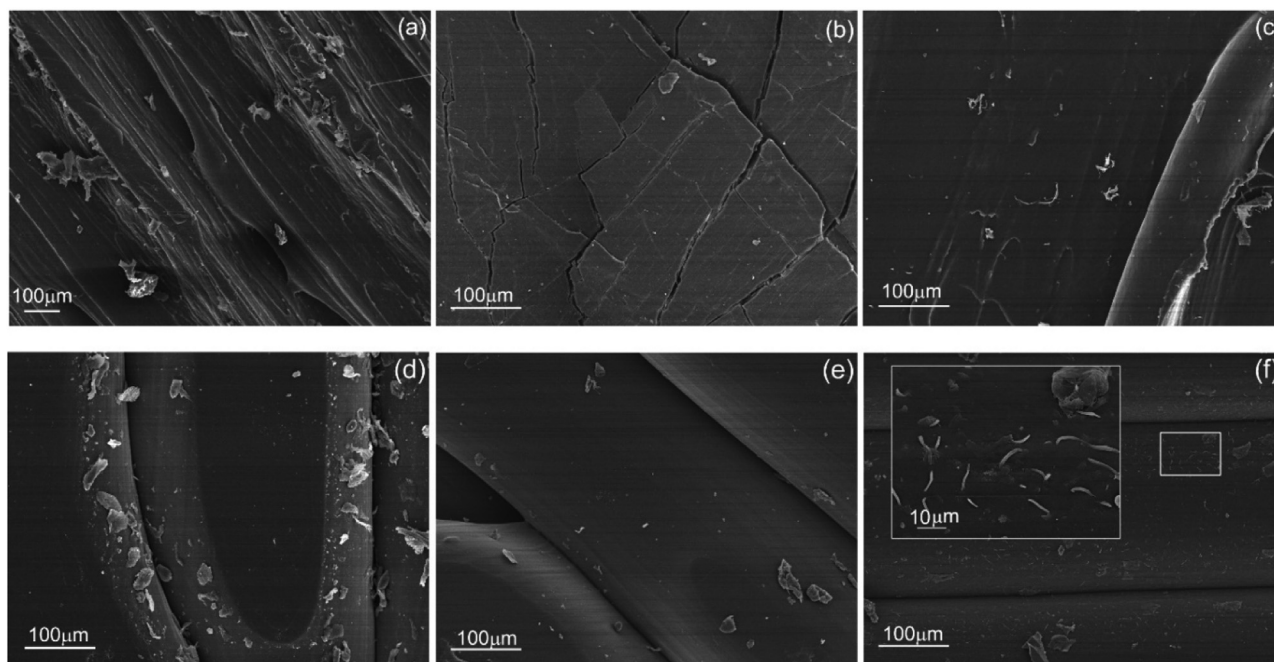


Fig. 7. SEM (SE) images of ABS reference (a), after 500 h of UV ageing (b) and after 500 h of temperature ageing (c); SEM (SE) images of PLA reference (d), after 500 h of UV ageing (e) and after 500 h of temperature ageing (f).

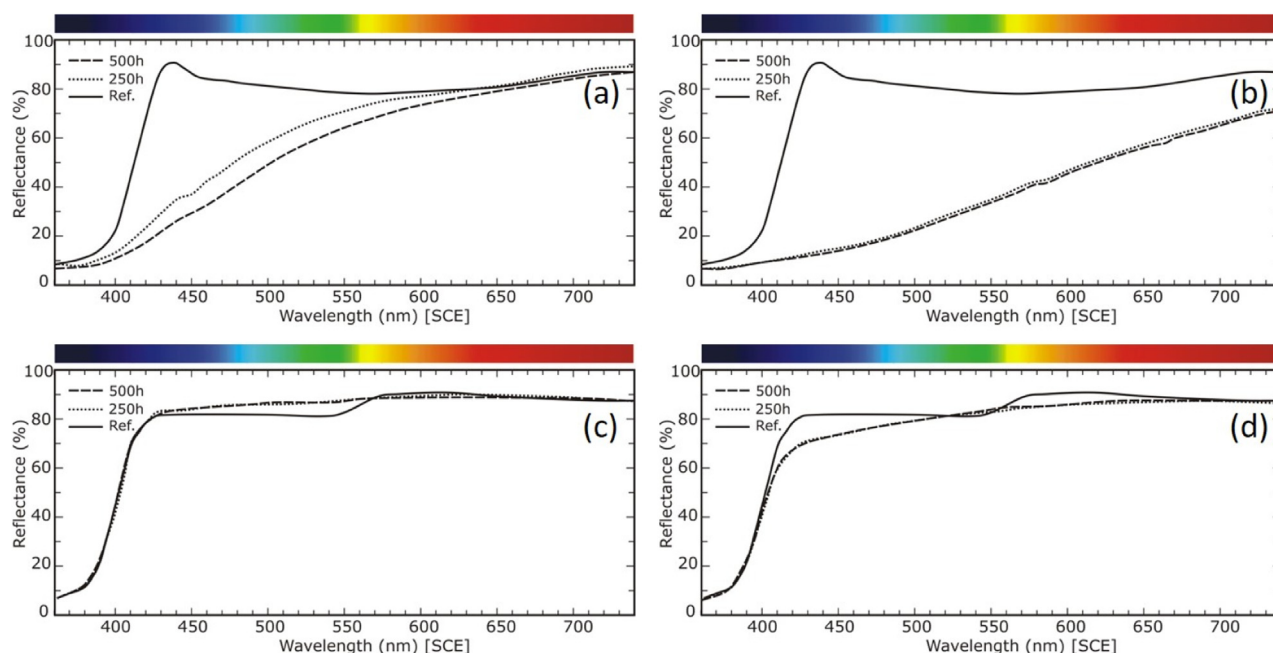


Fig. 8. Reflectance curves of ABS after UV ageing (a) and T ageing (b) and PLA after UV ageing (c) and T ageing (d).

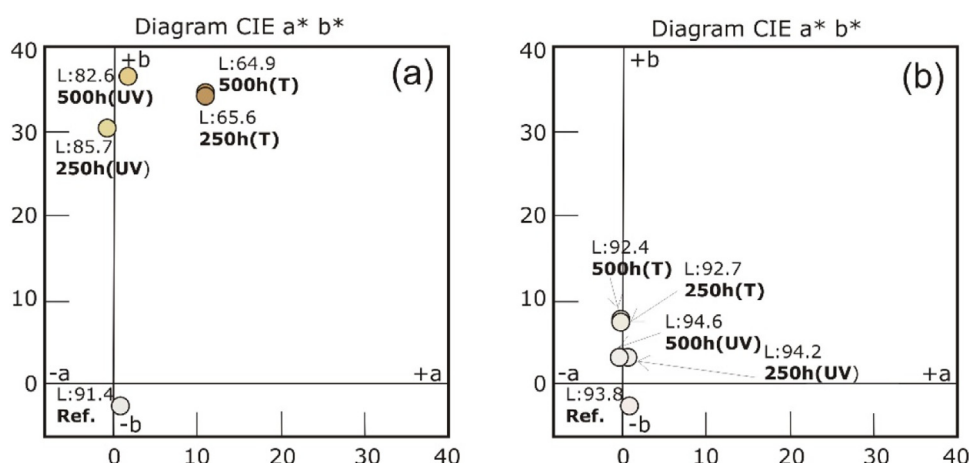


Fig. 9. CIE a^*b^* diagram of ABS (a) after UV and T ageing and PLA (b) after UV and T ageing.

changes were observed in the morphology of PLA samples after UV ageing; conversely, after temperature ageing small and numerous bulges appeared along the surface of the sample. To summarize, these results reveal a correlation between modifications in the chemical composition of the material and the variations produced in its surface. Moreover, in this case, ABS presented significant alterations after UV radiation, while PLA resulted damaged after T ageing. Likewise, these samples suffered the greatest variation in their composition, as Figs. 5 and 6 show.

Finally, colorimetric measurements were made to quantify the colour changes compared to the preliminary visual inspection. Fig. 8 shows the reflectance curves measured on the samples after each ageing cycle. In the case of ABS, yellowing increased after each UV ageing cycle (Figs. 8a and 9a). After T ageing (Figs. 8b and 9a), a drastic variation of the colour, stabilized after the first cycle, was observed. In contrast, only small variations in PLA material colour were observed either after UV ageing (Figs. 8c and 9b) or temperature ageing (Figs. 8d and 9b). These results confirmed that the colour variation is related to the chemical and morphological transformations of the polymer. In both cases, changes were generated due to the action of UV radiation and tempera-

ture, but PLA experienced fewer alterations in its properties than ABS.

5. Conclusions

The results obtained confirmed acrylonitrile butadiene styrene as the main compound of ABS samples and poly (L-lactic acid) that of PLA samples.

Samples were prepared in two different shapes (filament and printed parts) and exhibited the same initial composition as well as similar behaviour facing the two ageing procedures (UV radiation and temperature).

Regarding the behaviour of the samples studied in this paper, PLA showed better resistance than ABS in general. This way, ABS displayed considerable changes against both sources of exposure, highlighting the ones produced by UV ageing. PLA, on the contrary, experienced a higher alteration after temperature ageing than UV radiation, considering this last one barely significant.

The evaluation of the transformations experienced by the samples after ageing processes applying colorimetric and chemical analysis was limited to a superficial level. Thus, in depth studies

of the degree of penetration of these alterations in the structure of the samples should be carried out. Likewise, with this purpose, the use of TGA and DCS analyses of the samples after the exposure to the ageing tests is highly recommended. These techniques would assess whether the changes produced in the samples are superficial or structural damages.

Finally, further studies considering longer ageing cycles as well as the combined effect of light and temperature on these polymers should be relevant to delimit their degradation characteristics and ideal conservation environments.

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