Tribological characterization of Fused Deposition Modelling parts

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Abstract: The customisation or redesign of parts for Additive Manufacturing (AM) to meet the design requirements is an increasing trend. In this context, numerous studies related to the improvement of the mechanical properties of Additive Manufacturing parts used for static applications are emerging. However, the use of these parts in dynamic applications or in relative movement situations has not been deeply developed. Some studies have been focused on the fatigue properties of AM parts while few authors have analysed the sliding behaviour of these parts. This paper presents a characterisation of the wear behaviour of Fused Deposition Modelling (FDM) parts using Pin-on-Disc techniques with the aim of studying their possible implementation in dynamic applications.

Keywords: FDM, Additive Manufacturing, Tribology, Wear, Pin-on-Disc.

1. Introduction

Traditionally, the manufacturing processes have been understood as the transformation of a starting material into a product through the application of energy [1,2]. The different industrial revolutions have modified this concept up to date, when a new technological revolution is taking place. This revolution is supported by the development of new forms of manufacturing and the development of new processes, such as Additive Manufacturing (AM). This process, opposed to the traditional subtractive technologies so widely used in the industry, improves the energy and environmental aspects without renouncing the possibility to produce highly complex parts and dispensing with any tooling (clamping, moulds, etc.) [1,3].

According to ASTM F2792-12a, AM can be considered as a process of adding or joining materials, usually layer by layer, to create objects from 3D CAD computer models, as opposed to its subtractive opposite, machining, where material is cut or removed.

While conventional manufacturing is governed by processing constraints related to industrial mass production, AM is inherently agile, allowing faster changes in design. This fact makes easier the manufacturing of customised objects designed to meet the demands of specific people and applications [4,5]. Highly developed in recent years, AM not only provides parts with a certain geometric accuracy, but also with mechanical or surface properties. One particular process, Fused Filament Fabrication (FFF) also known as Fused Deposition Modelling (FDM), has become a very important process with a high economic and low environmental impact [4,6].

Despite the AM maturity has acquired in such a short time, certain aspects of the AM parts behaviour are not well studied. This is even more pronounced in the case of thermoplastic polymers, which
applications are increasing [4,7]. To date, the studies in AM have focused on static analyses referring to
the improvement of tensile strength [7-9], compressive strength [8,10,11] or process control to obtain
customised parts by modifying their internal structure with different patterns [12]. Nevertheless, far too
little attention has been paid to moving parts or dynamic analyses of AM parts. A search of the literature
revealed few studies referred to classical applications such as vibration on [11] or fatigue [13], but the
effects of the tribological properties have not been closely examined.

The use of polymers in anti-friction applications is not so rare [14]. They are usually doped with
some type of additive, such as reinforcing agents or lubricants, to improve their tribological properties.
This fact is not usually compatible with the improvement of mechanical strength. For this reason, a
compromise solution has to be achieved to simultaneously improve mechanical and wear properties
[14,15]. Therefore, achieving parts that combine both properties is a challenge that can be transferred to
the case of polymeric AM, where FDM is the main exponent of this technology.

Initially, the study of wear and friction of polymeric materials presents many similarities with to
metallic materials. Nevertheless, there are significant differences in the involved wear mechanisms and,
as a consequence, in the level of friction that occurs. These differences can be exploited to produce
materials usable in friction parts, which can change the commonly accepted expectations of their
tribological performance [14].

Mohamed et al. [16] studied the case of PC-ABS (Polycarbonate (PC), Acrylonitrile Butadiene
Styrene (ABS) bonding) and determined that the wear caused by sliding can produce delamination,
deformation of the material and structural damage at a high number of cycles. Likewise, cracks can be
called at the junction of the various filaments that make up the part, which can progress beneath the
stressed surface. Later studies, such as those presented by Sood et al [17] found that ABS alone shows
similar behaviour. However, it was also determined that this behaviour is very sensitive to the process
parameters and they decisively influenced the wear rate.

Poly Lactic Acid (PLA) has a similar behaviour. According to Roy et al. [18] under similar
manufacturing conditions there do not seem to be large variations in tribological properties. As
mentioned above, additives can improve this behaviour. In the case of PLA, there are a large number of
filaments with PLA matrix and particles of different materials and it has been proved as a easy to additive
material. For example, bronze, which has good tribological properties, improves the behaviour of PLA
[19].

Additionally, as for metallic materials, an improvement of the surface design can control the wear
process. Surface treatments can be applied to customized AM parts with a considerable surface
improvement using PLA [20]. Similarly, the contact between the filament layers and the air gap
parameters have a high importance on the surface behaviour [17,18]. Likewise, the external shape,
usually semi-cylindrical, of the deposited yarns makes a difference between printed parts and continuous
parts even for the same material. This fact complicates the modelling of the process [21], in which the
material, the manufacturing process and the strength of the part have to be considered. Gurrala et al.
[22] observed that the normal load, sliding speed and part orientation have a significant influence on the
wear rate for Pin-on-disk tests of AM parts.

Finally, the wear behaviour of other materials with very interesting characteristics such as PETG
(Polyethylene terephthalate glycol) or ASA (Acrylonitrile styrene acrylate) have not been properly
analysed. This work presents a study of the tribological properties of these materials manufactured in
FDM to fill this gap of the literature and to analyse them as possible substitutes for certain industrial
applications.

2. Experimental Procedure
The studied samples were Fused Deposition Modelling flat specimens manufactured in different
materials. The specimen geometry was 45x45 mm² and 3 mm thickness. They were manufactured on a
standard commercial Fused Deposition Modelling equipment. The materials selected for the study were
PLA, PETG, ASA and Nylon. PLA and PETG were supplied by the manufacturer SUNLU and ASA
was supplied by Winkle. The Nylon specimen was used for comparative purposes due to its antifriction properties and PLA specimens were selected since it is the most used material in FFF.

Full filled parts were obtained using a fixed set of parameters for every material. Extrusion speed was set up at 30 mm/s, overlap at 55%, environmental temperature at 60º and filling of 100%. Likewise, rectilinear trajectories without perimeters were selected to avoid the effect of the perimeters trajectories on the tribological behaviour of the specimens.

Nevertheless, the printing parameters were adapted to the material (table 1). Particularly, the extrusion temperature was selected based on the manufacturer's recommendations. It is understood that by using a constant temperature the mechanical parameters will not be altered. Three different layer thicknesses were used for PETG and ASA (0.15, 0.25 and 0.35 mm) to analyse their effect on the friction behaviour. Only one layer thickness was selected for PLA and NYLON (0.25 mm), since these samples were used comparison purposes. The specimens were processed using Repetier Host® software.

| Material | T (°C) | Layer thickness (mm) |
|----------|--------|---------------------|
| PLA      | 200    | 0.25                |
| PETG     | 240    | 0.15/0.25/0.35      |
| ASA      | 260    | 0.15/0.25/0.35      |
| NYLON    | 250    | 0.25                |

After printing, the surface of the specimens was characterised using a stereo optical microscopy (Nikon SMZ 800) and a roughness measurement station (Mahr Perthometer PGK 120). Then, the specimens tribological behaviour was studied using a Pin-on-Disc test equipment from Microtest MT series. The surfaces were tested against a stainless steel pins. All the tests were carried out with a under 15N load, 100 rpm angular speed and 250 m sliding length.

Wear measurement were taken using the same roughness measurement station used to analyse the specimens surface. The geometric data of the groove pattern were obtained using this machine and then they were exported and processed by a CAD software. Since it is not possible to apply any existing standards, these characteristic profiles were studied measuring the minimum distance between the lowest point of the groove and the least squares regression line of the profile.

3. Results

Traditionally, a rough surface is related to bad wear behaviour. Therefore, it is expected to obtain high wear rates on surfaces obtained by FFF. The geometrical characteristics of these surfaces have a decisive influence on the tribological behaviour of the specimens [21]. The topography generated is not a perfect cylinder but an ovalised profile, which depends on the extrusion parameters and the material [23]. For this reason, the initial surface was characterised.

Figure 1 shows the images obtained for PETG and ASA for different layer thickness. Both materials presented similar patterns, with the characteristic motor pitch effect [23]. It was also observed an effect of the layer thickness on the generated surface. For lower, layer thickness, the wave profile of the surface is transferred to the next layer, obtaining complex pattern that disappear for 0.35 mm layer thickness. However, this behaviour was not noticeable for PLA or NYLON samples (figure 2). Particularly, the NYLON topography seems less periodic. This was probably due to the plasticity of the material, which causes problems during its extrusion.

This behaviour was checked analysing the roughness of each specimens (figure 3). PETG and ASA presented better roughness results than PLA and NYLON. The worst roughness results were observed for NYLON, verifying the optical analysis. PETG and ASA showed stable average behaviour for the different layer thickness. Although as it can be seen in the error bars, there is a large variability in terms of roughness. This behaviour is much more pronounced in the case of PETG. This fact may be produced by the plasticity of the material which has a tendency to create bubbles.
Figure 1. Optical microscopy of the upper surface of the PETG and ASA specimens at difference layer thickness.

Figure 2. Optical microscopy of the upper surface of the PLA and NYLON specimens for 0.25 mm layer thickness.

Figure 3. Evolution of the arithmetic mean roughness obtained for the different specimens manufactured.
Regarding the tribological results, on the one hand, ASA samples presented a high stability in its wear behaviour. Its friction coefficient tended to stabilize at 0.4 (figure 5). This value is close to the one obtained for ABS parts [17,18] and lower than PLA parts, even they are mixed with metallic additives [19]. This stabilization was achieved in the first instants for the highest layer thickness (0.25 and 0.35 mm). This fact proved that for ASA samples, the roughness of the process does not have a negative impact.

![Figure 5. Evolution of the friction coefficient as a function of layer thickness in: (a) ASA, (b) PETG.](image)

On the other hand, PETG samples had a different behaviour. Although the coefficient of friction is the lowest for the studied materials, it had a clear dependence on the layer thickness. There was found no clear relation between the roughness and the average friction coefficient. Nevertheless, the tests for 0.25mm layer thickness, the sample with the highest roughness, presented aperiodic peaks. These picks were probably caused by the material dragging phenomena, where particles were detached from the surface and deposited on both the periphery of the groove and on the pin (figure 6 and 7). It should be considered this phenomena had not damaged the piece or broke the fibres as in ASA samples (figure 7) and it was not observed in in PETG or NYLON samples. This fact may be related to the material properties. For low friction coefficient, particles do not detach from the sample but the sliding phenomenon occur anyway. This is clearly seen when comparing the four materials under the same layer thickness conditions (figure 8), where the best results were obtained for NYLON and PETG.

![Figure 6. Pin adhered material for PLA and ASA for 0.25 mm layer thickness.](image)
Figure 7. Groove marks in all materials analysed for 0.25 mm layer thickness.

Figure 8. Coefficient of friction as a function of the material at a constant layer thickness of 0.25 mm.

The materials with lower layer thicknesses do not show particle detachment and those with higher layer thicknesses do. This will also be related to the depth of the groove that appears. Low friction materials had no significant grooves, while for materials with a higher coefficient the groove is noticeable and measurable (figure 9). However, this had not a direct relationship. For instance, PETG plasticity prevented particles from detaching easily, on the contrary dragging created jumps and even burrs on the wear track. In fact, it was precisely on the most visible jumps where the deeper grooves appeared (figure 9). This proved that the material characteristics combined with the printing parameters
influenced the wears behaviour. Therefore, processing parameters such as extrusion temperature had an impact on the final surface behaviour and its optimisation will be critical for industrial applications.

![Comparison of the depth of the grooves obtained for all the materials studied.](image)

Figure 9. Comparison of the depth of the grooves obtained for all the materials studied.

4. Conclusions
This paper studied the tribological behaviour of Fused Deposition Modelling samples manufactured in PETG, ASA, PLA and NYLON. It has established an interesting base to study the dynamical friction behaviour for industrial applications.

An approach to the friction behaviour of PETG and ASA had been made. This two interesting materials were selected due to their special characteristics and their good environmental performance. PETG friction coefficient results were comparable to NYLON under low load tests. Whereas, ASA presented debris on both pin and track wear. Either ways, it could be an alternative for wet applications due to its good stability and resistance in chemical environments.

Further studies are recommended to determine the possible applications of these materials and different ones and enhance the industry competitiveness.

Acknowledgements
The authors would like to acknowledge to the Mechanical Engineering and Industrial Design Department from the University of Cadiz and the Ministry of Science, Innovation and Universities of the government of Spain for providing their assistance in the development of this research.

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