

Investigating the manufacturing of a UHMWPE complex geometry part using a locally developed Selective Laser Sintering equipment

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Abstract. Additive manufacturing (AM) techniques, such as Selective Laser Sintering (SLS), is moving from being an industrial rapid prototyping process to becoming a mainstream manufacturing process for polymer free form fabrication. However, a very small variety of available polymers restricts the intense use of SLS process for industrial production. The use of Polyamide 12 or its compounds, in AM applications far outnumber the use of any other polymeric material. The Brazilian industry is demanding for other polymeric “commodities”, such as Polyethylene (PE), which can open new markets for AM applications. This paper investigates the feasibility of processing a UHMWPE complex shape part using a selective laser sintering (SLS) equipment designed and manufactured in Brazil. Due to its high mechanical properties, excellent wear resistance, low friction and chemical resistance UHMWPE is a semi-crystalline polymer that can be used in many applications such as sporting goods, medical artificial joints, bullet proof jackets and armours. UHMWPE cannot be produced easily because of its very high melt viscosity resulting from its very long chains. The influence of the bed temperature, laser power and scanning speed on the quality of a complex geometry was investigated. The results showed the feasibility of producing a UHMWPE complex shape part via SLS without presence of visual defects. The best parts were manufactured with a combination of laser power and scan speed that resulted in a density energy around 0.09 J/mm². For the same density energy applied the bed temperature parameter has proven to have little influence over the quality of the part.

Keywords: Selective Laser Sintering, UHMWPE, Additive Manufacturing, Polyethylene

1. INTRODUCTION

Additive manufacturing (AM) is a technology that is rapidly developing and being integrated into manufacturing and our day-to-day lives. AM, also known as three-dimensional (3D) printing, is an approach where 3D designs can be built directly from a computer-aided design (CAD) file without any part-specific tools or dies. In this freeform layer-wise fabrication, multiple layers are built in the X–Y direction one on top of the other generating the Z or third dimension.

Selective laser sintering (SLS), as a typical additive manufacturing technique, can generate complex free-form components by selectively fusing and solidifying successive powder layers in a layer-by-layer fashion based on CAD model. The SLS process utilizes a laser beam to fuse powder particles together to form a solid layer representing a numerically defined cross-section of a prior generated CAD model. By depositing new layers of powder and repeating the laser scanning process, a solid representation of the CAD model is generated.

Equation (1) gives the applied laser energy density (ω) at the surface of the powder bed, the most widely applied function for predicting the response of the SLS process, where P is the laser power, H is the scan spacing, and v is the laser beam velocity (Ho et. al., 1999).

$$\omega = \frac{P}{H \times v} \quad (1)$$

Goodridge et al. (2011) declared that despite some advances in SLS material choice over the past few years occurred, these has been very limited and Polyamide 12 remains by far the most widely used laser sintering polymer making up more than 95% of the current market. Most of the published work, predominantly performed by universities and public sector institutes, has focused on polyamides (PA12 and PA11) based materials, as a single material, blended or reinforced with other materials. Very little published work has been carried out on distinctly new polymers.

A reason that has prevented the use of many polymers to date is the range of process parameters that could be successfully used in combination to achieve these parts, known as the processing window. Materials that can be processed at a wide range of temperatures (processing window) without having processing problems (part curling, for example) are the most desirable, as they allow greater processing latitude, particularly when optimizing other processing conditions, such as laser power and scan speed.

Determining the temperature processing range of a given material in a given machine is to some extent an empirical process, due to variances in the thermal characteristics of each material and in the heating mechanisms of different laser sintering systems. If the temperature of the powder bed is too low, the corners and edges of the sintered layer will ‘curl’. Although, if the powder bed temperature is too high, the supporting powder around the part, known as the “powder cake”, absorbs too much heat and when the laser scans the contour of the part the neighboring powders will also be affected. This cake becomes hard, making removal of the parts more difficult, reducing the degree of recyclability of the support powder and resulting in poor definition and accuracy. This unsintered powder that also sinters in the part is known as “part cake”. The feed temperature, or the temperature of the powder as it is spread over the build area, is also an important consideration (Goodridge, et al., 2011).

Goodridge et al. (2011) affirmed that an empirical approach, commonly used for PA12, determines the part bed temperature by gradually raising the temperature up to 12°C below the point at which the material starts to melt. Some materials (e.g. certain thermoplastic elastomers) need to have part bed temperatures significantly lower than their melt point, mainly due to issues with achieving uniform powder deposition. Therefore whilst knowing the melting temperature of the material can provide a useful starting point, the actual temperature needs to be found by taking other factors into account which ultimately results in a systematic trial-and-error process.

Ultra-high molecular weight polyethylene is a thermoplastic with a microstructure consisting of amorphous and crystalline regions, with Tie molecules crossing over the amorphous regions from one crystalline region to another, preventing the different phases from separating. According to Goodridge et al. (2009), it is the high density of Tie molecules, combined with the entanglements in the amorphous phase, which is believed to give rise to UHMWPE’s mechanical properties, including high abrasion resistance, impact strength and low coefficient of friction. These special properties allow the product to be used in several high performance applications including artificial bones, body armour, pipes, panels, bars, shuttles, gears.

Processing UHMWPE, even by conventional techniques, is a challenge due to its high molecular weight which induces a very high melt viscosity. Rimell and Marquis (2000) have attempted to process UHMWPE using additive manufacturing and multilayer parts were successfully achieved but the processing window was extremely narrow due to the high degree of shrinkage on sintering the UHMWPE powder. In terms of its suitability for laser sintering, UHMWPE is readily available in powder form and has a significant advantage over current laser sintering polymers in that it is relatively cheap.

2. EXPERIMENTAL PROCEDURES

2.1. Materials

The UHMWPE powder used in manufacturing laser-sintered parts was UTEC 3040 from Braskem (Brazil) with a reported average particle size (D_{p50}) of 205 μm . UTEC 3040 UHMWPE is a polyolefin with a molecular weight of around 3×10^6 g/mol, a bulk density of 0.45 g/cm³ and the melt temperature is 133°C (UTEC 3040 UHMWPE datasheet).

It is not possible to process UTEC through conventional methods such as injection, blow or extrusion molding, because this material does not flow even at temperatures above its melting point. It demands special processing techniques, being the most common RAM extrusion and compression molding. In this work SLS processing technique is being tested to build UTEC UHMWPE parts.

This extremely high molecular weight yields several unique properties to this polymer such as high abrasion resistance and impact strength and low coefficient of friction, what makes it a self-lubricating material.

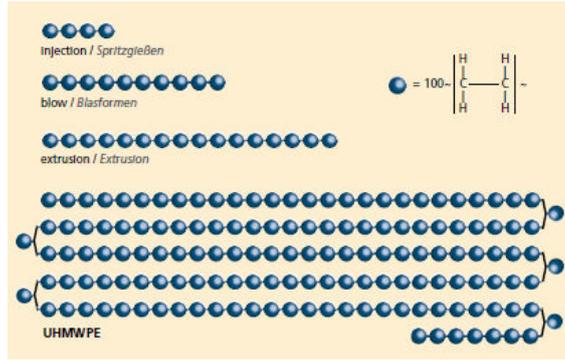


Figure 1: Schematic drawing comparing polyethylenes for injection, blow and extrusion molding with UTEC UHMWPE polymeric chain [Datasheet BRASKEM]

2.2. SLS equipment

The sintering experiments were carried out using a SLS equipment developed and manufactured in Brazil [Model: LaserFunde, ALKIMAT Tecnologia Ltda.]. The schematic of LaserFunde processing system is shown in Figure 2.

The machine consists of a CO₂ laser of 80 W power, delivered through a galvanometer scan head system and F-θ optical lens resulting in a beam diameter of 0.35 mm. Inside the build chamber, there is a build platform, powder dispensing platform and a recoater blade which is used to smear powder over the build platform.

Two infrared heaters are used to heat the powder in the build and power dispenser platforms through a digitally programmable temperatures controller with two infrared sensors. Process parameters can be settled in owner computer software that sends process information to a programmable logic controller (PLC) of SLS machine. The main parameters are:

- Powder dispenser platform temperature (°C)
- Build platform temperature (°C)
- Laser power (W)
- Laser beam velocity (mm/s)
- Scan spacing (mm)
- Layer thickness (mm)

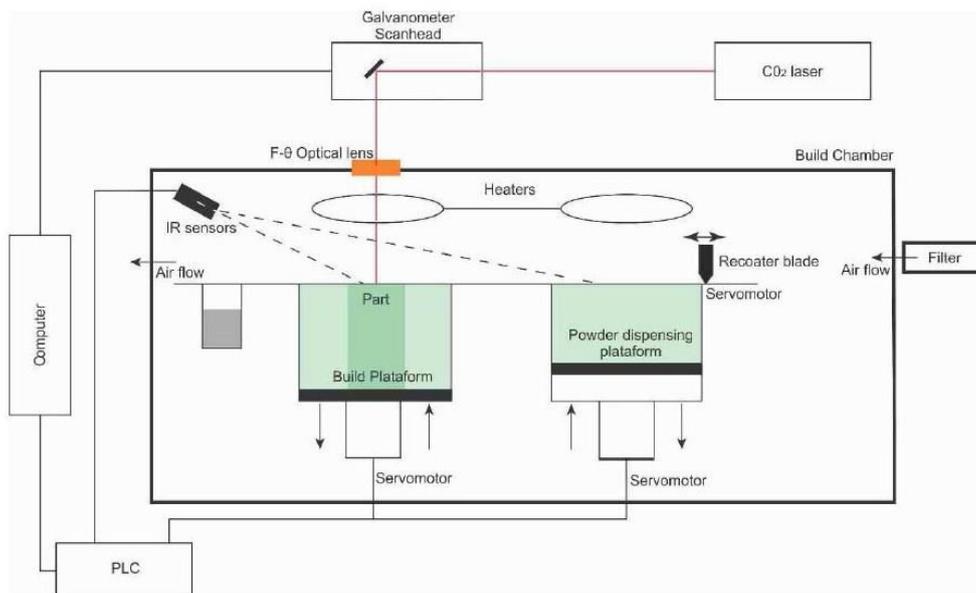


Figure 2: Schematic of SLS LASERFUNDE processing system.

3. MANUFACTURING DESCRIPTION OF THE UHMWPE COMPLEX GEOMETRY

3.1 Geometry selection and general manufacturing procedures

A torus geometry, depicted in figure 3, was chosen for the challenge of optimize the processing parameters due to its complex, but feasible, shape. The printed torus had a maximum diameter of 50 mm containing a curved cylinder with an external diameter of 10 mm.

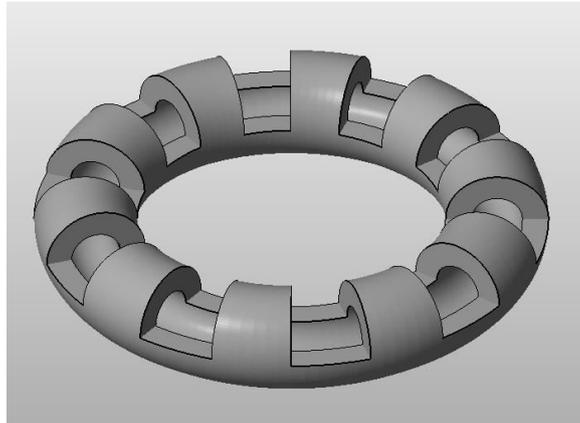


Figure 3 – Geometry of the part selected for the investigation. [LASERFUNDE software]

As the torus is a circular part and the part heater of the equipment is a circular infrared lamp, the parts were built in the centre of the build area of the chamber to ensure that the bed temperature would be equally constant all over the 360 degrees of the laser scanned powder.

The powder used for printing the torus was pre heated in the feed chamber at around 90°C for one hour so that when the powder was spread over the part bed, minimal provision of additional thermal energy was required.

The manufacturing started with temperatures close to the melt temperature of UHMWPE (~130 °C) used as feedstock as suggested by Goodridge et al. (2011), being that the only temperature that they could produce multiple layer parts. They also evidenced that the only multiple layer parts that could be produced from UHMWPE were produced using a double scan count tool, which means that the laser beam traverses a scan vector twice per layer. In this work the laser just scanned one time per layer.

The layer thickness and scan spacing were kept constant. Khalil and Hopkinson (2016) laser-sintered UHMWPE with a reported average particle size of 130 µm and manufactured rectangular parts for flexural three point bending tests with a layer thickness of 0.1 mm and scan spacing of 0.15 mm. Following the same ratio, a layer thickness of 0.2 mm and scan spacing of 0.25 mm for a feedstock with 205 µm as average particle size was used.

The software resources of Sinterscan, which alternates the scan vectors in 90° in the x and y axis on each layer, and the Contour tool, which commands the laser to first sinter the contours of the computer-aided designed layer with a predetermined number of contours, were both used in this work. In this experiment, we believe that, during the LASERFUNDE equipment operation, the Contour tool could help to avoid the parts to “curl” during printing, allowing the process to occur normally and preventing the blade to not move the part when spreading the powder.

After the manufacture, the part was cooled down to room temperature before it was removed from the build platform. The rate at which the material is allowed to cool down can affect the densification and mechanical properties of the part (Venuvinod, P. et. al., 2004). The mechanical properties of semi-crystalline materials such as UHMWPE are largely dependent on the overall crystalline morphology of the material, which evolves during cooling of the melt. A greater crystalline content, resulting from a slow cooling rate, corresponds to lower ductility, due to the corresponding reduction in amorphous regions that are responsible for the polymers ability to yield without breaking (Kong, Y. et al., 2003). Goodridge et al. (2011) showed that if the part is removed too early it may distort as a result of uncontrolled shrinkage through the high thermal gradients. In this work, cooling rate of the torus was kept the same to achieve similar mechanical properties, maintaining reproducible properties, and to avoid the parts to shrink or “curl”. The part cooling occurred inside the “powder cake” until its temperature decreased closely to 40°C. This temperature was measured by a Fluke 62 digital infrared mini-thermometer.

3.2 Investigating build chamber temperature and energy density

Two of the most influential parameters, and thus most commonly investigated for SLS applications, are laser power and scan speed, which form part of the laser energy density equation (1). The limits of each parameter were identified through several trials of sintering onto the powder, leading the optimum laser parameters to be found through different analysis. Goodridge et al. (2011) affirmed that for each material there is an optimum energy density that generally needs to be determined on an empirical basis, although some general rules apply. The build bed temperature is often overlooked by researchers who focus only on the energy density value. Whilst ω is a useful indicator, the bed temperature at the time of scanning and the relationship between the various parameters that contribute to a given ω value should also be considered.

According to Gusarov et al. (2002), to estimate the temperature field in the part bed in selective laser sintering process is a key issue for understanding the sintering/binding mechanisms and for optimising the technique. This indicates that calculation of temperature fields in the bed in SLS plays a key role in understanding the operating sintering mechanisms, depending on the powder type and process parameters.

Lasing of the UHMWPE powders caused a high degree of shrinkage in the lased material perpendicular to the laser path direction. This shrinkage separates the lased material from the rest of the bed creating a physical gap between sintered material and powder cake, as illustrated in figure 4. This is particularly a difficult for semi crystalline polymers due to the rearrangement of the polymer chains during the crystallization process. The degree of shrinkage in laser sintered parts is material specific and it is significantly affected by the build temperature, laser processing parameters and cooling rate. For laser sintering, the rate at which a semi-crystalline polymer crystallizes was indicated to significantly influence its proneness to curl and the possibility of obtaining good dimensional accuracy. In order to achieve optimum results, it is important that the material should re-crystallize at a slow rate (Kruth et al., 2007). However, as the focus of this study is not to measure and solve the dimensional accuracy issue, this material shrinkage gap was not been taken in consideration.

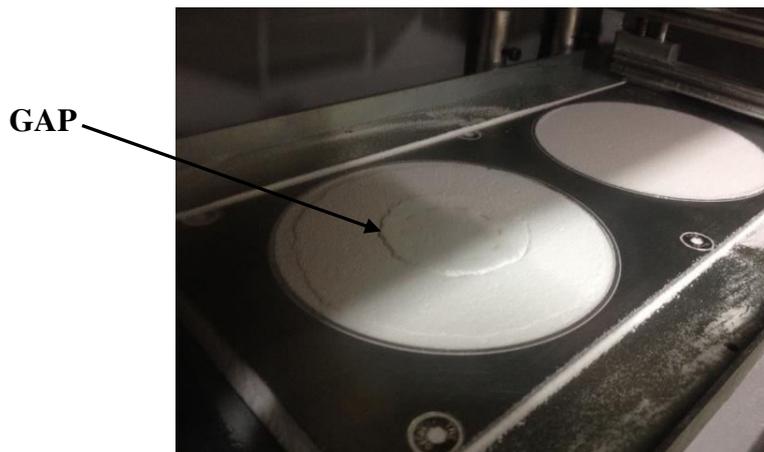


Figure 4 – Fabricated torus evidencing the gap between the part and powder cake.

As already mentioned the temperature range within which a given material is processed has an important ability to reduce shrinkage and eliminate distortion and also has an effect on the mechanical properties of the parts. Tontowi and Childs (2001) demonstrated that the density of sintered polyamide parts was affected by the powder bed temperature, with higher densities being experienced when built with higher bed temperatures. At 182 °C, 100% density was observed, whereas at 178 °C the density was only 96%. However, geometric accuracy can be lost with higher build temperatures and thus a balance between these two factors is required.

In this work, the laser sintering parameters alternated were the laser power, scan velocity and build chamber temperature and the optimization procedure was given by empirical tests on the SLS equipment. The first two parameters both influence directly on the laser energy density. To evaluate the quality of the torus part after its manufacturing, the parts were classified as having good look (G), weak look (W), part cake (PC) and degradation (D) following the considerations explained below:

Good (G) - the good parts are those that were sintered, no degradation occurred and no “part cake” were formed inside the torus. The cooled parts had enough structural integrity and mechanical strength to be cleaned up without break.

Weak (W) - as a result of less energy being inputted into the system, the laser energy density and temperatures were not sufficient to provide enough structural integrity for the parts to be handled. After the sintering and cooling, the parts broke during handling and cleaning;

Part Cake (PC) - due to the conduction of excess heat into the surrounding supporting powder, provided both by too high laser energy density or high temperature, caused heat to be conducted into the powder bed, melting surrounding powder particles in addition to those actually targeted by the laser, bonding it to the boundaries of the part. On brushing and cleaning of the part, a hard powder cake, known as “Part cake”, was formed, which made clean up of the parts difficult;

Degradation (D) - as a result of too much laser energy density inputted to the system, the sintered polymer degraded. The part surface created holes, and became yellowish;

The trials were first conducted with a temperature within the range of 120 to 130 Celsius degrees in the center of the building bed and a combination of laser power and scan velocity, resulting in a low laser energy density. Goodridge et al. (2009) affirmed that processing UHMWPE with laser powers below 10W did not sinter the particles to any degree that would allow removal from the machine, so the minimum laser power tested was 10W and was the power used in the first test, adjusting the scan velocity and laser beam power in attempts to achieve a optimized energy density that allow the manufacture of good torus. Table 1 below shows the first attempts of building the torus with UHMWPE, using high temperatures and low energy densities.

Table 1 - Laser sintering parameters combinations at a temperature of 120 to 130 Celsius

Combinations	Scan Velocity (mm/s)	Laser Beam Power (W)	Energy Density (J/mm ²)	Results
1	1000	10	0,04	W
2	1000	16	0,06	W
3	500	10	0,08	W
4	500	16	0,13	PC

After the trials with high temperature and low energy density the next step was to manufacture parts with medium temperature, within the temperature range of 100 to 110 Celsius degrees in the center of the bed, and medium energy density. The intensity of the energy density set as low, medium and high is defined by comparing the laser beam power used and the maximum power that the equipment laser can provide. Table 2 shows the attempts and results of laser sintering with 100/110 degrees.

Table 2 - Laser sintering parameters at a temperature of 100 to 110 Celsius

Combinations	Scan Velocity (mm/s)	Laser Beam Power (W)	Energy Density (J/mm ²)	Results
1	500	27	0,22	PC / D
2	500	16	0,13	PC
3	1000	27	0,11	PC
4	500	10	0,08	W

For the last attempts, as show in table 3 below, the parts were manufactured within the temperature range of 90 to 100 Celsius degrees in the center of the bed, which is around 40 degrees below the melt temperature of the feedstock, and high laser energy density.

Table 3 - Laser sintering parameters at a temperature of 90 to 100 Celsius

Combinations	Scan Velocity (mm/s)	Laser Beam Power (W)	Energy Density (J/mm ²)	Results
1	500	35	0,28	PC / D
2	1000	35	0,14	PC
3	1000	27	0,11	PC
4	1000	16	0,06	W
5	500	16	0,13	PC
6	700	16	0,09	G

The attempts in different temperatures demonstrated the major influence of the laser energy density on sintering this ultra-high molecular weight polyethylene and on its heat transfer to adjacent unscanned powders that should not get hard. This conclusion can be easily noted when it is compared the manufacturing of parts with an energy density of 0.13 J/mm² (Scan spacing of 500 mm/s and laser power of 16W) in the three different temperature ranges showing equal quality results .

By the fourth attempt of laser sintering in 90/100 degrees, it was noted that the temperature was not influencing on the part quality as much as the energy density were. It was also noted that energy densities of 0.08 and 0.11 J/mm² led to the same results in any temperature, wherein the 0.08 J/mm² energy density resulted in weak parts and 0.11 J/mm² density resulted in formation of part cake. As said before on this paper, the UHMWPE has a very narrow processing window, and it can be noted that in any temperature, the parts that resulted in weak structures has energy densities equal, or below, 0.08 J/mm² and parts resulted in part cake formation were manufactured with energy densities equal, or higher than, 0.11 J/mm².

By that observation, the next attempt was to selective sintering a torus part with an energy density in between these two values, with a low temperature, to see the results. These results are presented in the sixth attempt on table 3. As can be seen, the energy density able to fabricate a good torus part was 0.09 J/mm², and it was achieved when the scan velocity was changed to a value of 700 mm/s, between 500 and 1000 mm/s, with a 16W beam power. As noted before, the temperature did not had a major influence on parts quality, so the 0.09 parts were fabricated in the lowest temperature in order to save time and costs.

Figure 5 shows the torus part manufactured with 0.08, 0.09 and 0.11 J/mm² of energy density. As also reported by Rimell and Marquis (2000), an apparent change from a semi-crystalline state to a transparent glassy material upon laser sintering was noted by which is evidenced by the transparent nature of the lasered material compared with the opacity of the starting powder.

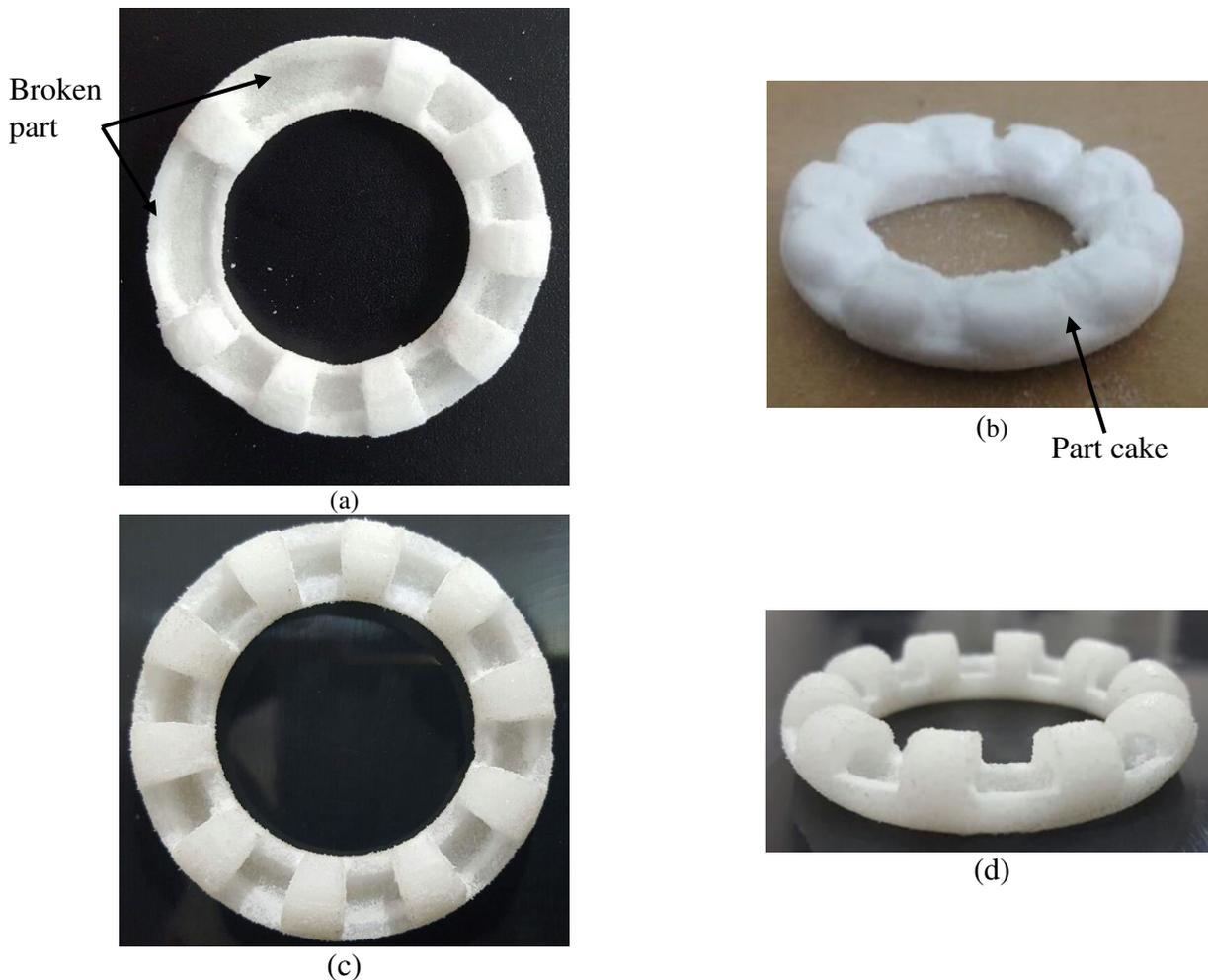


Figure 5 – Examples of printed torus that resulted: (a) weak; (b) formed part cake; (c) and (d) good torus.

4. CONCLUSION

This work has attempted to process UHMWPE via a home-made laser sintering equipment. The results showed the feasibility of producing a UHMWPE complex shape part via SLS without the presence of visual defects.

The best parts were manufactured using a low build temperature (about 30 °C below the UHMWPE melt temperature) with a combination of 16W and 700 mm/s of laser power and scan velocity, respectively. This

combination resulted in density energy around 0.09 J/mm^2 . When applied higher density energy the bed temperature parameter has proven to have little influence over the quality of the part.

This work shows that although the processing window of UHMWPE is narrow, it is possible to fabricate well defined multiple layer parts with this material. The small processing window could limit the feasibility of processing UHMWPE commercially due to variation and inconsistencies between and within current laser sintering systems.

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