DOI: 10.5604/01.3001.0053.7286
Volume 118 • Issue 1 • May 2023

Journal of Achievements in Materials and Manufacturing Engineering

International Scientific Journal published monthly by the World Academy of Materials and Manufacturing Engineering

A comprehensive review of polymer materials and selective laser sintering technology for 3D printing

F.E. Jabri [a,*], A. Ouballouch [b], L. Lasri [c], R. El Alaiji [a]

[a] Laboratory of Innovative Technologies (LTI), Abdelmalek Essaadi University, ENSA, Road Ziaten Km 10, Tangier Principale, BP: 1818 - Tangier, Tangier 90060, Morocco

[b] Laboratory of Mechanics, Production and Industrial Engineering (LMPGI), Hassan II University, EST, Road El Jadida Km 7, BP: 8012 - Oasis Casablanca, Casablanca, Morocco

[c] Systems Engineering and Innovation Laboratory, Mechanics and Systems Engineering Team, Moulay Ismail University, ENSAM, Marjane 2, B.P. 15290 - Al Mansor, Meknes 50000, Morocco

* Corresponding e-mail address: fatimaezzahrae.jabri1@etu.uae.ac.ma

ORCID identifier: https://orcid.org/0000-0002-2453-3210 (F.E.J)

ABSTRACT

Purpose: This review analyses different approaches used to study selective laser sintering (SLS) technology of polymer materials. These main approaches concern: thermal behaviour, fatigue and surface roughness.

Design/methodology/approach: Regarding the first behaviour, researchers extensively studied the impact of process parameters, including scan speed, laser, power and laser energy density, on the thermal behaviour of 3D printed parts. Numerical and experimental analyses are used to conduct process parameter evaluations.

Findings: Laser power and scan speed are the most significant parameters of the laser energy density. For the second, according to test protocols and quantitative analysis performed, the authors concluded that the combination of small and large laser energy density particles generates higher sintering and better fatigue resistance. Moreover, tensile analysis in different environments showed that testing in the water decreased the fatigue life of polymer samples. The influence of process parameters on the mechanical properties and surface roughness of 3D parts is also analysed. In addition, the investigators found that the additives increase the surface roughness of 3D printed parts.

Practical implications: This review shows that researchers can focus on creating a combination of these approaches to expand the use of this process for industrial part production.

Originality/value: All these investigations have made it possible to determine the optimal process conditions to ensure higher quality, optimal surface quality and better fatigue strength.

Keywords: Selective laser sintering (SLS), Polymer, Thermal behaviour, Fatigue, Surface roughness, Process parameters

Reference to this paper should be given in the following way:

F.E. Jabri, A. Ouballouch, L. Lasri, R. El Alaiji, A comprehensive review of polymer materials and selective laser sintering technology for 3D printing, Journal of Achievements in Materials and Manufacturing Engineering 118/1 (2023) 5-17. DOI: https://doi.org/10.5604/01.3001.0053.7286

MANUFACTURING AND PROCESSING

1. Introduction

Additive manufacturing (AM) or 3D printing is a process of creating 3D printed objects by following a series of operations [1]. Layer by layer, until obtaining the final part from a numerical model obtained with computer-aided design (CAD) software. The evolution of this technology in terms of equipment, materials and software has led to a wide range of activities and real advances in many applications. These applications are: aerospace, automotive, biomedical and energy [2,3]. Polymers are the most widespread materials used for 3D printing. Particularly for stereo-lithography (SLA), fused deposition modelling (FDM) and selective laser sintering (SLS) [4,5]. Principally, selective laser sintering received particular attention. Due to its relativity to high dimensional accuracy, ease modification, design changes, and flexibility in the type of materials [6]. In this context, SLS is a technology that consolidates the powder particles. This fact is obtained by transmitting energy as a result of a CO_2 laser beam that will pass through the scanning mirrors [2,7]. A selective laser sintering system is shown in (Fig. 1). These SLS printers are equipped with a powder placed on the print bed. The print bed takes a translation along the Z-axis during the manufacturing process by means of a power delivery piston. After preheating the roller, print bed, and sintering powder at a temperature below the polymer melting point. A first layer of powder is applied to the bed using a roller. Then, the laser beam is scanned to melt the first layer, another layer is added, adhering to the previous one. The bed lowers as each layer is completed and covered with the surface of the material. These steps are repeated until a 3D printed part is produced [8,9]. Furthermore, this technology is often used for industrial plastic parts [10]. Because of its advantages compared to other conventional production methods (especially injection moulding). These include short cycle time from design to manufacturing, high geometric freedom, personalised components, and low-cost production of small numbers of parts [11]. Numerous research have highlighted the range of applications for AM employing the 3D printing method from polymer filament compared to conventional manufacturing procedures. In this regard, to compete effectively with conventional production methods, some quality issues need to be resolved to meet the operational and in-service load requirements. These involve inaccuracies in dimensions and form, unexpected mechanical performance and internal defects [12]. Two critical factors must be considered to provide a high-quality and mechanical strength of 3D printed products. First, control of thermal distribution to ensure optimised process parameters. Because it's related to heat distribution, radiation and thermal convection phenomena provided in the SLS-built chamber [13]. For that, thermal behaviour is one of the critical factors influencing the transformation of the microstructure. As a result, thermal phenomena significantly influence dimensional accuracy, surface finish, mechanical and microstructure strength [13-15]. Hence, different aspects are studied to thoroughly understand the effect of various process parameters and material characteristics on the quality and surface roughness of 3D printed parts. The second factor is the ability of 3D-printed parts to withstand environmental and mechanical stresses. These considerations subsequently cause material failure and fatigue crack propagation. So, fatigue can occur in polymers under applied stresses below their yield point [16]. Moreover, there are factors that decrease the mechanical strength during the fatigue analysis. This involved process parameters and geometrical and environmental considerations. So, it is essential to have a comprehensive understanding of the fatigue behaviour to improve the final parts' reliability and durability [17]. Consequently, this paper gives an overview of surface roughness, thermal and fatigue behaviour of 3D printed polymers. The main goal is to determine whether there are models that can shed light on the printing parameters that produce the best fatigue resistance. Also, to pick optimised parameters and physicochemical properties of powder that will result in high surface quality of the product. This review is structured as follows. Section 2 provides a description of the impact of process parameters, particle size and morphology, melt pool and temperature distribution on product quality. Section 3 identifies the parameters that directly affect fatigue life and mechanical properties. These comprehend process parameters, powder bed density, geometric and environmental considerations, and material properties. Section 4 shows the parameters and properties that influence the surface roughness exhibited by parts produced via the SLS process. These parameters included process parameters, powder and polymer type. The review's conclusion is reached at the end.

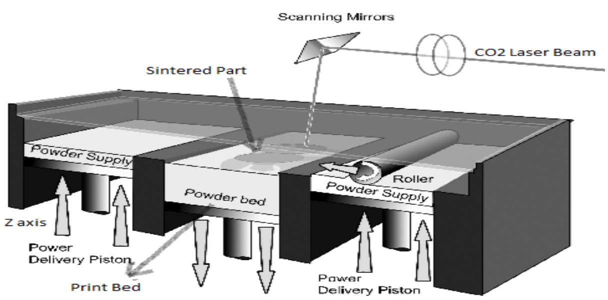

Fig. 1. Schematic of the SLS process [18]

2. Thermal behaviour

The laser projection process involves a complex set of thermal phenomena that results in specific properties of the projected material [19]. In this section, numerical simulations and experimental tests are utilised to analyse and investigate these thermal phenomena. The researchers first defined the process parameters: scan speed ,hatch spacing, energy density and laser power. Then, the influence of process parameter variations, particle size and morphology on part quality and mechanical properties was examined. Also, they analysed the impact of process parameters on temperature distribution and melt pool (see Tab. 1). Additionally, it is shown how particle size affects temperature variation.

2.1. Effect of process parameters and particle size and morphology

The thermal behaviour is a mechanism that links process parameters to product quality. Therefore, process parameters, such as scan speed, hatch spacing, energy density, and laser power, significantly impact the thermal behaviour. These parameters have been widely reported in the literature to have varying effects on the surface qualities of parts produced by SLS. [20] reported that scan speed and laser power are two tied parameters. Because they define the quantity of energy transferred to the volume, which refers to energy density. The laser power represents the quantity of energy delivered per second, while the scan speed governs the time spent in the same section (see Fig. 2).

Therefore, these two parameters must be balanced to prevent the formation of pores due to insufficient or excessive energy. To reduce build times for industrial manufacturing, [21] investigated the powder bed fusion (PBF) at high scan speeds. In this work, they claimed that high-speed processing decreases the density of printed parts and particle fusion. Moreover, [22] revealed from his experimental analysis that with non-constant values of the scan speed during the sintering process . Local overheating and notable deformations are obtained, which also influenced the mechanical performance of 3D parts. In order to explain the combined influence of scan speed and laser power on energy density. [23] concluded that with high scan speed and low laser power, the energy density is insufficient to melt a single layer.

As a consequence, it leads to low part density and poor mechanical properties. Additionally, due to the high energy density generated, the powder may partially decompose with relatively high laser power and low scan speed. This equation (1) confirms the results [20]:

$$E_d = \frac{P_{laser}}{v_{scan} * h_{space} * t_{layer}} \quad (1)$$

where E_d, P_{laser}, v_{scan}, h_{space}, and t_{layer} represented the energy density, laser power, scan speed, hatch spacing and layer thickness, respectively. In this context, [23] noted that high energy could result in undesirable outcomes during the part's construction and might deteriorate the properties of the polymer. [24] confirmed the same result, concluding that using an energy density of less than 0.1 J/mm^2 remains the desired technological and energetic solution. Selecting this particular input could result in energy consumption. Moreover, the thicknesses of the laser-melted powder are also examined by [24]. In this study, the authors correlated these thicknesses with the used density energy. Based on the heat point source model, depth grows with energy density and proves that heat diffusion along z becomes dominant. The hatch spacing (Fig. 2) represents the separation between the sintering lines formed as the laser spot moves [25]. In this regard, [20] announced that it is required to determine the proper track distance. In order to avoid zones with no or incomplete interactions with the laser beam, resulting in unfused powder particles. Also, for obtaining a high-quality part and optimising the processes build rate.

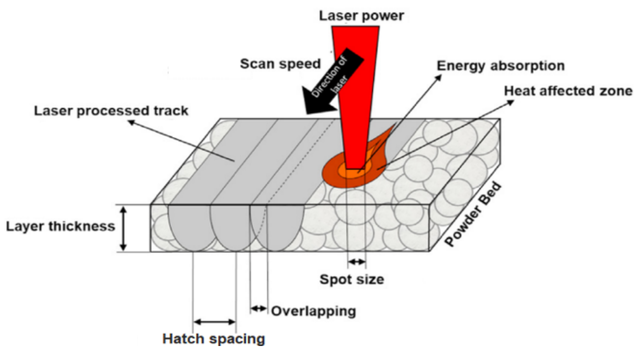

Fig. 2. Scheme of process parameters involved during the SLS process [20]

Furthermore, particle size and morphology really affect the flowability and powder bed density [26]. Researchers reported that particle shape is a crucial element of the PBF sub-functions, namely recoating and coalescence [27]. In this regard, [26] discovered that spherical particles (Fig. 3) improve the dimensional accuracy of 3D printed parts. In turn, it contributes to the creation of a denser powder bed. [10] also showed in their study that a non-spherical particle decreases the properties of 3D printed parts. According to [26], the fine particles are small enough that surface forces induce them to agglomerate, opposing flow and hindering smooth layer coverage unlike parts produced with larger

Table 1.
A summary of process conditions, properties and results from the studies that used selective laser sintering of polymers

Ref.	Polymer type	Powder properties	Laser and constant parameters	Properties of produced parts
[21]	PA12	• Mean particle diameter dv50: 60-80 µm. • Refreshed powder mix of 50:50 new and recycled powders.	• Energy density E_d values: 0.3-0.4 J/mm². • Hatch spacing: 0.25 mm. • The temperature of the build chamber: 173°C. • The feed temperature of the powder: 80°C. • Build orientation: y-axis. • Coating speed: 250 mm/s with a counter-rotating roller.	**At E_d =0.3 J/mm²** • The porosity grows from 2.5% to around 6.5% as the scan speed increases. • There is a significant link between the density and porosity. • Higher scan speed results in partial melting of the particles. • With a lower scan speed value, the particles occur to be completely molten. **At E_d =0.4 J/mm²** • The porosity is almost constant at about 4%. • The part density is relatively constant at a level of 0.98 g/cm³. • Deterioration of the mechanical properties.
[22]	PA12 and PEKK	• Powder grain diameter: 30 and 70 µm (for PA12). • More spherical shape for the PA12 powders than for the PEKK. • Powder grain diameter: 10 and 90 µm (average value D50 =50 µm for both) (for PEKK).	• CO_2 laser, 50 W. • Laser radius: 120 µm. • Layer thickness: 30-80 µm. • Spreading temperature: 373 K (for PA12). • Spreading temperature: 373-473 K (for PEKK).	• 15% is the optimum porosity rate (for PEKK).
[23]	PA6	• A nearly spherical shape. • The average particle size: 25.6 µm. • The particle size: 12.3-50.7 µm.	• CO_2 laser, 55 W with radius of 0.35 mm. • Preheating temperature: 190°C.	• Excessive energy density reduced part quality due to the possibility of material degradation. • High porosity and distinct layer separation caused by the low energy density resulted in poor bonding strength and mechanical qualities, and also the unfused powder can be seen between the two layers.
[24]	PA 12		• CO_2 laser, with maximum average power: 50 W. • The laser spot diameter 0.7 mm. • The scan speed: 500-2500 mm/s. • The laser power: 12.5-50 W. • Room temperature (20°C).	• With lower energy density values, real agglomeration process begins. • High energy may generate negative effects during the part construction process and may damage the polymer, reducing its properties.
[30]	CNTs/ PA12	• A near-spherical shape • The average size: 60-70 µm.	• The length and width of the powder layer: 30 mm. • The thickness of the powder layer: 0.1 mm. • Diameter of the laser beam: 0.42 mm • Bed temperature: 174°C. • Temperature of fusion finish: 190°C.	• The energy density level: 0.015-0.04 J/mm². • The optimized parameters for SLS process of the material CNTs/PA12 are obtained as P = 40 W, s = 3800 mm/s and h = 0.3 mm.

particles, which can induce layer scarring by disrupting the smooth surface of the powder bed. These defects impact directly the quality of manufactured parts.

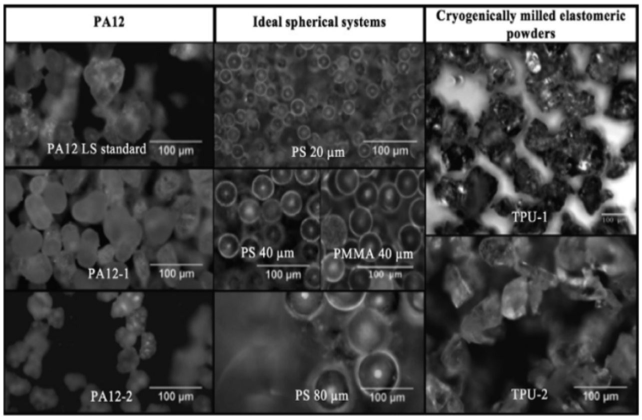

Fig. 3. Examples of powder morphology from commercially available nylon-12, polystyrene, poly(methyl methacrylate), and thermoplastic polyurethane [28]

2.2. Melt pool

According to the literature, the melt pool is impacted by the process parameters. So, it is important to figure out the reaction of the melt pool under various process parameters. For this reason the melt pool generates descriptive relationships between process parameters, mechanical properties and surface performance [29] (see Fig. 4). Using a three-dimensional finite element model (FEM), [22] accurately estimated the resulting fusion depths of two polymers, PA12 and PEKK, during SLS. In other words, they indicated that the powder bed reflects or diffuses most (60%) of the incident laser light. Whereas just 40% contributes to polymer melting.

Similarly, [30] have made predictions of melt dimensions for sintered PA12/CNTs nanocomposite. In the opinion of [31], both the physical properties and the laser power have an influence on the melt pool. Furthermore, [30] related that the maximum temperature, width and depth of the melt pool all increase as the laser power increases while the scan speed decreases. In some cases, for multi-track scanning, the hatch spacing controls the overlap of melt pools in adjacent tracks, impacting the total melt pool volume. As well as [23] stated numerous experimental and numerical simulation analyses for the polyamide 6 (PA6) processing. In this study, they concluded that the melt depth increases with increasing laser power because of higher heat penetration.

Moreover, the depth decreases with increasing scan speed due to inappropriate heat input. [23] also observed that the depth of melt pool directly affected the bond strength between the powder layers. A higher melt depth leads to a higher sintering conditions and better mechanical properties. As a result, the optimized parameters are in the region where the powder can be remelted. This ensures a sufficient depth of the melt pool, while the maximum temperature is lower than thermal decomposition temperature of powders.

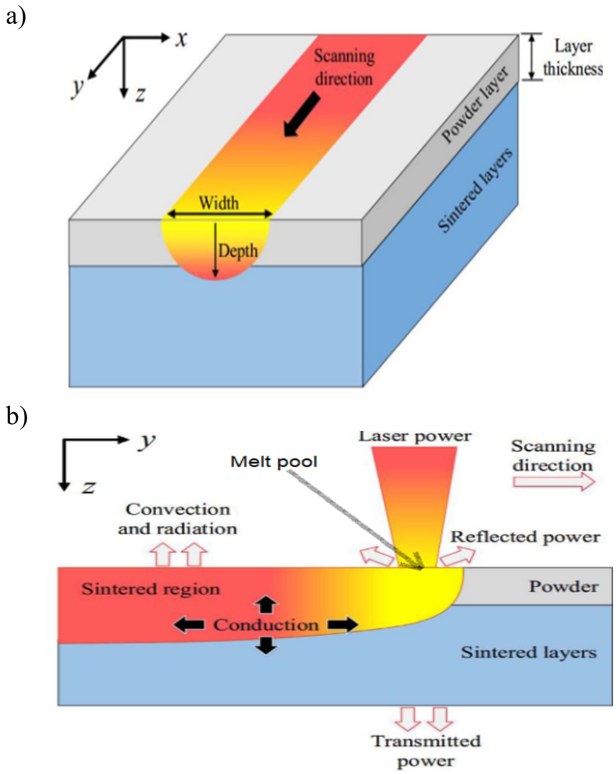

Fig. 4. Illustration showing the powder bed sintering process: (a) overall view and (b) cross section view [30]

2.3. Temperature distribution

Inconsistent thermal distribution of laser sintering machines is one of the major problems experienced by SLS users. Scientists, users, and machine producers have remarked that the temperature distribution is irregular on some commercial machines .This conduce to discrepancies in the mechanical characteristics of the parts [32]. Various experiments to deconstruct all parameters of this problem have been introduced in the form of experimental research and numerical simulations. [23] noticed that the temperature increased rapidly as the laser beam approached, while temperature decreased slowly as the laser beam moved away. Also they found that the maximum temperature of the melt pool increased as the laser moved, which is related to the impact of the heat stored in the first path. Besides, [31] proposed a three-dimensional finite element (FE) method by COMSOL Multiphysics software, in order to calculate the maximum temperature at the centre of the laser spot. In this simulation, the phenomena of convection and thermal radiation are considered. They concluded that the preheating power and the application of temperature with a small beam from the laser caused a large temperature change on the surfaces of the polyamide layer. In addition, [32] emphasized the importance of the powder bed temperature when it is projected over the build area. In fact, if there is a large difference between the powder bed temperature in the powder bed and the new powder layer, flow/deposition or curling problems in the previously scanned layer can arise. Furthermore, [33] supported this result by considering that the bed temperature had a significant influence on the geometric accuracy of the part. [22] and [34] focused in their studies on the thermal cycle of the PBF process. They reported that the low temperature (lower than the crystallization onset temperature) promotes thermal shrinkage during crystallization and layer deformation. So it is essential for polymers to have their melting temperature higher than the crystallization temperature. For the raison, that crystallization can be delayed and reduced during the construction process. Moreover, to figure the impact of process parameters on temperature distribution. [23] proved that as the three-dimensional and maximum melting temperature increases, the laser power raises and the scan speed decreases. [35] asserted also that printing with low bed temperatures lead to parts with low density.

3. Fatigue behaviour

The main disadvantages of polymer SLS parts are porosity, shrinkage/warpage caused by thermal distortion, and low strength in the Z-direction [6]. These failures can lead to cracking or fracture. Especially when the structure is subjected to repeated critical loads, resulting in fatigue damage [36]. There are many types of fatigue tests that examine the structure's response to cyclic loading, including axial loading, repeated or alternate bending, rotational bending, mechanical fracture tests and torsional fatigue. There are other types of fatigue tests namely: combined bending and torsional fatigue and biaxial and triaxial fatigue, that are used in more complex fatigue analyses [36]. Furthermore, the stress-cycle diagram, or the S-N curve, represents the fatigue behaviour of polymers .They also illustrate the evolution of stress as a function of the number of cycles until failure [37]. Hence, fatigue behaviour is a long-term factor that has an impact on mechanical properties such as tensile strength and yield strength. Therefore, the effects of process parameters including energy density, powder bed density and printing orientation are first introduced. Then, the impact of section thickness and particle affinity on fatigue life are discussed in section 3.2. Finally, the influences of materials properties and environment considerations on mechanical properties are examined in details.

3.1. Process parameters and the powder bed density

Several experiments were conducted to analyse the behaviour of the structure during fatigue tests. In this reference [38], in fatigue tests for PA12 material , each load cycle induces an increase in temperature near the failure point as illustrated in the (Fig. 5) performed by IR-camera. It was also reported that the fatigue life of the parts was affected by the density of the PA12 samples. A lower density would raise the probability of fracture initiation due to unfused powder particles. Furthermore, [39] claimed that the quantity of energy deposited during scanning has a strong relation with tensile characteristics and mechanical performance. In this context, [40,41] concluded that as the energy input increases, the penetration of laser increases, resulting in a denser part morphology, increased elongation at break, and tensile strength. In addition, [41] focused on particle sizes to see how they affected fatigue life. They discovered that a combination of large laser energy densities and smaller particles results in a higher degree of sintering and elevated fatigue life. [7] also proved that the density of the powder sample is an important parameter for the sintering quality. A high value results in good agglomeration and gives more particle-to-particle contacts and a smaller pore size. This leads in turn to faster sintering. However, a low density makes the material difficult to consolidate. Furthermore, by raising the powder bed density for both nylon-12 and a thermoplastic polyurethane (TPU) powder. Due to better packing and flowability of the powder, [42] observed an increase in printed density, an increase in ultimate tensile properties and a decrease in surface roughness. [41] reported that the energy density of the laser has a significant impact on the mechanical properties, particularly the porosity and microstructure of poly-caprolactone (PCL) material. According to [40,43] porosity between layers generates weak interfaces, which reduces the overall strength of the part. The porosity [44] can arise for two reasons. First, sufficient time scales and energy levels can prevent the imperfect densification of particles. Second, high levels of laser energy can cause extremely high temperatures, resulting in the pyrolysis of the polymer, which appears as porosity. This explains that porosity is not only the result of an insufficient energy level, but of an excessive energy level. Another factor affecting the mechanical properties of produced parts is printing orientation. The authors of a study [45] examined the impact of built orientation on notched and un-notched nylon-12 (PA12) hourglass specimens. The studies reveal that notched specimens have a longer fatigue life. This is that because notched specimens receive less thermal stress and a smaller volume is exposed to cyclic loading.

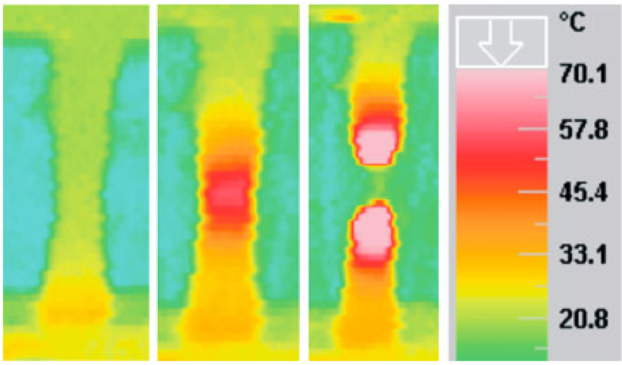

Fig. 5. IR-camera temperature measurements during fatigue testing [38]

On the other hand, they indicate that orientation has no effect on fatigue life. Furthermore, in this reference [46], the samples were tested in the X and Z axis orientations and at 30 Hz and 50 Hz frequencies. According to the results, printing in the Z direction has no impact, but the 50 Hz tests reduced fatigue life. Another test was performed for rotational and reversed bending for specimens printed parallel to the Y and Z axes [47]. The two types of orientations and tests gave no significant difference, showing that the specimens are isotropic. (Fig. 6) showed the three build orientation of test parts. However, studies that do not include frequency testing and notched/unnotched samples prove that printing orientation directly impacts mechanical performance. In this regard, [48] showed that flexural and tensile [49] testing of components created in the Z-axis orientation revealed the lowest strength and stiffness values. At the same time, tensile testing of parts built in the y-axis orientation revealed the highest mechanical property values. Furthermore, [48] and [50] found that the highest strength and stiffness appeared in parts printed in the x-axis orientation, i.e., an orientation parallel to the laser scan direction. The influence of the anisotropy [51] was examined on samples plotted in perpendicular (90°) and parallel (0°) directions for both PA12 and thermoplastic polyurethane configurations (TPU). Figure 7 represented the test specimen configurations. The semi-brittle failure behaviour of the SLS-printed TPUs was particularly noticeable for printing directions perpendicular to the stress (90°). They also asserted that the influence of the printing orientations, or more specifically, the weak interfaces between layers, had a mitigating effect on the smooth notch. In addition, [51,52] concluded that the maximum fatigue strength was found for the 0° printing orientations specimens. While the lowest fatigue strength was found for the 90° printing orientations specimens. (Fig. 8) illustrated the test specimen configurations of [52]. Overall, the specimen printing direction induced anisotropy is crucial for further strength investigation.

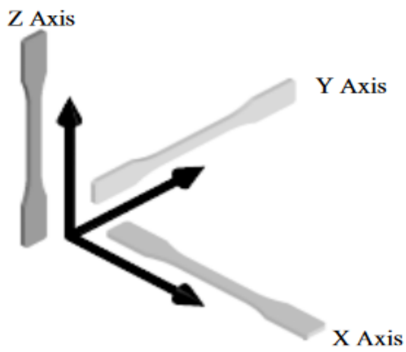

Fig. 6. Build orientation of test parts [48]

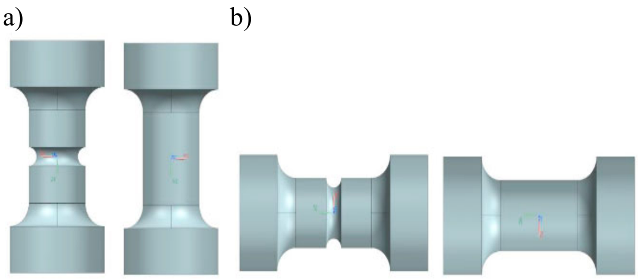

Fig. 7. Configurations of cylindrical test specimens (a) printing orientation vertical (90°); (b) printing orientation parallel (0°) [51]

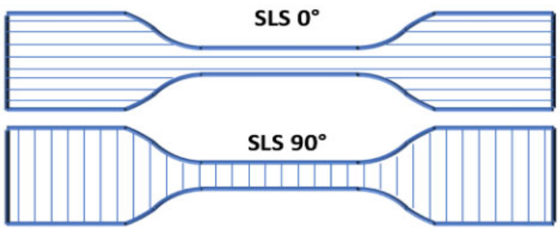

Fig. 8. Specimen geometry for the experimental program, lines indicating layer orientation in SLS for tensile and fatigue life testing [52]

3.2. Geometric consideration

In addition to process parameters, geometric considerations such as section thickness and particle affinity substantially impact fatigue life. Studies by [53] examined the effect of geometry on fatigue life by altering section thickness (2, 4, and 6 mm) of PA12 dog bone specimens. These specimens are subjected to tension-compression loading and uniaxial tension-tension. In both situations, a higher section thickness resulted in improved fatigue life. However, the results for tension-tension loading were not statistically significant. This is mainly due to the fact that the temperature increases faster in small-section thicknesses than in large ones. According to literature researches, if there is a poor affinity between the powder particles, the part starts to lose its rigidity and degrade more quickly [36]. In this regard, studies conducted by [54,55] explored the relationship between fatigue life and particle affinities. In the first study [54], rectilinear boxes ($35 \times 5 \times 1.4$ mm^3) were made from a combination of PA6 and PA12. The 50/50 and 20/80 blends exhibited the best fatigue life, although there was an overall low affinity between the two particles.

Similarly, [55] created rectilinear boxes from polybutylene terephthalate (PBT) and PA12. The 90/10 blend has the longest fatigue life. Moreover, the 90/10 combination did not harden or soften during cyclic loading because the stress change remained constant.

3.3. Material properties and environment

According to the literature, the fatigue life of SLS polymers is affected more by material characteristics and ambient factors than by process parameters and geometric considerations. Many experiments have compared injection moulded and 3D printed specimens, varying materials, and conditions in order to present the effect of different material properties on fracture fatigue life. In [56], compact tensile specimens made of PA12 were constructed by injection moulding and 3D printing. The finding revealed that the SLS components had longer fatigue life and less deformation. In [57], compact tension specimens ($50 \times 48 \times 10$ mm^3) made of pure PA12 (PA12) and short glass fibre PA12 (PA12-f) were examined in a dry atmosphere at 23 and -50°C. Both materials have similar characteristics at 23°C and -50°C. Both materials have comparable fatigue life at 23°C, while PA12-f has a much better one at -50°C. Similarly, [58] compact tensile specimens ($50 \times 48 \times 10$ mm^3) were fabricated from PA12 and PA11 and tested in three different environments: wet at 23°C, dry at 50°C, and dry at 23°C. From the results, PA11 exhibited better fatigue resistance at low temperature than at room temperature. It also showed better fatigue crack propagation behaviour than PA12. Moreover, they also claimed that the water test decreased the fatigue life of both samples, with a reduction in fatigue parameters, especially for PA12. Therefore, the toughness, stiffness, and strength of polyamides decrease with humidity while their ductility increases.

4. Surface roughness

The surface irregularities that appear on the 3D part define the texture and appearance of the surface. Therefore, they play an important role in the characterisation of the surface. In this regard, process parameters, powder, and polymer type have been widely reported in literature to have varying effects on the surface roughness of 3D parts produced by SLS (Fig. 9). In this context, [59] shows that controlling or modifying the parameters can augment the surface quality. So, a deeper understanding of the effect of process parameters is needed for optimal surface quality. These process parameters included: laser power, scan speed, hatch spacing, bed temperature and layer thickness. During the investigations of the impact of process parameters on surface roughness, [60] found a strong relationship between hatch spacing, laser power and bed temperature. Also, [60,61] revealed that laser power is the most crucial factor in reducing surface roughness. At that [62] emphasised that a less uniform surface is the result of reduced laser power. This leads to less interaction between the powder particles and less compact particles for the 3D printed part. In this reference, [59] reported that the rises values of bed temperature cause the increase in surface roughness. As a result, the material starts to recrystallise faster. So, they noticed a low bed temperature (176°C) is the appropriate working value to reduce surface roughness. For improved dimensional accuracy and surface quality, [61] use the grey relational analysis (GRA) approach in their work. In order to optimise process parameters namely hatch spacing, layer thickness, and laser power for glass-filled polyamide plastic components. They claimed that when the layer thickness is thin, a higher laser power value may sinter the previous layer.

Consequently, sintering inconsistencies emerge in some areas of the product, resulting in a rough surface. Besides, surface roughness increased at [63] with smaller hatch spacing and higher roller speed. Because the smaller hatch spacing provides more energy density to the powder. This leads to a higher melting temperature and lower melt viscosity. As [62] stated, the scan speed has a varying effect on surface roughness. They reported that the average surface roughness R_a rises as the scan speed increases, due to the fact that the powder particles do not have enough time to be properly sintered, resulting in a less uniform surface.

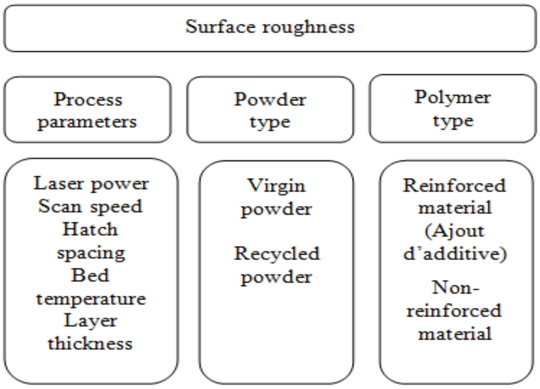

Fig. 9. Parameters and properties impacting surface roughness

On the other hand, other research shows that adding additives to polymers has a real impact on the surface quality of the 3D parts. This study [64], aimed to explore whether the surface or mechanical characteristics of polyamide 12 were affected by additions like flame retardants, glass fibre, carbon fibre, and aluminium powder. Samples prepared from pure PA12 and PA12 with aluminium powder exhibited the poorest surface quality. While PA12 with a mix of carbon fibres and glass material produced the best surface quality. It was also found that the proportion of additives in the powder affected the surface quality.

Furthermore, they concluded that additives increase the surface roughness of printed components. Moreover, compared to parts built with virgin powder, [63] found that those made with recycled powder often had rougher surfaces. As a result, they confirmed that the use of aged powder engenders a significant improvement in the surface roughness of SLS parts.

5. Conclusions

This review article summarises the fundamental aspect of thermal behaviour, surface roughness and fatigue of SLS 3D printing for polymers materials. The effect of process parameters on temperature distribution, melt pool, product quality and mechanical properties has been investigated in thermal behaviour. In the third section, the fatigue life and mechanical properties are studied in relation to process parameters, material characteristics and geometrical and environmental determinations. As well as section four focuses on the impact of process parameters, powder and polymer type on surface roughness. The outcomes of this review are listed as follows:

- The two factors that have a significant effect on laser energy density are scan speed and laser power;
- Using an energy density of less than 0.1 J/mm^2 is the optimal technological and energetical solution for polyamide material;
- Higher melting depth leads to improved sintering conditions and mechanical properties;
- The optimised values are situated in the remelt area of the powder;
- Temperature is more affected by scan speed, laser power, and density of 3D printed parts;
- The use of spherical particles increases the dimensional accuracy of 3D-printed components;
- The fatigue life of the parts was affected by the energy density and the powder bed density;
- The thickness of the section improves the fatigue resistance of polymer materials;
- Smaller particles combined with high laser energy densities result in more sintering and longer fatigue life;
- The water test decreased the fatigue life of polymer material;
- Bed temperature, laser power, and hatch spacing significantly influence surface roughness;
- The surface roughness of SLS parts increases when recycled powder is used.

More investigations and experiments are required to find the parameters and conditions that would provide long fatigue life, high surface quality and robust mechanical properties, resulting in high-quality 3D printed parts.

References

[1] P. Baras, J. Sawicki, Numerical analysis of mechanical properties of 3D printed aluminium components with variable core infill values, Journal of Achievements in Materials and Manufacturing Engineering 103/1 (2020) 16-24.
DOI: https://doi.org/10.5604/01.3001.0014.6912

[2] B.A. Praveena, N. Lokesh, A. Buradi, N. Santhosh, B.L. Praveena, R. Vignesh, A comprehensive review of emerging additive manufacturing (3D printing technology): Methods, materials, applications, challenges, trends and future potential, Materials Today: Proceedings 52/3 (2022) 1309-1313. DOI: https://doi.org/10.1016/j.matpr.2021.11.059

[3] N. Guo, M.C. Leu, Additive manufacturing: technology, applications and research needs, Frontiers of Mechanical Engineering 8/3 (2013) 215-243. DOI: https://doi.org/10.1007/s11465-013-0248-8

[4] S. Safaee, M. Schock, E.B. Joyee, Y. Pan, R.K. Chen, Field-assisted additive manufacturing of polymeric

composites, Additive Manufacturing 51 (2022) 102642. DOI: https://doi.org/10.1016/j.addma.2022.102642
[5] B. Karaş, P.J. Smith, J.P.A. Fairclough, K. Mumtaz, Additive manufacturing of high density carbon fibre reinforced polymer composites, Additive Manufacturing 58 (2022) 103044. DOI: https://doi.org/10.1016/j.addma.2022.103044
[6] A. Nouri, A. Rohani Shirvan, Y. Li, C. Wen, Additive manufacturing of metallic and polymeric load-bearing biomaterials using laser powder bed fusion: A review, Journal of Materials Science and Technology 94 (2021) 196-215. DOI: https://doi.org/10.1016/j.jmst.2021.03.058
[7] A. Mokrane, Modélisation numérique du frittage laser des polymères en poudre, PhD thesis, INSA, Lyon, 2019 (in French). Available from: https://theses.hal.science/tel-03173067v1/file/these.pdf
[8] B. Bosserelle, T. Gauliard, J. Delode, Impression 3D : mise en place d'une plateforme collaborative de modèles 3D de pièces détachées et accessoires non critiques de dispositifs biomédicaux (AFIB3D), IRBM News 42/6 (2021) 100356 (in French). DOI: https://doi.org/10.1016/j.irbmnw.2021.100356
[9] J.P. Schultz, Modeling Heat Transfer and Densification during Laser Sintering of Viscoelastic Polymers, PhD thesis, Virginia Polytechnic Institute and State University, Blacksburg, VA, 2003, 24. Available from: https://vtechworks.lib.vt.edu/bitstream/handle/10919/11091/Schultz_Disertation.pdf?sequence=1&isAllowed=y
[10] M. Schmid, A. Amado, K. Wegener, Polymer powders for selective laser sintering (SLS), AIP Conference Proceedings 1664 (2015) 160009. DOI: https://doi.org/10.1063/1.4918516
[11] B. Van Hooreweder, D. Moens, R. Boonen, J.-P. Kruth, P. Sas, On the difference in material structure and fatigue properties of nylon specimens produced by injection molding and selective laser sintering, Polymer Testing 32/5 (2013) 972-981. DOI: https://doi.org/10.1016/j.polymertesting.2013.04.014
[12] W. Zhu, C. Yan, Y. Shi, S. Wen, J. Liu, Y. Shi, Investigation into mechanical and microstructural properties of polypropylene manufactured by selective laser sintering in comparison with injection molding counterparts, Materials and Design 82 (2015) 37-45. DOI: https://doi.org/10.1016/j.matdes.2015.05.043
[13] Z. Yan, W. Liu, Z. Tang, X. Liu, N. Zhang, M. Li, H. Zhang, Review on thermal analysis in laser-based additive manufacturing, Optics and Laser Technology 106 (2018) 427-441. DOI: https://doi.org/10.1016/j.optlastec.2018.04.034
[14] F. Lupone, E. Padovano, F. Casamento, C. Badini, Process Phenomena and Material Properties in Selective Laser Sintering of Polymers: A Review, Materials 15/1 (2022) 183. DOI: https://doi.org/10.3390/ma15010183
[15] E.O. Olakanmi, R.F. Cochrane, K.W. Dalgarno, A review on selective laser sintering/melting (SLS/SLM) of aluminium alloy powders: Processing, microstructure, and properties, Progress in Materials Science 74 (2015) 401-477. DOI: https://doi.org/10.1016/j.pmatsci.2015.03.002
[16] J.A. Sauer, M. Hara, Effect of molecular variables on crazing and fatigue of polymers, in: H.-H. Kausch (ed), Crazing in Polymers Vol. 2. Advances in Polymer Science, vol 91/92, Springer, Berlin, Heidelberg, 1990, 69-118. DOI: https://doi.org/10.1007/BFb0018019
[17] V. Shanmugam, O. Das, K. Babu, U. Marimuthu, A. Veerasimman, D.J. Johnson, R.E. Neisiany, M.S. Hedenqvist, S. Ramakrishna, F. Berto, Fatigue behaviour of FDM-3D printed polymers, polymeric composites and architected cellular materials, International Journal of Fatigue 143 (2021) 106007. DOI: https://doi.org/10.1016/j.ijfatigue.2020.106007
[18] N. Hopkinson, R.J.M. Hague, P.M. Dickens (eds), Rapid manufacturing: an industrial revolution for the digital age, John Wiley, Chichester, England, 2006.
[19] J. Maisonneuve, C. Colin, Y. Bienvenu, P. Aubry, Etude des phénomènes thermiques associés à la fabrication directe de pièces en TA6V par projection laser, Proceedings of the Conference Materiaux 2006 Dijon, France, 2006 (in French).
[20] D. Grossin, A. Montón, P. Navarrete-Segado, E. Özmen, G. Urruth, F. Maury, D. Maury, C. Frances, M. Tourbin, P. Lenormand, G. Bertrand, A review of additive manufacturing of ceramics by powder bed selective laser processing (sintering / melting): Calcium phosphate, silicon carbide, zirconia, alumina, and their composites, Open Ceramics 5 (2021) 100073. DOI: https://doi.org/10.1016/j.oceram.2021.100073
[21] M.M. Lexow, M. Drexler, D. Drummer, Fundamental investigation of part properties at accelerated beam speeds in the selective laser sintering process, Rapid Prototyping Journal 23/6 (2017) 1099-1106. DOI: https://doi.org/10.1108/RPJ-04-2016-0060
[22] P. Peyre, Y. Rouchausse, D. Defauchy, G. Régnier, Experimental and numerical analysis of the selective laser sintering (SLS) of PA12 and PEKK semi-crystalline polymers, Journal of Materials Processing Technology 225 (2015) 326-336. DOI: https://doi.org/10.1016/j.jmatprotec.2015.04.030

[23] M. Li, Y. Han, M. Zhou, P. Chen, H. Gao, Y. Zhang, H. Zhou, Experimental investigating and numerical simulations of the thermal behavior and process optimization for selective laser sintering of PA6, Journal of Manufacturing Processes 56/A (2020) 271-279.
DOI: https://doi.org/10.1016/j.jmapro.2020.04.080

[24] A. Franco, L. Romoli, Characterization of laser energy consumption in sintering of polymer based powders, Journal of Materials Processing Technology 212/4 (2012) 917-926.
DOI: https://doi.org/10.1016/j.jmatprotec.2011.12.003

[25] J. Rudloff, M. Lang, S. Mohseni-Mofidi, C. Bierwisch, Experimental investigations for improved modelling of the laser sintering process of polymers, Procedia CIRP 94 (2020) 80-84.
DOI: https://doi.org/10.1016/j.procir.2020.09.016

[26] C.A. Chatham, T.E. Long, C.B. Williams, A review of the process physics and material screening methods for polymer powder bed fusion additive manufacturing, Progress in Polymer Science 93 (2019) 68-95. DOI: https://doi.org/10.1016/j.progpolymsci.2019.03.003

[27] S. Berretta, Y. Wang, R. Davies, O.R. Ghita, Polymer viscosity, particle coalescence and mechanical performance in high-temperature laser sintering, Journal of Materials Science 51/10 (2016) 4778-4794.
DOI: https://doi.org/10.1007/s10853-016-9761-6

[28] M. Van den Eynde, L. Verbelen, P. Van Puyvelde, Assessing polymer powder flow for the application of laser sintering, Powder Technology 286 (2015) 151-155.
DOI: https://doi.org/10.1016/j.powtec.2015.08.004

[29] J. Li, S. Yuan, J. Zhu, W. Zhang, S. Li, C. Wang, Numerical investigation of novel process planning in the polymeric powder bed fusion, Journal of Manufacturing Processes 67 (2021) 195-211. DOI: https://doi.org/10.1016/j.jmapro.2021.04.060

[30] F. Shen, S. Yuan, C. K. Chua, K. Zhou, Development of process efficiency maps for selective laser sintering of polymeric composite powders: Modeling and experimental testing, Journal of Materials Processing Technology 254 (2018) 52-59.
DOI: https://doi.org/10.1016/j.jmatprotec.2017.11.027

[31] H. Yaagoubi, H. Abouchadi, et M. Taha Janan, Numerical simulation of heat transfer in the selective laser sintering process of Polyamide12, Energy Reports 7/5 (2021) 189-199.
DOI: https://doi.org/10.1016/j.egyr.2021.08.089

[32] R.D. Goodridge, C.J. Tuck, R.J.M. Hague, Laser sintering of polyamides and other polymers, Progress in Materials Science 57/2 (2012) 229-267. DOI: https://doi.org/10.1016/j.pmatsci.2011.04.001

[33] S. Singh, V.S. Sharma, A. Sachdeva, Optimization and Analysis of Shrinkage in Selective Laser Sintered Polyamide Parts, Materials and Manufacturing Processes 27/6 (2012) 707-714.
DOI: https://doi.org/10.1080/10426914.2011.593247

[34] H. Zarringhalam, C. Majewski, N. Hopkinson, Degree of particle melt in Nylon-12 selective laser-sintered parts, Rapid Prototyping Journal 15/2 (2009) 126-132.
DOI: https://doi.org/10.1108/13552540910943423

[35] A.E. Tontowi, T.H.C. Childs, Density prediction of crystalline polymer sintered parts at various powder bed temperatures, Rapid Prototyping Journal 7/3 (2001) 180-184.
DOI: https://doi.org/10.1108/13552540110395637

[36] L. Safai, J.S. Cuellar, G. Smit, A.A. Zadpoor, A review of the fatigue behavior of 3D printed polymers, Additive Manufacturing 28 (2019) 87-97. DOI: https://doi.org/10.1016/j.addma.2019.03.023

[37] K.S.R. Chandran, Mechanical fatigue of polymers: A new approach to characterize the S-N behavior on the basis of macroscopic crack growth mechanism, Polymer 91 (2016) 222-238.
DOI: https://doi.org/10.1016/j.polymer.2016.03.058

[38] B. Van Hooreweder, F. De Coninck, D. Moens, R. Boonen, P. Sas, Microstructural characterization of SLS-PA12 specimens under dynamic tension/compression excitation, Polymer Testing 29/3 (2010) 319-326. DOI: https://doi.org/10.1016/j.polymertesting.2009.12.006

[39] T.L. Starr, T.J. Gornet, J.S. Usher, The effect of process conditions on mechanical properties of laser-sintered nylon, Rapid Prototyping Journal 17/6 (2011) 418-423.
DOI: https://doi.org/10.1108/13552541111184143

[40] C. Majewski, H. Zarringhalam, N. Hopkinson, Effect of the degree of particle melt on mechanical properties in selective laser-sintered Nylon-12 parts, Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture 222/9 (2008) 1055-1064.
DOI: https://doi.org/10.1243/09544054JEM1122

[41] G.V. Salmoria, D. Hotza, P. Klauss, L.A. Kanis, C.R. M. Roesler, Manufacturing of Porous Polycaprolactone Prepared with Different Particle Sizes and Infrared Laser Sintering Conditions: Microstructure and Mechanical Properties, Advances in Mechanical Engineering 6 (2014) 640496.
DOI: https://doi.org/10.1155/2014/640496

[42] S. Ziegelmeier, P. Christou, F. Wöllecke, C. Tuck, R. Goodridge, R. Hague, E. Krampe, E. Wintermantel, An experimental study into the effects of bulk and flow behaviour of laser sintering polymer powders on

resulting part properties, Journal of Materials Processing Technology 215 (2015) 239-250. DOI: https://doi.org/10.1016/j.jmatprotec.2014.07.029

[43] D.L. Bourell, T.J. Watt, D.K. Leigh, B. Fulcher, Performance Limitations in Polymer Laser Sintering, Physics Procedia 56 (2014) 147-156. DOI: https://doi.org/10.1016/j.phpro.2014.08.157

[44] S.R. Athreya, K. Kalaitzidou, S. Das, Processing and characterization of a carbon black-filled electrically conductive Nylon-12 nanocomposite produced by selective laser sintering, Materials Science and Engineering: A 527/10-11 (2010) 2637-2642. DOI: https://doi.org/10.1016/j.msea.2009.12.028

[45] B. Van Hooreweder, J.-P. Kruth, High cycle fatigue properties of selective laser sintered parts in polyamide 12, CIRP Annals 63/1 (2014) 241-244. DOI: https://doi.org/10.1016/j.cirp.2014.03.060

[46] J. Munguia, K. Dalgarno, Fatigue behaviour of laser-sintered PA12 specimens under four-point rotating bending, Rapid Prototyping Journal 20/4 (2014) 291-300. DOI: https://doi.org/10.1108/RPJ-07-2012-0064

[47] J. Munguia, K. Dalgarno, Fatigue behaviour of laser sintered Nylon 12 in rotating and reversed bending tests, Materials Science and Technology 31/8 (2015) 904-911. DOI: https://doi.org/10.1179/1743284715Y.0000000014

[48] U. Ajoku, N. Saleh, N. Hopkinson, R. Hague, P. Erasenthiran, Investigating mechanical anisotropy and end-of-vector effect in laser-sintered nylon parts, Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture 220/7 (2006) 1077-1086. DOI: https://doi.org/10.1243/09544054JEM537

[49] J.H. Koo, R. Ortiz, B. Ong, H. Wu, Polymer nanocomposites for laser additive manufacturing, in: M. Brandt (ed), Woodhead Publishing Series in Electronic and Optical Materials: Laser Additive Manufacturing, Woodhead Publishing, Sawston, 2017, 205-235. DOI: https://doi.org/10.1016/B978-0-08-100433-3.00008-7

[50] J.R.C. Dizon, A.H. Espera Jr., Q. Chen, R.C. Advincula, Mechanical characterization of 3D-printed polymers, Additive Manufacturing 20 (2018) 44-67. DOI: https://doi.org/10.1016/j.addma.2017.12.002

[51] Z. Major, M. Lackner, A. Hössinger-Kalteis, T. Lück, Characterization of the Fatigue Behavior of SLS Thermoplastics, Procedia Structural Integrity 34 (2021) 191-198. DOI: https://doi.org/10.1016/j.prostr.2021.12.028

[52] A. Salazar, A.J. Cano, J. Rodríguez, Mechanical and fatigue behaviour of polyamide 12 processed via injection moulding and selective laser sintering. Analysis based on Kitagawa-Takahashi diagrams, Engineering Fracture Mechanics 275 (2022) 108825. DOI: https://doi.org/10.1016/j.engfracmech.2022.108825

[53] H. Amel, J. Rongong, H. Moztarzadeh, N. Hopkinson, Effect of section thickness on fatigue performance of laser sintered nylon 12, Polymer Testing 53 (2016) 204-210. DOI: https://doi.org/10.1016/j.polymertesting.2016.05.027

[54] G.V. Salmoria, J.L. Leite, L.F. Vieira, A.T.N. Pires, C.R.M. Roesler, Mechanical properties of PA6/PA12 blend specimens prepared by selective laser sintering, Polymer Testing 31/3 (2012) 411-416. DOI: https://doi.org/10.1016/j.polymertesting.2011.12.006

[55] G.V. Salmoria, V.R. Lauth, M.R. Cardenuto, R.F. Magnago, Characterization of PA12/PBT specimens prepared by selective laser sintering, Optics and Laser Technology 98 (2018) 92-96. DOI: https://doi.org/10.1016/j.optlastec.2017.07.044

[56] M. Blattmeier, G. Witt, J. Wortberg, J. Eggert, J. Toepker, Influence of surface characteristics on fatigue behaviour of laser sintered plastics, Rapid Prototyping Journal 18/2 (2012) 161-171. DOI: https://doi.org/10.1108/13552541211212140

[57] A. Salazar, A. Rico, J. Rodríguez, J. Segurado Escudero, R. Seltzer, F. Martin de la Escalera Cutillas, Fatigue crack growth of SLS polyamide 12: Effect of reinforcement and temperature, Composites Part B: Engineering 59 (2014) 285-292. DOI: https://doi.org/10.1016/j.compositesb.2013.12.017

[58] A. Salazar, A. Rico, J. Rodríguez, J. Segurado Escudero, R. Seltzer, F. Martin de la Escalera Cutillas, Monotonic loading and fatigue response of a bio-based polyamide PA11 and a petrol-based polyamide PA12 manufactured by selective laser sintering, European Polymer Journal 59 (2014) 36-45. DOI: https://doi.org/10.1016/j.eurpolymj.2014.07.016

[59] S. Negi, S. Dhiman, R.K. Sharma, Investigating the surface roughness of SLS fabricated glass-filled polyamide parts using response surface methodology, Arabian Journal for Science and Engineering 39/12 (2014) 9161-9179. DOI: https://doi.org/10.1007/s13369-014-1434-7

[60] A. Sachdeva, S. Singh, V.S. Sharma, Investigating surface roughness of parts produced by SLS process, The International Journal of Advanced Manufacturing Technology 64 (2013) 1505-1516. DOI: https://doi.org/10.1007/s00170-012-4118-z

[61] D. Pradeep, T. Rameshkumar, M. Kumar, Parameter optimization of SLS Sinterstation 2500plus using GRA for better surface finish and dimensional accuracy, Materials Today: Proceedings 45/9 (2021) 8105-8109. DOI: https://doi.org/10.1016/j.matpr.2021.01.638
[62] M.E. Imanian, F.R. Biglari, Modeling and prediction of surface roughness and dimensional accuracy in SLS 3D printing of PVA/CB composite using the central composite design, Journal of Manufacturing Processes 75 (2022) 154-169. DOI: https://doi.org/10.1016/j.jmapro.2021.12.065
[63] S. Petzold, J. Klett, A. Schauer, T.A. Osswald, Surface roughness of polyamide 12 parts manufactured using selective laser sintering, Polymer Testing 80 (2019) 106094. DOI: https://doi.org/10.1016/j.polymertesting.2019.106094
[64] L. Zárybnická, J. Petrů, P. Krpec, M. Pagáč, Effect of Additives and Print Orientation on the Properties of Laser Sintering-Printed Polyamide 12 Components, Polymers 14/6 (2022) 1172. DOI: https://doi.org/10.3390/polym14061172