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ORIGINAL ARTICLE

Challenges and issues in manufacturing of components using polymer-based selective laser sintering (SLS): a review

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Abstract

Selective Laser Sintering (SLS) is a highly promising method that plays a crucial role in advancing the development of high-performance and intricate structural materials. Polymer powders are widely recognized for their exceptional strength and versatility as a lightweight structural material. Significant improvements in processing parameters have also expanded the use of SLS polymer parts for structural applications. This research paper thoroughly analyzes the challenges and issues related to SLS from various perspectives. I have a deep understanding of SLS parameters, metallurgical processes, microstructure evolution, metallurgical defects, mechanical properties, and surface roughness. The goal is to create a foundation of knowledge for future research efforts focused on improving productivity in SLS. In addition, the conclusion emphasizes the challenges encountered in research and the possible avenues for future advancements in SLS polymer parts.

Keywords Polymer · Powder · SLS · Properties · FEA · CAD · LOM · FDM · Simulation

1 Introduction

The selective laser sintering (SLS) technique involves the targeted sintering of a polymer, ceramic, or hybrid powder material through the use of a high-intensity laser light, such as a CO_2 laser. Following the required sintering process of particles in accordance with the CAD drawing within the part bed, a new layer of powder is mechanically distributed onto the previous layer to achieve the layer-by-layer completion of the 3D part. The sintering process is conducted at a laser intensity that possesses the capability to bond particles both within a single layer and between adjacent layers [1–3]. Casting the sacrificial metal prevents this region in the preliminary stage from irregular fusion, which later becomes a position reinforcement of the positions above it. The (Fig. 1) is a visual illustration that portrays the sintering mechanisms (Including time scales to each mechanism) summarized below [4]. To avoid any improper alterations of the original properties, and have the artefacts showcase the desired attributes, the balance between biopolymers and ceramics should be maintained. As a result of the fact that the sintered products features such as mechanical and physical characteristics are the result of a number of factors that differ from each other, they can generate a very differential response. Hence, it is essential that the mechanism of sintering is understood completely in order to fabricate the components which would

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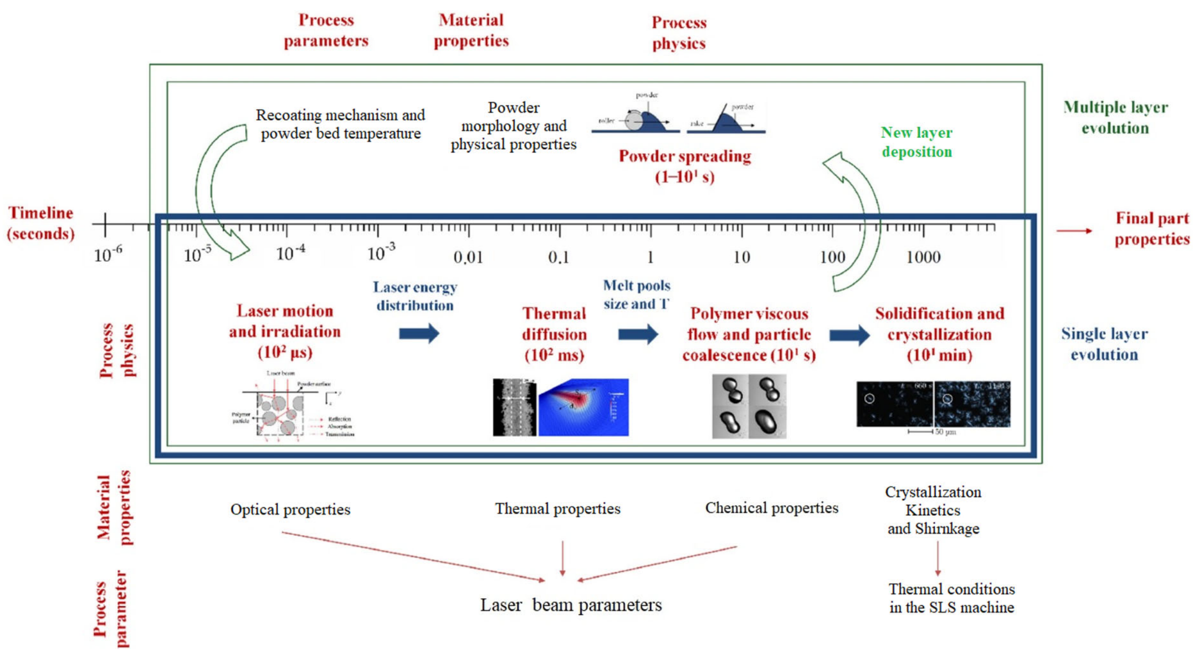

Fig. 1 Duration of the various physical phenomena involved in the SLS procedure [4]

have optical properties [5]. In the mink manufacturing process, engineers can create products that possess the desired properties, by their knowledge of the sintering process [6]. Some of these technologies, which still undergo development though, may be associated with a wide array of applications ranging from aircraft engines and those used in automobiles to medicine to name a few. Reduction to the above mentioned Even perfectinly everyday operation, incrementing reliability and providing cost cutting attribution allowed it. Besides, this leverage enables engineers fabricate customizable components that address the challenges of the target processes, but it also gives engineers the chance to build the improved components that are the best performers than the crucial ones in the present commercial field [7].

The heat- transfer issue has been concentrated in so far as the resource available concurs with the melting modeling modeling. In the figure which is located below you can see the drawing that is without the correlating events and it describes the process of a forming a melt pool (Fig. 2). The energy conveyed by laser light can be compared to the process of conduction, convection, and radiation. They all work together and as the energy passes through the part [8]. Through the use of this parameter, the amount of energy that is delivered to the powder bed can be controlled. While increasing the power of the laser causes the powder to reach a greater temperature, this has an effect not only on the sintering process but also on the qualities of the product that is ultimately produced. It is important to note that the rate at which the laser moves across the powder bed has an impact on both the heat input per unit area and the rate at which the sintered material cools. With slower scan speeds, the energy input is often higher, and the sintering process is likely to be more complete [9].

Heating moves into the environment by the means of heated air. The type of characteristics being observed on the surface affects the process of energy transmission from the source to the melt pool. The quantity transferred from the laser beam is determined by the laser power, scan speed, material conductivity, along with the environment temperature. In melt pool, heat transfer must be kept under control to enable quality output of products manufactured by this process. The purpose of this work is to design a relevant model for what a simulation of this SLS will look like [10]. Such model assesses all the procedures involved in the process as well as looks into what results each parameter gives as regards the quality of the powder metallurgy processed components. This approach is precise and accurate to ensure quality of output and costs saving in productions. It will not only lead to enhancement of the knowledge of the SLS process rather designing machineries for its use of SLS would be more efficient [11]. Beer–Lambert method is practiced in relation to the estimation of the amount of visible light rays that will be faded due to transmission into the semi-transparent medium. Attributing the spatial–temporal distribution of energy on the basis of a modified Monte Carlo methodic with the theory of Mie integrated is practically simulated. With such accounting for the changes in the universe it takes into account the physical parameters in both time and space. In the case of the time depthended of the source's laser radiation, the beginning allows evoking the image of a Gaussian curve, and the

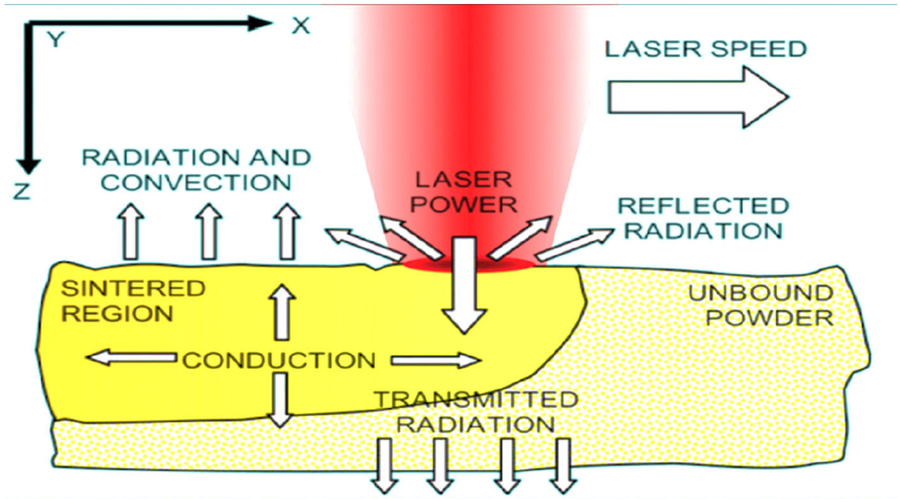

Fig. 2 Diagram depicting the energy-transfer events that take place in SLS [9]

courses of waves are depicted by the means of a probabilistic method [12].

To put it simply, what these essential computing component decisions or core computing procedures entail will be further expanded on within the next section or so. For health simulations and fitness, a group of test matrices tools are vigorously deployed throughout the Monte Carlo simulations throughout the process. The results that the computerised modelling systems generate are validated by checking it with what was done by in real time data at the same experiments. This tactic does more than good just on the performance tracking and improving, rather such tool can be tweaked and ameliorated as well [13]. Therefore, this hybrid technique can be viewed as an effective toolkit for characterizing the optical and electrical behavior of device. Besides, optoelectronic devices can be diverse and can be used in various disciplines in future. It can be of much help to such people in the way that it can be used to improve the performance of the device or reduce the time used to design it. The advantage in these techniques is that it can assist to reduce cost and shorten development time which is brought about by using a prototype simulation rather than physical problems. The technique also step by step helps the prediction of new device designs, which can be highly contagious to the manufacturing of by-the-minute optoelectronic devices [14].

When it's time to deal with powderization, polymer powders are the type o AM that is actively engaged. On the basis of the type of base material that is utilized, additive manufacturing (AM) can be divided into three separate types: pellets, powders, or liquids, with the number of operations listed in Fig. 3. In this kind of AM technology, solid material is used, and from rods, sheets, or filaments available in the market [15]. In powder AM systems, the powder solutions run through sintering process made by a laser or an electron beam, however other forms of energy can be used as well. In the additive manufacturing (AM) process which is based on liquid materials a liquid binder is deemed to be the most useful to bind the powder ingredients into a single permanent structure. The technique referred to as Layered Object Manufacturing, often known as LOM, is one of the methods mainly used in the area of quick prototyping. The technology is actually a procedure that facilitates the easy fabrication of three-dimensional products consistent with the corresponding CAD drawings [16].

It is a procedure which combines the strands of paper, plastic and aluminum foil through cutting, nesting and laminating to get an object. LOM is one of the foundations of the future, because it's one of the least complex and ranking ways that things can be created quickly in large numbers and with high accuracy. FDM can be used to cast thermoplastic or metal filaments in the form of a three-dimensional (3D) object by adding one layer after another. The spool feeds the filament into the printing platform where the printer experiences different laser types that are used through the nozzle to extrude the filament in order to form the model [17]. The ability of FDM technology is not only to give versatility of design and inexpensiveness but also the precise nature of the design. This is a printer type that resembles extrusion, requiring the input material to be converted prior to the process. The stress is built up on a process called WAAM which is given as an acronym meaning “wire and arc additive manufacturing”. Unlike any other product on the market, it provides for high levels of accuracy and costs at the same time, and here comes the reason for its extra fast adoption within the industrial sector. The faceshield of a large production iron interface parts shows the utility in it, a several statements only [18]. There is a particular type of 3D printing technology which is referred to as “Electron beam free form fabrication” EBF3.This technology uses electron beam to weld, shape, and form the metal components. Creation of complex mold is one of the main application of this technology like over moulding, insert molding, as well as

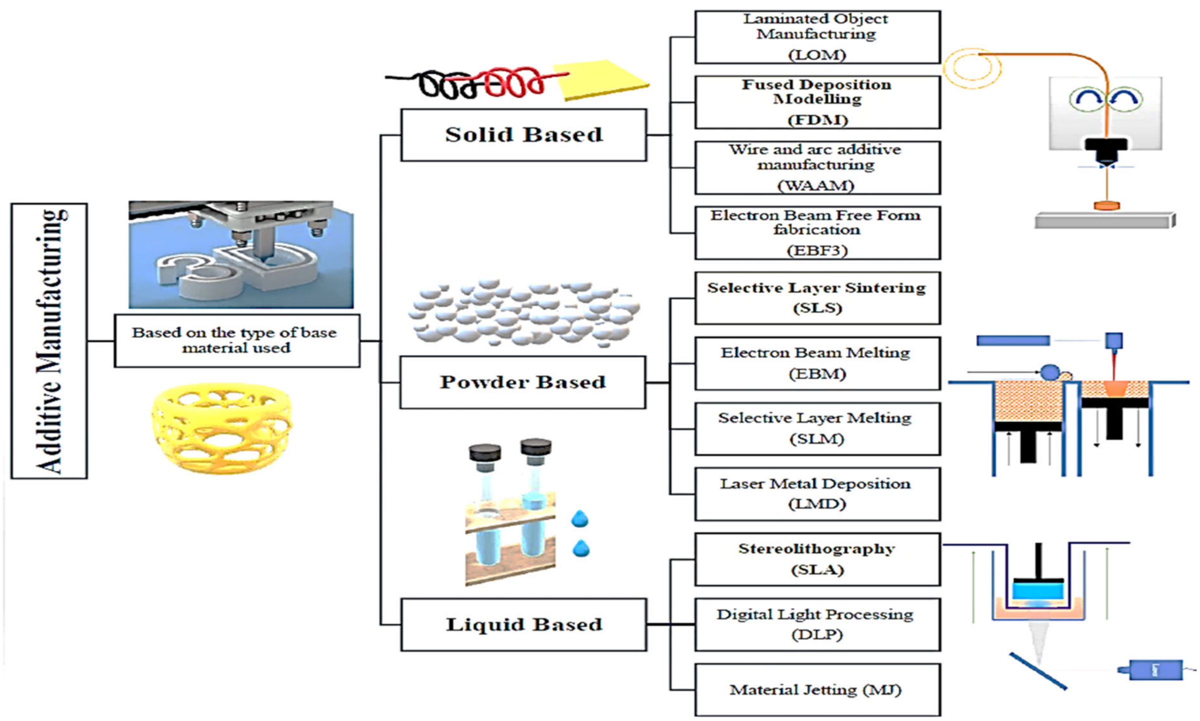

Fig. 3 It must be emphasized that the division of various additive manufacturing (AM) methods is made based on the concrete base materials used. In this review's essence, three principal AM processes—Fused Deposition Modelling (FDM), Selective Laser Sintering (SLS) and Stereolithography (SLA)—are all discussed [15]

overmolding. It is to be noted that it can be produced using the conventional manufacturing methods [19]. Beyond this, DML provides a higher resolution as compared to other 3D printing technologies and therefore features a higher surface finishing. The technique of powder-based additive manufacturing (AM) has the 3 main categories including SLS, direct metal laser sintering (DMLS), and electron beam melting (EBM) [20]. Melting or minimizing of the particles with the help of a laser is one of the base methods. As a consequence, the underlying principle of 3D printing is related to the creation of the voluminous artifact, component by component. One of the impacting characteristics of the powder based additive manufacturing technique is its effectiveness both in cost and time as well as the fact that it offers the possibility to precision process and even sculpt three dimensional objects that may have intricate shapes into existence while at the same time minimizing the wastage of material [21]. Even further, this implements precise system constituent parts as can be made with a stunning degree of perfection. This process has been through innovating a new method to produce complex geometries directly from three-dimensional CAD data, it has revolutionized industry worldwide due to its uniqueness, in addition to its inherent benefit such as quick lead time and design freedom [22, 23]. When comparing AM to conventional subtractive manufacturing techniques, it is evident that AM utilises a sequential layering methodology [24–26]. In its early stages, AM was primarily employed for the purpose of prototyping. To recognize the advantages of AM in terms of its efficiency and cost-effectiveness, utilizing the technology to fabricate models for theoretical investigations and product development endeavours. The potential of AM is currently being harnessed across diverse sectors such as automotive, aerospace, construction, and healthcare [27–32].

The energy density, as represented by Eq. (1), plays a crucial role in the process and property of parts in (SLS). The term "energy density" refers to the quantity of energy contained inside a specific system or spatial area, measured in terms of energy per unit volume.

$$ED = \frac{P}{v \cdot h} \times \frac{d}{h} \tag{1}$$

In this context, ED represents the energy density, P denotes the laser power, d signifies the laser beam diameter, v represents the scan velocity, and h stands for the hatch spacing. As shown in the (Fig. 4) determination of process parameters, including hatch spacing, laser scanning speed, laser power, and preheat temperature, plays a crucial role in shaping the qualities of objects produced through (SLS) [33–35]. It is particularly important to establish that the parameters of the process are correctly determined to bring about the

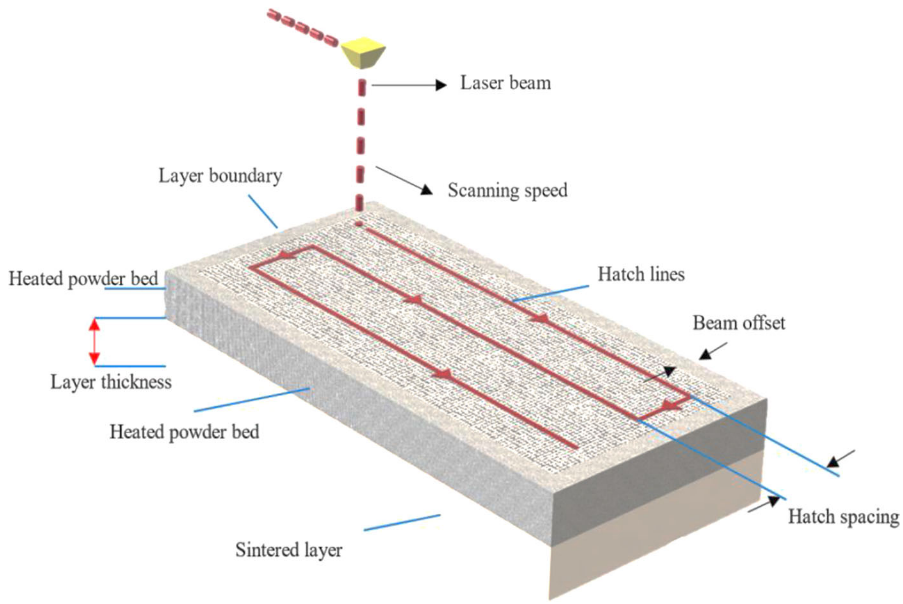

Fig. 4 The process parameters utilized in (SLS) printing [33]

required properties, e.g. surface finish expected and mechanical properties expected. SLS (stereolithography) technology made manufacturing of small parts at the submm scale and with micro millimeter accuracy possible. In order to attain this, the laser power is being regulated, the layer thickness and the scanning speed is controlled and the hatching spacing is maintained. Such a process is a result not only in the cost-effective but also in the highly-efficient production using of the components with intricate geometries and high-performance materials [36].

These polymers vary in terms of their mechanical properties; some are strong whereas others are flexible and some very durable. For instance, Nylon (PA) material type is highly appreciated for its strength and toughness therefore the most advisable for using functional prototypes and end use parts. The materials as TPU (thermoplastic polyurethane) have more flexible and elastic properties, which is useful for products needed to have rubber like values [37]. The selection of the polymer determines the surface finish of the printed part as seen in the following sub-sections. Some of them such as Nylon are likely to produce a rougher surface than others such as TPU or TPE (thermoplastic elastomer) which can produce smoother surface finishes. Smooth surfaces are used in cosmetic parts or items which ought to experience minimum polishing after manufacturing. The above polymers exhibit differences in their thermal characteristics. These materials such as PA12 (Nylon) possess good heat endurance hence can be used in parts that are to be exposed to excess heat. In the same regard, some of the materials may get damaged easily or undergo changes in their physical properties at relatively low temperatures; hence their applicability in such conditions may be compromised [38]. All SLS materials are not chemically resistant to the same degree. For instance, Nylon is immune to many chemicals, oils, and greases therefore it fits the industrial use. Other materials may not provide this sort of resistance and this is well suited in areas where there is chemical exposure. Some of these polymers including the medical grade Nylon used in SLS printers can be used in health-related industries where there is need to have a direct contact with patient's body. Furthermore, SLS technology is significantly faster than other 3D printing processes, resulting in shorter lead times and reduced costs [39].

In the field of advanced materials science, new boundaries are being explored, with applications in the creation of smart polymer materials structured materials and bio printing. The expeditious assimilation of AM showcases its advantageous attributes, encompassing exceptional accuracy, adaptability, and an extensive assortment of printable substances, such as metals, ceramics, polymers, hydrogels, and composites, among various others [40]. As AM progresses from its initial role in rapid prototyping to encompass rapid manufacturing applications, it becomes imperative to possess comprehensive knowledge not only of the AM process itself, but also of the mechanical properties and microstructure of the produced components, which are influenced by various process factors. Consequently, the characteristics and qualities of the manufactured parts are impacted [41–45]. Among the several technologies that are currently available, The SLS is extensively utilised to produce polymer components that meet the demands of industrial applications. The link between process, material, microstructure, and characteristics is investigated in depth in this overview for the SLS method, which has the largest industrial importance at the time.

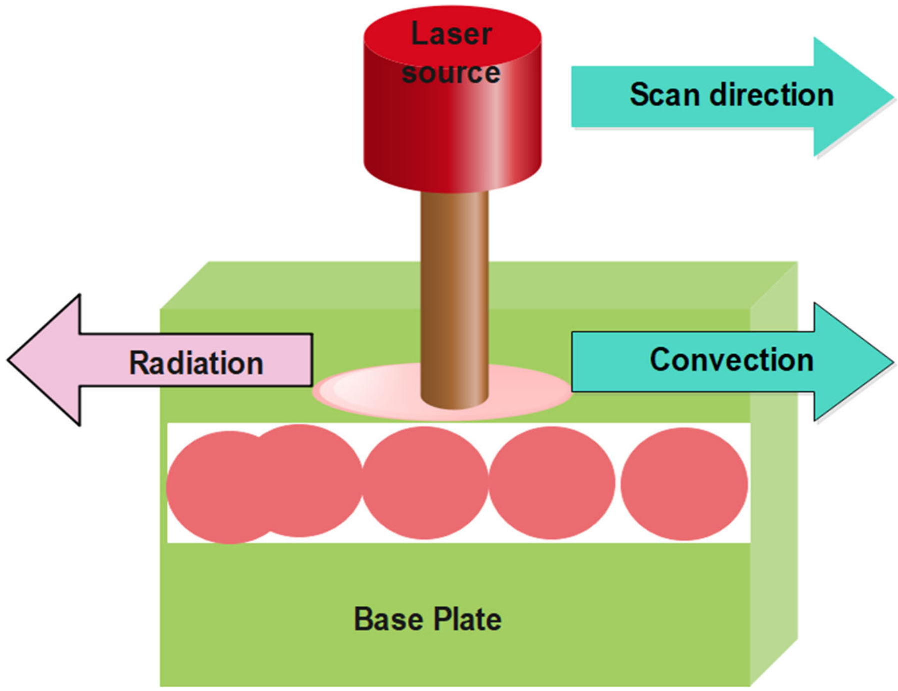

Fig. 5 Thermal nomenclature in the (SLS) process

1.1 Thermal simulation of SLS procedure

The thermal history depicted in (Fig. 5) within the powder bed is comprehensively characterized by a model that considers the convection occurring in the SLS build chamber as a form of natural convection, incorporating the spatial distribution of the laser heat source [46].

The polyamide powder bed was regarded as a uniform and uninterrupted medium, exhibiting heat conductivity that is consistent in all directions. The pilot directed the laser beam along the boundary which was in the presence of heat flux, and it was applied to the upper layer of the polyamide powder bed. The graphing approach emerges because the constant lacks temperature dependence. Here, a specific instance is focused where a polyamide powder bed is somehow affected through the action of a laser beam [47]. At stake here is the type of material in its powder form, it is commonly used in processes such as SLS—Selective Laser Sintering and SLM—Selective Laser Melting. In this present context, it is assumed that the heat conductivity of the polyamide powders is unidirectionally the same without any gap of the inconsistence or unevenness. In this experimental installation thermo radiation power of the laser beam as a warm source is used. The application is carried directly bare on the top of the polyamide powder bed [48]. Laser-induced heat flux is the quantity in the boundary conditions depicted by the laser beam. The heading claims that there is a direct relation between the thermal coefficient and temperature, but this relationship does not vary with the temperature. Therefore, in this case, the rate of conduction will be the same regardless of any variations in temperature. What seems to be demonstrated is nothing but a not-complicated model that explains travelling of heat into a polyamide powder bed during laser processing [49]. It should be noted that the process of heat transfer displays more complexity. It features, but is not limited to, absorption, reflection and scatting of the laser energy that takes place within the powder layer. This complexity should be considered in the study of the accuracy of the laser sintering of the polyamide powder bed. The purpose is developed further by also considering the experimental validation of the given heat transfer model [50].

Figure 6a is a microscope image x–z plane of the axial trajectory of temperature from three tracks ablation showing the temperature distribution projected to the x–z plane afterward. The rise in the energy puts the powder bed through complete melting, bringing up the sintered plastic with a compact and uniform microstructure, as shown in Fig. 6b [51].

The uniform microstructure of the sintered specimen leads to improved mechanical properties. The results suggest that the laser intensity should be carefully adjusted to achieve optimal sintering [52]. Higher laser intensity can result in over-sintering, leading to a decrease in mechanical properties. Therefore, it is important to find the correct balance between the laser intensity and the sintering process for the best results.

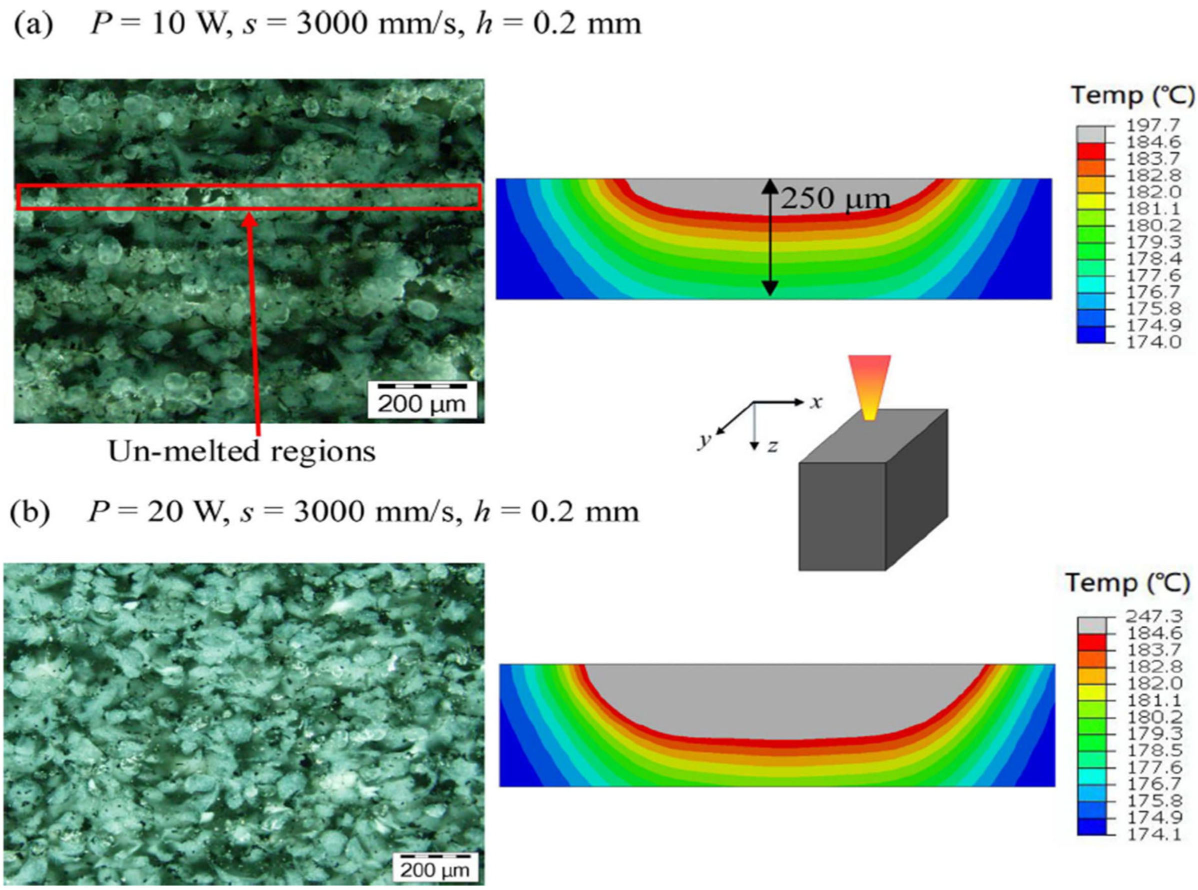

Fig. 6 After scanning three tracks with the prescribed process parameters, the microstructures of the sintered specimen in the x–z plane and the fusion zones were studied [51]

1.2 Several ways to incorporate sensors and other functional components into SLS procedure

This renders the integration of sensors and other functional components into SLS-made polymer components. This integration can be resolved at the design phase, using specific material and through the application of post processing treatments. In case of SLS printing, the structure can be interrupted to place the sensors or any other circuits at the preferred location in the part. It is then possible to continue making the print, thereby encapsulating the constituents in the printed item. This calls for some good planning, in as much as not to cause some havoc to the normal printing process of the sub-modules [53]. More modern SLS systems can work with multiple materials and therefore the conductive or sensing material can be incorporated into the polymer matrix during the build. This method can be used to form conducting tracks or to integrate sensors. Part with conductive paths can be printed using polymers incorporated with conductive filler like carbon black, silver particle or graphene. These paths can used like a switch for electronic circuits or paths through which various components are connected. Conductive inks can be used after printing where traces of conductivity are made on the surface of the SLS parts. There are methods such as screen printing or inkjet printing through which the inks can be deposited on the substrate in a controlled manner [54].

There will be specific cavities or necessary mounting points that are integrated into the SLS design for PCBs. These PCBs can accommodate almost any type of sensors or electronic parts that can physically connect with the printed part. This enables PCBs and other components to be firmly connected to other parts of a product without requiring fasteners such as screws thru the use of snap-fit or press-fit features. Incorporating SLS with direct-writing technologies in which conductive materials are successively coated can include functional elements in the printing process. Some of the enabling new technologies include the creation of an electronic circuit and or components directly on or deep within a three dimensional printed structure. They can be achieved by methods that are commonly known as aerosol jet printing or direct ink writing [55]. Some of the processes encompass the partial activation of the polymer surface to promote adhesion for conductive materials or other functional layers. This paper also found that ultrasonic welding can be used to insert parts into SLA parts after the printing is done. This method employ ultrasonic waves of high frequency to bond materials without the use of any glue or any pin. With the mentioned SMA materials, such as shape memory polymers, the parts can transform the shape or complete a specific task based on the energy applied such as heat changes. Large sensor networks can be embedded into SLS parts by designing them as the geometry of the parts, providing for sensing at many locations within the structure [56].

To link sensors for recording the physiological state into individually tailored medical devices. The sensor integration to measure the physiological characteristics that can be installed in medical devices specially fashioned to fit the patient's body. Designing original housing to have sensors and other electronics features built-in for communication devices. These techniques, thus, allow for the design of advanced multifunctional SLS components with embedded sensors and electronics that would expand the horizons of the creation of smart products and the application of sophisticate manufacturing techniques [57].

2 Polymer powder

2.1 Types of polymer powders

Polymer powders are widely used in fabrication of SLS parts. The variety of variations and performance of such materials, as well as numerous modification procedures, make them useful in SLS. A polymer is a substance made up of several molecules connected by repeated repetitive units of covalently bound atoms [58–61]. Natural polymer repeatability, on the other hand, is particularly unique to each species, and synthetic synthesis of these materials is difficult because to their complicated structural structure. The predominant materials utilised in SLS are thermoplastic polymers and composite materials. Thermoplastic polymers can be categorised into two distinct types: crystalline or semi-crystalline polymers and amorphous polymers [62]. As shown in the (Fig. 7) here are some common types of polymer powders used in SLS.

Nylon-based powders are often favoured in SLS processes owing to their exceptional tensile qualities, high heat resistance, and notable endurance. Additives can be incorporated into nylon to improve its stiffness and strength. Thermoplastic Polyurethane, often known as TPU, is a versatile material characterised by its flexibility and elastomeric properties. It has notable impact resistance and flexibility. It is frequently employed in applications that necessitate the presence of characteristics resembling those of rubber. Polycarbonate (PC) powders has notable attributes such as exceptional resistance to high temperatures, commendable impact strength, and the ability to maintain transparency. Components manufactured with polycarbonate (PC) are frequently employed in scenarios that demand both exceptional durability and excellent visual transparency [63]. Polypropylene (PP) powders are recognised in academic literature for their characteristic features such as low density, chemical resistance, and flexibility. These materials demonstrate suitability for implementation across the automotive, packaging, and consumer products sectors [64]. The intrinsic properties of polyethylene (PE) powders, that include low density and flexibility, are consistent with features of polypropylene (PP). The materials used in production of such lightweight objects exhibit great properties of chemical resistance. PS powders are mostly used in SLS with the intention of making models, samples and tutorial venues [65]. It presents the technique of its being economical and ease to work with. The advantages of the PEKK powders are namely the fact exactly that they can be used up to extremely high temperatures, the resistance of these powders to all sorts of chemical substances and the ability to stand up to mechanical stress. With their biocompatibility to the aircraft and medical applications, these materials can be safely used [66]. Polyetherimide (PEI) powders are widely recognised for their exceptional mechanical, thermal, and electrical characteristics. They are frequently employed in rigorous engineering applications. Polyamide 11 and 12 powders are considered as distinct variations of nylon and possess commendable mechanical qualities, rendering them highly suited for a wide range of technical applications [67]. Polyphenylsulfone (PPSU) powders demonstrate notable characteristics such as elevated thermal resistance, chemical resistance, and exceptional mechanical qualities. Medical and aerospace applications frequently employ them. It is noteworthy to mention that the accessibility of distinct polymer powders for SLS can differ based on the producers and the progressions in additive manufacturing technologies [68]. It is vital to consistently employ compatible materials in conjunction with the SLS machine to attain the intended outcomes.

2.2 Powder size

Spherical particles (as seen in Fig. 8a) are formed through a coextrusion process involving a blend of soluble and non-soluble components. The particles commonly referred to as "potato-shaped" (Fig. 8b) are formed via a precipitation process. This structure is prevalent in PA12, which is the most extensively utilised material in SLS applications. In contrast to the morphologies, cryogenically milled particles (Fig. 8c) exhibit a random and highly uneven geometry [69]. These particles are produced by mechanical milling at low temperatures, which preserves the polymeric backbone. As a result, they provide an advantage in terms of mechanical performance and stability due to the enhanced surface area.

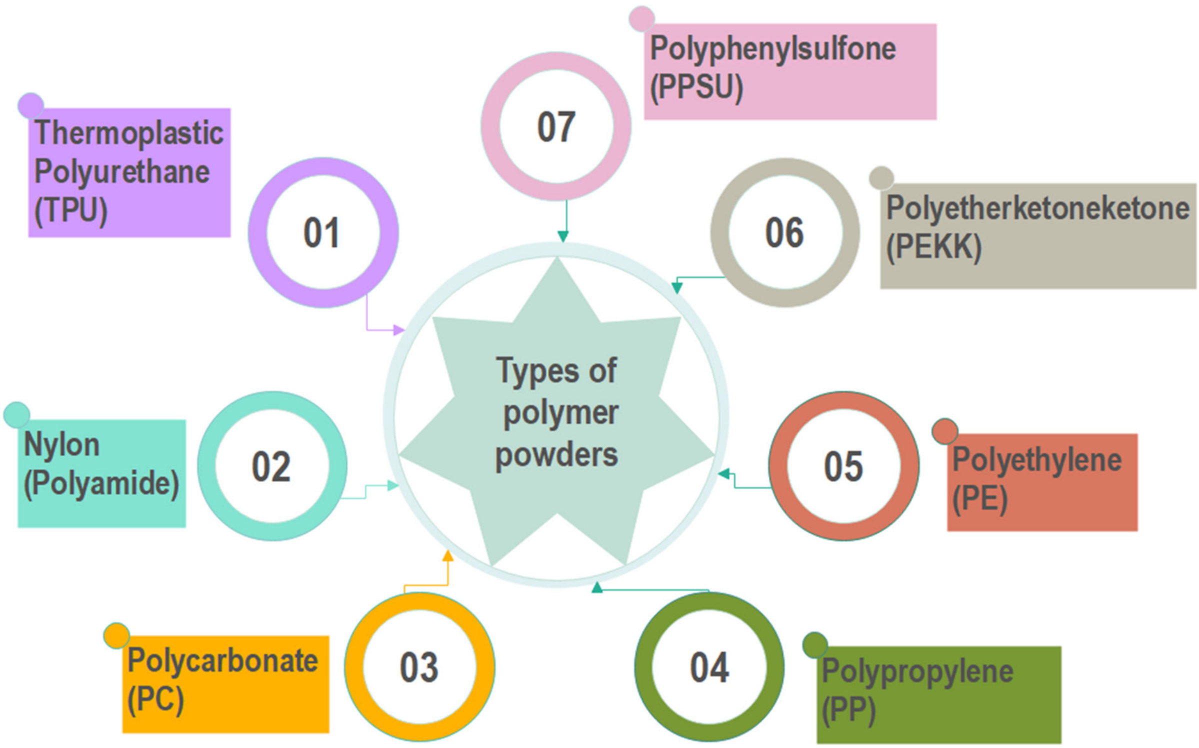

Fig. 7 Various classifications of polymer powders

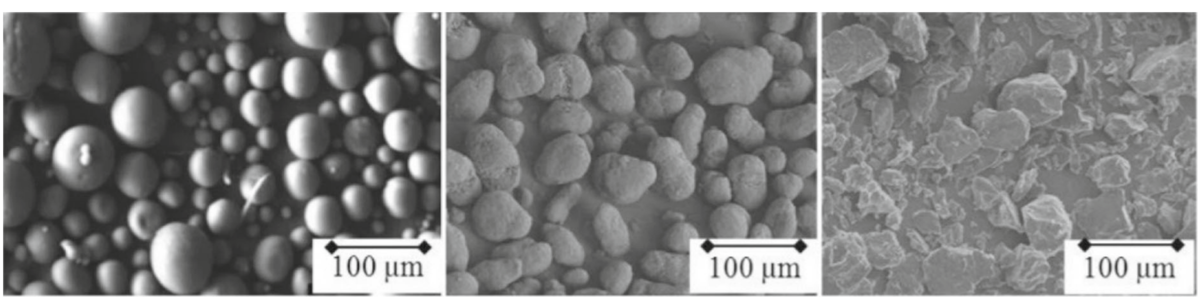

Fig. 8 Various production methods yield particles with diverse shapes, including **a** spherical, **b** potato-shaped, and **c** cryogenically milled particles [69]

The size and shape of powder particles influence the flow ability and laser reflection behavior in the laser sintering [70–74]. The flow ability of powder is reduced with increase in powder particle size and irregularity in shape. This effect the distribution of powder on the bed and powder layer density. The workability of powder is enhanced if the particles are of spherical shape with smooth and uniform surfaces. Further the laser interaction with powder particles is also influenced by the size and shape of powder particles because of change in the melting behavior [75–79]. It has also been discovered that powder particles of a size between 0.04 and 400 mm produce superior sintering results than particles with finer or coarser diameters. Shi et al [80] discussed that the accuracy and density of the SLS component are heavily influenced by particle size. The 'step effect' of SLS parts manufactured with varying particle sizes is shown in the Figure 9.

The 'step effect' shows that a smaller particle size is better for producing a more precise SLS part. On the other hand, a polymer powder with an excessively small particle size (75–150 µm) will be difficult to disseminate since the powder will self-reunite because of the over small particle size.

2.3 Powder characteristics

In laser sintering, flow ability and packing qualities are critical for powder distribution and component attributes [81]. The sphericity of fine powder particles, in addition to their size, is important for occupational safety. Determining the Hausner ratio, in combination with the particle parameters

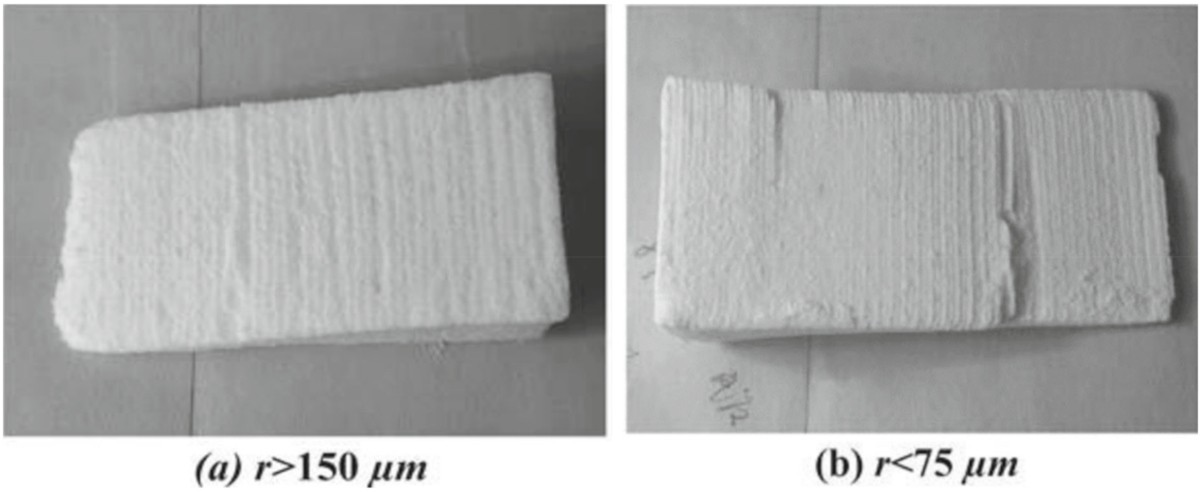

Fig. 9 Impact of particulate size on the accuracy of an SLS part [80]

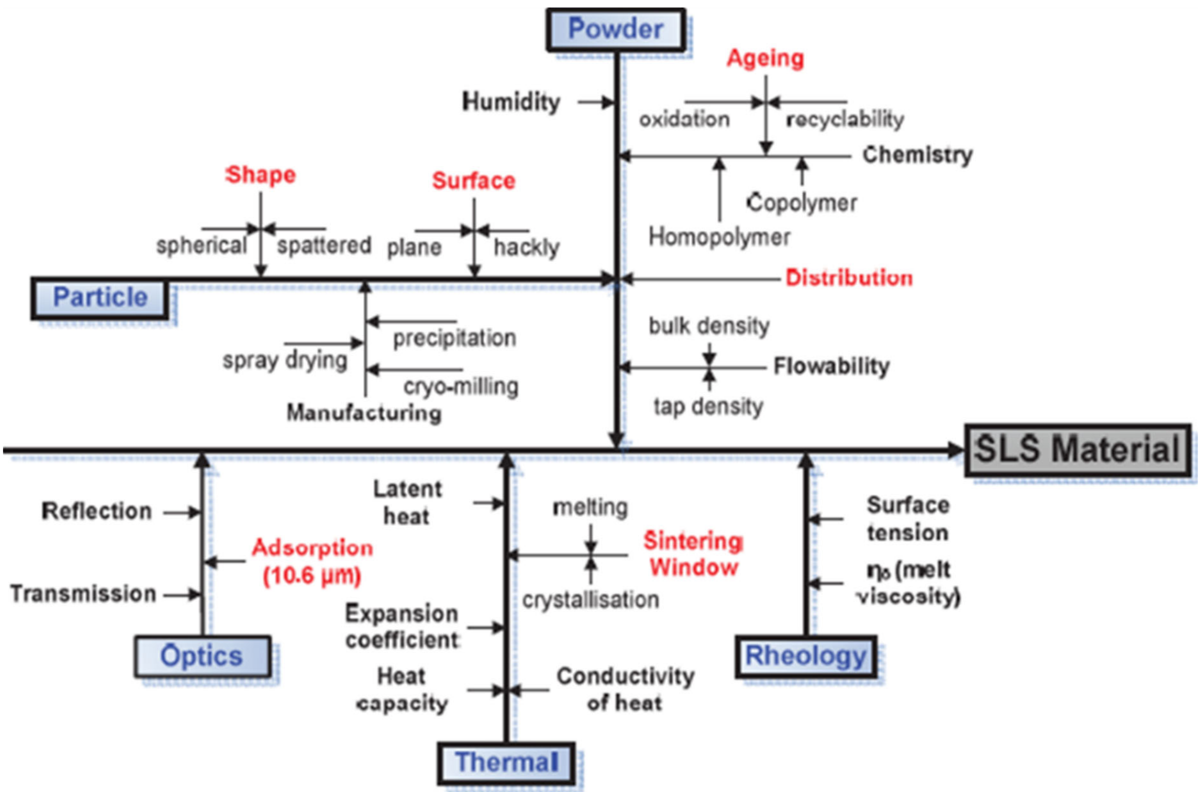

Fig. 10 The organisation of various polymer characteristics is crucial for the development of promising SLS materials [90]

found, should offer a straightforward estimate of the flow ability of thermoplastics in powder form [82–85]. Apart from crucial thermal and optical qualities, particle shape and distribution influence powder process ability, notably the recoating process during powder application, and hence the quality and performance of the manufactured parts. Powders with strong flow ability are critical because of the tendency to typically demonstrate good spread ability during the powder deposition stage, ensuring a dense and homogenous powder coating (Fig. 10). This results as low porosity parts [86–89]. Particle shape, powder distribution, thermal, optical, and rehological needs must all be considered to improve laser sintered polymer powder applications. A combination of controlled qualities (Fig. 11) leads to the desired fabrication or process implementation [90].

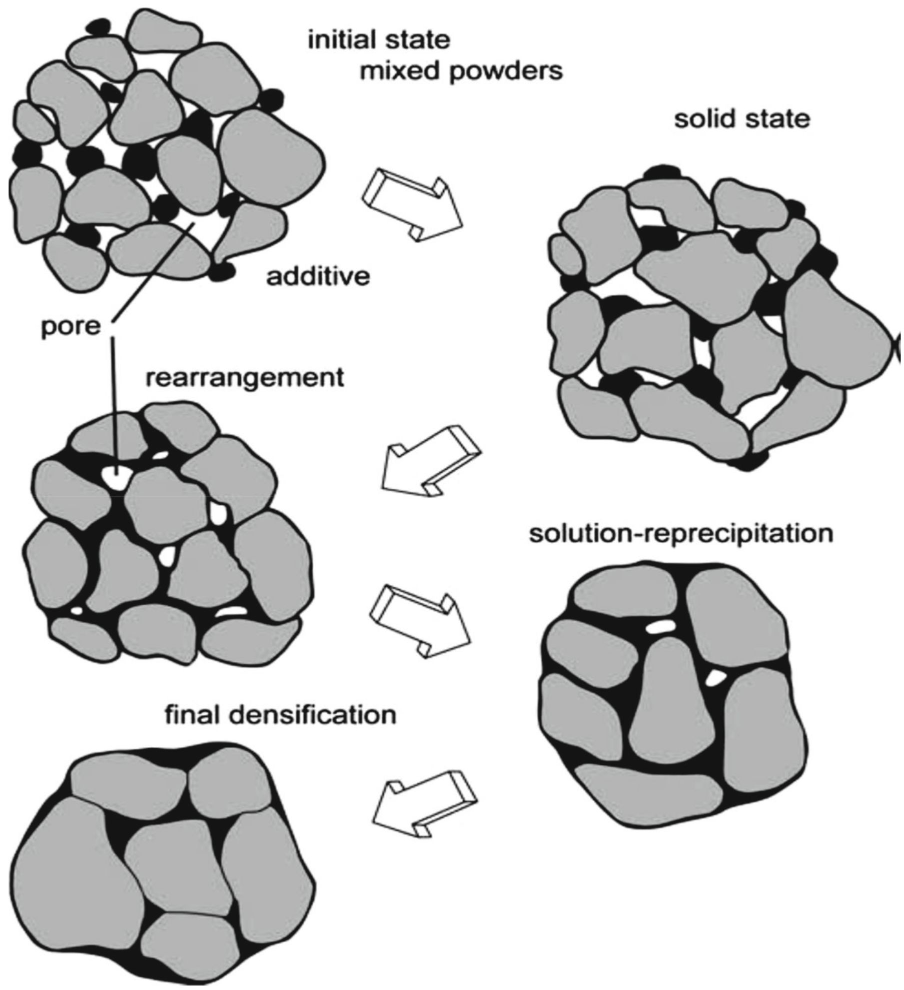

Fig. 11 A schematic of the microstructure changes during LPS [103]

2.4 Commercial polymer powders

Semi-crystalline thermoplastics, such as polyamides, are the most popular polymers used in selective laser sintering. High-density polyethylene, polypropylene and polyetheretherketone are also commercially available. Laser sintering can be used to treat amorphous polymers like polystyrene as well as semi-crystalline polymers [91]. Amorphous thermoplastics are less commonly utilized in laser sintering due to their wide softening range, which results in less dense parts with worse mechanical properties. The major factors that affect the ability of SLS process for polymer powder along with part properties are presented in Table 1 [92–94].

2.5 Enhance the z-direction mechanical characteristics of SLS-printed polymer components:

The main focus when it comes to mechanical characteristics of the SLS-printed polymer components in z-direction (vertical) is needed to be improved to enhance the strength and durability of most components. The orientation of the part during printing determines mechanical characteristics of the material to a large extent. To increase the mechanical strength—in the z-direction, the part should be oriented in such a way that the major load-bearing features are parallel to the build direction [95]. This orientation minimises the chances of peeling of one layer from another and improves the general strength of the part as a whole. Normally, there is always the option to control the layer thickness in most SLS printers currently in the market. One can get increased z-direction strength through thicker layers as this increases strength in that particular direction because the lesser the number of layers the better for not just the composite but the structure as well because interfaces are known to be areas of weakness [96]. But at the same time, the layers are having to be thicker to construct larger layers, which could impact on the finish and tolerance, meaning that some compromise is required. Specific to SLS printing, orientations of infill patterns (internal structure of the printed part can be set to improve z-axis strength. Complex infill patterns including solid or higher percentage infill densities (for instance, 100%)

Table 1 Factors affecting SLS process

Material Properties		
1	Thermal Properties	Melting Temperature
		Glass Transitions Temperature
		Crystallization Temperature
		Thermal Conductivity
		Specific Heat
2	Physical Properties	Particle Size
		Particle Shape
		Bulk density
3	Behaviour of Material	Powder form
		Liquid form
SLS process parameters		
1	Laser based parameters	Spot Size
		Laser Power
2	Scan based parameters	Scan Speed
		Scan Spacing
		Scan Strategy
3	Build based parameters	Powder form
		Molten state

yield a better provision of material in the z-direction, and thus, superior part strength. Some printers also provide special infill patterns meant to provide more force resistance in pre-designated axes [97]. Adhesion can be achieved by regulating the temperature of the chamber in which the build is done and maintaining evenly spaced temperature gradients across the build plane. What is more it enhances uniform distribution of mechanical properties along the z-direction. Some of the post-processes like thermal-annealing or stress-relieving could further improve the mechanical behaviors of the SLS printed parts in the z-direction as well. These treatments assist to minimize internal stresses and enhance the degree of crystallinity of the materials so as to increase the strength and ductility ratios. Inherent z-direction mechanical properties of the selected polymer material can improve the strength of the final part considerably [98]. Different types of plastics such as PA12 (Nylon) can be characterized by their moderate mechanical performances and good strength in the z-direction. Other properties that can be enhanced are a combination of specialty materials or filled polymers for instance carbon fiber reinforced may also exhibit superior mechanical properties in particular directions. It is also suggested to avoid sudden changes in the cross-section of the part and use gradual fillets should help to enhance z-direction strength [99]. Thus, such design considerations ensure that stress is evenly spread all through the part. Future developments of the SLS printing and the methods used can involve multi-layer printing strategies or the integration of SLS with other forms of AM. This methods can help in achieving maximum possible deposition of material and bonding of layers specially in seeding geometry. Through the following strategies, engineers and designers get to improve the z-direction mechanical properties of the SLS printed polymer Parts for the application with high demands and requests on mechanical capabilities [100].

3 Consolidation phenomena of polymer powders

The consolidation or binding in polymer powders are mainly carried out by liquid phase sintering or partial melting [101], liquid phase melting or full melting and occasionally chemical induced binding [102]. In liquid phase sintering low melting powder particles and surrounded by high melting powder particles. While in the case of liquid phase meting complete melting of powder particles takes place. Further chemical induced binding be rarely occurs eg. Cross-linking of poly (methyl methacrylate) PMMA type of polymers. The amount of solidification is determined by the melt flow and how well it contributes to the filling of pores (Figure 11). Amorphous and semi crystalline polymers are the most common polymers which are used in SLS processing.

3.1 Consolidation phenomena in amorphous polymer powder

Polystyrene and polycarbonate are the most commonly used amorphous polymers in SLS. Although glass transition temperature is considered in case of amorphous rather than melting temperature. The viscosity of polymer is determined by molecular weight. The viscosity of a substance is proportional to its molecular weight. To consolidate, viscous melt flows and forms a neck between two particles. Gravity, capillary force, and temperature gradient are the three factors that influences the flow of molten material [103–106]. Further because of the high viscosity, the finished parts contain number of pores, low shrinkage and excellent dimensional accuracy. The density is fairly low as compared to injection moulded parts [8, 95, 107].

3.2 Consolidation phenomena in semi crystalline polymer powder

In semi crystalline polymers polyamide is widely used in fabrication, whereas other materials include polyethylene, polyether ether ketone, polycaprolactone, polyvinyl alcohol etc. The polymer forms a low viscosity melt as the laser energy raises the temperature above melting temperature. The viscosity in this case again determined by molecular weight, and high molecular weight is desired for high-dimensional parts. Semi crystalline polymer flows deeply into the recess and of low viscosity high density is achieved. Higher shrinkage occurs in semi crystalline polymers having lower viscosity [108]. As a result, while choosing the particular molecular weight polymer, a balance between dimensional accuracy (associated with high viscosity/high molecular weight) and density (related with low viscosity/low molecular weight) is required. At melting temperature, semi crystalline polymers do not consolidate (recrystallize) [109–113]. As the gap increases the time span of material to remain in liquid form also increases. For consolidation, a longer time span will allow the molten metal to flow well and stay wet longer (required for sufficient capillary action to occur). PA 12 has a higher sinter ability because to its broader temperature difference and lower melting temperature. Consolidation is difficult with polymers with a low temperature difference and no well-defined melting point [114–117].

3.3 Consolidation phenomena in semi crystalline polymer powder

The mechanical part concerning SLS-printed polymer components involve that such parts are dependent on time, since aging may impact the components' consistency and dependability. This is factor that occurs after a polymer has been printed and is characterized by the alteration of the polymer properties such as mechanical strength, thermal stability, chemical resistance and others by virtue of exposure to environment, prior history to heat or chemical reactions. Concerning the material aging that can manifest on SLS-printed polymer components, countermeasures and methods of its detection [118]. Periodically, aging results in the decline of the mechanical properties like strength, stiffness, and impact resistance. This high dimension of engineering appeals and complicacy of the material typically reduces the scale at which the material can be processed and used due to sensitivity to UV, humidity, temperature, and chemical quality. The stiffness, or measuring ability for bear up against deformation load, can be reduced as the material creeps or relaxes with time. It can be the case that upon applying fatigue to the material the material's capability to absorb energy and not fracture in the process of suddenly applying load can diminish. This might impair the mechanical characteristics and stability of the printed parts after sometime [119]. Dimensional stability is the measure of the changes in the size of the material when exposed to conditions or agents such as when the material undergoes aging or degradation. It is, therefore, true that changes in the properties of the material with effects such as aging will lead to changes in dimensions such as shrinkage or expansion. These alteration of parameters may alter the dimensions and performance characteristic of components in the areas of application. For instance, plastics and polymers tends to shrink with time thus affecting tolerances that are critical in determination of spacings for use in assemblies [120]. To exhibit changes in size depending on the loss or gain of heat hence they undergo changes in dimensions appropriate in mechanical assemblies. To counter such effects, engineers and designers try to factor in areas like type of material used, mode of processing, and conditions under which the components shall work. Dimensional stability knowledge is critical in analyzing the long-term dependable and usable nature of products in the set use or service environments. Accompanying the process of ageing the external properties of the printed part as well as the way it interacts with other components or an environment may be changed. Steps to monitor and reduce consequences are depicted in Fig. 12, which can be found here [121].

These are evaluations in which the material is exposed to some conditions like high temperature, humidity, or UV light to find effects which, otherwise, would naturally take a considerably long period. This process assists in early estimates of printed parts or materials' performance and their ultimate degradation. The main objective is to carry out accelerated aging to obtain results faster than natural on tests specimens degradation. This makes it possible to determine what the actual performance of a material or printed part would be over a given life cycle [122]. It depended on what was being done with the material, wherein different conditions can be applied for the material depending on where it is to be used. High temperatures may cause certain chemical reactions and physical deterioration to happen at a faster rate. This characteristic closely resembles moisture related degradation and environmental exposure by making use of high humidity. It also achieves a similar effect to sunlight and is responsible for such outcomes as material spoilage or change of color, for example. Accelerated aging tests must be carried out under a strictly controlled environment, which may be a chamber housing goods and equipment [123]. These conditions are then applied to samples of the material or printed parts for a period of week or months as dictated by the chosen accelerated rate. During the test period, the samples which are taken at regular intervals are also checked for the variation of properties such as tensile strength, elasticity, color and chemical composition and any other desirable properties as the case may be. It also assists in determining the manner in which the material will behave in actual working conditions over a given time frame [124]. Although accelerated aging cannot mimic the actual aging environment it offers insights of long-term environmental performance characteristics based on accelerated aging data. Companies are able to utilize this data to enhance their raw materials, modify their compositions, or support the reliability of their claims of product's lifespan before they release their products to the market. Although accelerated aging cannot mimic all the

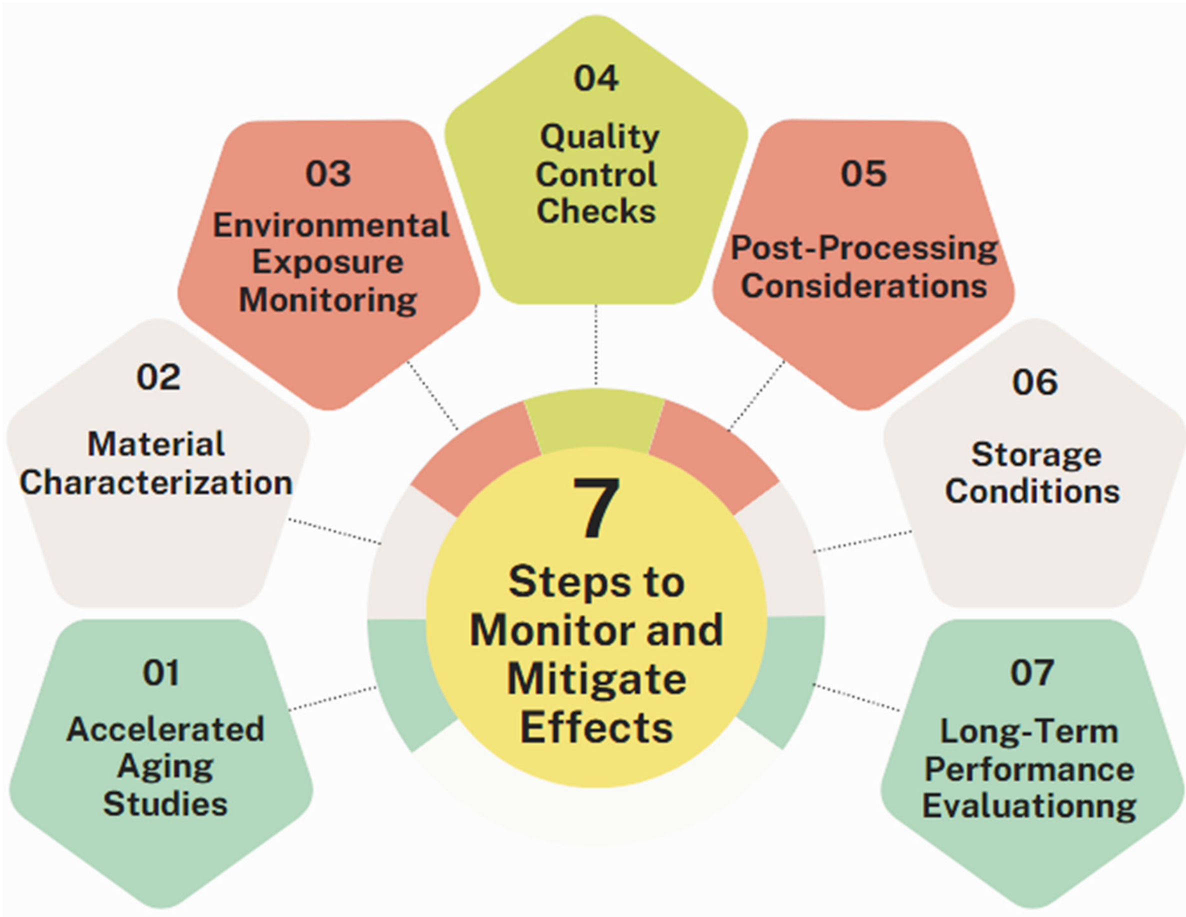

Fig. 12 Taking Measures to Monitor and Reduce the Effects

natural aging processes, it offers very useful information on long-term performance behavior. This information can be utilized by manufacturers to enhance aspects of materials, modify recipe or clearly substantiate expected longevity prior to hitting the consumer channel. This makes it possible to estimate their function in the future, how the printed parts will endure in the foreseeable future [125]. Since there are always changes in the mechanical and thermal properties of the material, material characterization studies are supposed to be done frequently. Other testing carried out include tensile test, flexural test, hardness test, and thermal analysis test such as Differential Scanning Calorimetry (DSC) and Thermogravimetric Analysis (TGA) [126]. Pay attention to the storage conditions of the printed parts (temperature, humidity, exposure to chemicals or UV-light). Document such conditions so that they can be associated with any variation in the part performance [127]. Perform periodic checks on part quality in the course of printing to boost quality standards of the parts to be printed. These consist of laser power density, scan rate, build plate temperature and condition of the applied powder [128]. Thermal annealing/Heat treatment or surface treatments like sealing/ coating can improve the stability of the material and avert early aging. Original printed parts should also be stored in prescribed environmental conditions to reduce effects of environmental management on the parts over time. Assess the durability of the parts that are produced by SLS printing in practical applications for long hours. Go back to the end users or do field tests for purpose of confirming the product's durability and reliability. Thus, it will help manufacturers make necessary adjustments in time to reduce the impact of material aging on the stability of the printed components of polymeric material through SLS and their reliability when used in different applications [129]. The above approach aids to maintain quality levels and thus the reliability of the additive manufacturing technologies.

4 Challenges

SLS parts commonly undergo extensive post processing after they have been printed. This includes depronation of unsintered powder from complex shapes, which may take some time and still is partly difficult to program. SLS operates with a variety of polymer materials, which including such significant descriptors as properties and characteristics. Refractory materials' aptitudes include mechanical strength, elasticity, temperature endurance, and surface texture to suit a unique application appropriately [130]. Heat treatment that occurs during the course of printing also leads to what are known as thermal gradients and residual stresses resulting into part warping or distortion. This is even more so the case when dealing with more complex or large geometries. Optimizing the build orientation and changing some of the printing parameters, to reduce distortion is usually an iterative process that can be very needy of time. SLS employs the use of powdered materials, and since they may by nature, be contaminated easily, they should be handled gently in order to retain the properties of the material in use [131]. One of the most important aspects of powder management is the process of its reutilization and quality; it plays a significant role in the development of high-quality parts and minimization of the wasted material. It is usually difficult to produce small features or smooth surface finish straight from the SLS process due to the layering nature of the process. Other finishing steps might include; sanding or polishing or chemical treatments may be required depending on the end use or appearance desired. SLS printers can be costly and require some care to be provided with the right quality always [132]. There is also the sophistication of the printing process in that it requires technical expertise to run the machinery which can also increase the cost. Existing constraints have to be considered for designing a part for SLS like the minimum thickness, size constraints, and more about the support structure. Depending on the mechanical and thermal requirements of the part, certain parts can sometimes be challenging to print without the effecting the strength and functionality of the final product and therefore, designing these part entails some knowledge about additive manufacturing principles. As for some disadvantages of SLS, there are many with regard to post-processing, material properties, part distortion, surface finish, equipments cost and design elements and complexity again as a result of the material flexibility and complexity of geometry for polymers for components made through SLS [133]. Solving such issues is usually a multifaceted process that involves not only specific knowledge of the material used but also the selection of a suitable material, the choice of printer parameters, and the choice of proper ways to process the final printed goods [134].

Despite the advantages of SLS, such as design flexibility, customization, and the ability to create complex structures, there are a few disadvantages that require further research and improvement in the system. The major challenges include poor mechanical properties, dimensional accuracy, microstructure as well as surface roughness and other are like higher cost of production, limited applicability in large constructions, lack in mass production and material related issues [135–140]. Some of these issues have been addressed with material research and with the improvement of the SLS process. However, a few remaining must require to be improved in order to apply SLS to a wider range of industrial applications. The major hurdles can be categorized in four types: Dimensional accuracy, microstructure, mechanical properties and surface roughness [141–145].

The SLS procedure, which utilises polymers as its primary material, is a prevalent technique in the field of additive manufacturing. However, this method is not without its own distinct set of difficulties and obstacles. As depicted in (Fig. 13), several prevalent challenges are observed in the context of SLS utilising polymer materials.

The process of selecting an appropriate polymer material for SLS might be a considerable challenge. Not all polymers are deemed acceptable for the SLS method, as certain polymers may demonstrate inconsistent sintering behaviour or give rise to complications during subsequent post-processing stages.

Mechanical finishing processes like sanding, grinding, or tumbling are examples for processes that can be applied to smoothen out the surface. By enzymatic treatments, layers of a rough surface can be removed using solvent vapor smoothing functionalities to attain a polished surface. There are several thermal processes that may help reduce internal stress; some of them are annealing which will in turn improve on the dimensional stability and the surface finish. Surface coatings: Some of the ways of enhancing its surface finish as well as protection against the degradation by the environment include the use of protective coatings [146]. The importance of the polymer powder utilised in SLS cannot be overstated, as it directly impacts the production of parts with superior quality and consistency. The differences and the existence of cracks is due to the fluctuation in the particles size, shape and chemical composition. One of the key techniques used in SLS has been the regeneration of excess or remaining powder that is a green move aimed at reducing wastage and cost saving [147]. However, at the same time I should remind you that every recycling revolution has the inherent possibility to produce mere degradation of powder and contamination. The precision in generating heat from the laser energy and duration of exposure on a part is of core significance so that all the interacting surfaces have uniform sintering consistence. Insufficient management of energy can lead to the occurrence of flaws in the parts, compromised mechanical qualities, or inadequate sintering. The SLS procedure entails the application of targeted thermal energy to heat and subsequently cool the polymer powder in a localised manner. The occurrence of thermal stresses has the potential to induce various forms of deformation, including warping, curling, and distortion, hence exerting an adverse impact on the dimensional accuracy of the components. In the context of SLS,

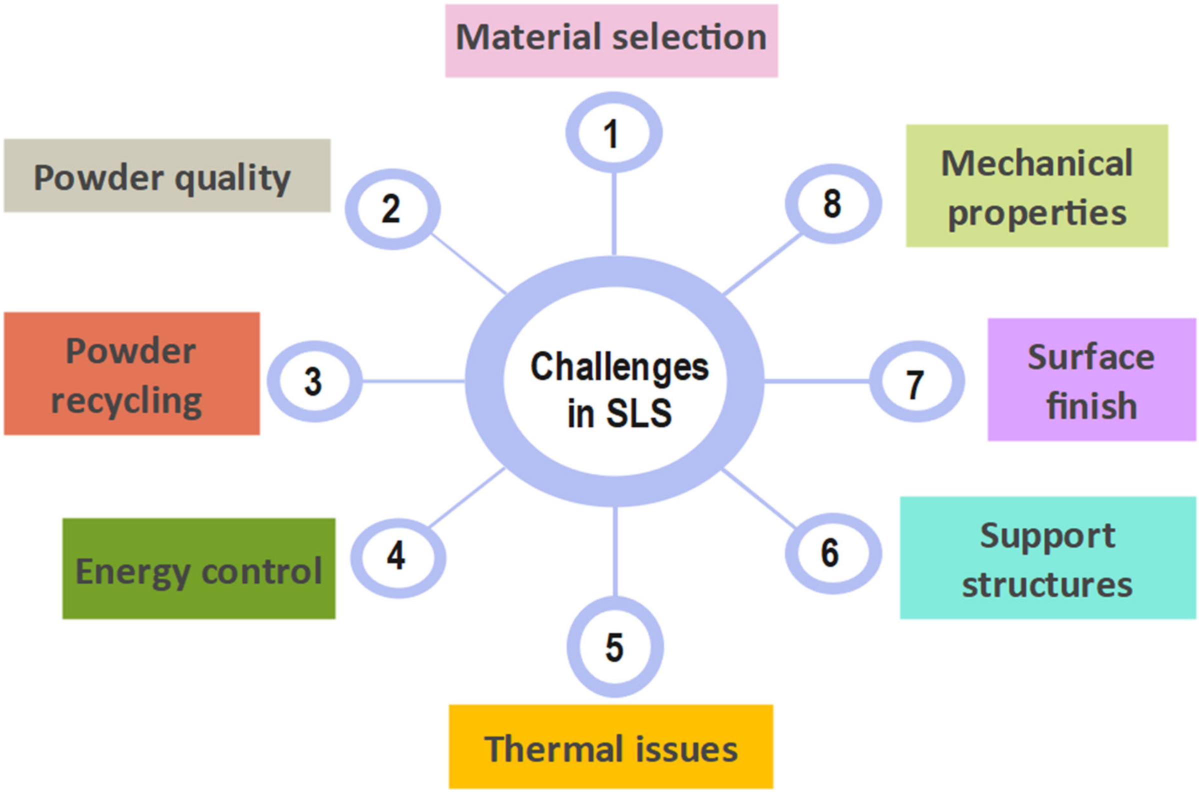

Fig. 13 Polymer-based SLS Challenges

the utilisation of support structures is frequently necessary in order to mitigate distortion and guarantee the stability of overhanging features. The process of removing these support structures post-printing can be a time-intensive task and has the potential to result in visible marks or surface flaws on the final component [148–150]. Powder deposition, surface pits, fractures, cracks, and holes, substrate quality, staircase effect, and orientation are some of the additional contributing factors that affect surface quality. Blow holes cracks, fractures and poor bonding between layers. Blow holes, cracks and fractures occur on the surface because of alternate scan patterns. Scan length and scan speed are more influential parameters for generation of deep longitudinal as well as narrow gaps. Further bonding between layers is influenced by layer thickness, sintering depth, scan overlap, laser spot diameter and gas flow direction. Smaller layer thickness may enhance the sintering by re melting the substrate layer and will enhance bonding between layers [151–155]. When the scan overlap is increased, the melt penetration is reduced, resulting in less layer bonding. While comparing the parts produced parallel to the gas flow direction with the parts produced perpendicular to the gas flow direction have much stronger bonding between the layers and hence exhibits better mechanical strength [156–160]. Porosity of SLS parts is influenced by orientation, as the porosity in the parts increases the strength of the parts lowers. Densification causes volumetric/sintering shrinkage, whereas cyclic heating cause's thermal shrinkage and CAD shrinkage occurs with operational errors [117, 161–163]. Controlling process parameters, calibrating the building approach, and using compensatory techniques can all help to reduce thermal shrinkage. Along with shrinkage, powder bed density, spot diameter, orientation, gas flow rate and microstructural waviness are some other parameters that affect dimensional accuracy of SLS parts. Further in Z direction staircase effect occurs because of geometric approximation in curved surface [164–169]. As a cusp height error, this feature is introduced. The larger the staircase effect, the thicker the layer.

The process of (SLS) is multifaceted, encompassing a range of factors including laser power, scan speed, and layer thickness. The process of optimising these characteristics for materials and applications necessitates a significant investment of time and effort in conducting thorough experimentation. In SLS parts microstructure is mainly influenced by heterogeneity, anisotropy, and porosity. In the case of heterogeneity scan pattern, bed temperature, energy density, conditions for solidification and pre preparation of powder are the influencing parameters. Higher energy density will improve homogeneity in the SLS parts. The variation in the bed temperature leads towards the heterogeneity in parts [170–175]. Raster type of scanning patterns result in inhomogeneous properties, and a small scan space results in a less homogeneous parts. During solidification of parts in the bed the change in the conditions generates different grain structures, this will result heterogeneity in parts [176–181]. Preheating or pre preparation of powder before sintering also improves the density homogeneity in the parts. The isotropic properties of the SLS parts are influenced by build orientation and scan direction. Porosity is another phenomenon that also influence the microstructure as well mechanical properties of SLS parts [182–186]. Notwithstanding these obstacles, SLS continues to be a valuable technology in the field of additive manufacturing, namely for the fabrication of functioning prototypes, customised components, and limited-scale manufacturing of polymer-based parts. As technological advancements progress, scholars and professionals persistently strive to tackle these obstacles in order to enhance the overall dependability and efficiency of parts produced through (SLS) printing.

5 Future of finite element analysis in polymer based (SLS)

With the help of finite element simulations, a numerical model of SLS is developed that the analysis considers both the heating and sintering phenomena that are associated with the process. The results of the simulation have shown good correlation with the physical experiments. This model can be used to optimize the SLS process parameters for improved performance. It can also be used to design the 3D printing process for a wide range of materials [187]. FEA is likely to prove as increasingly significant tool in the development and optimisation of SLS based on polymers. I am responsible for the spheres of business analysis and product management, so, for I offer to review FEA impacts on SLS. The fiber reinforced 3D printing is another significant transformation of polymer process modeling [188]. FEA is able to represent with exactitude the thermal and mechanical characteristics of the material which appear during SLS process for polymers. The simulation use has the potential to effectively detect such flaws as warpage, residual stress, part deformation by visualising the whole and local strains. Consequently, the developed data may be used as a source of optimisation for the manufacturing process and ultimately, for the enhancement of the quality and dimensional conformity of the final good. However, specific polymers provide thermal and mechanical features differently [189]. The FEA is great for this purpose and can help us understand the mechanical activities with which different materials behave during the SLS process. This analysis often yields crucial information helping engineering researchers to identify and choose suitable polymers for specified utilizations. The specialists of FEA simulations can optimize a large number of physical prototypes as there are simulations that are required for development and validation within organizations. Such a condition could be cost-effective at the same time provide scheduled manner of development. With the help of FEA, engineers and designers can easily analyze and refine vast numbers of alterations in a digital way [190]. This works out the product development and, and, the resultant design, is resilient and optimized. The FEA can provide the analysis tools need to predict the mechanical competence and the robustness of the parts built by SLS under a wide range of loading conditions. The presented information has been vital in determining whether or not the sustainable trio become items that can compete with the mass-produced. Using FEA, we can identify the main factors leading to part failure or manufacturing difficulties, such as stress concentration zones, as damage initiates, all thanks to the stress distribution visualization. FEA enables the prototyping of unique products by taking into account how the design characteristics of the custom components affect their functionality in the use-case scenario. Figure 14a presents the stress–strain relationship of the experimental data compared to the simulated data obtained from two different sources: one based on an ideal CAD model and the other based on a reconstructed (CT) scan. The reconstructed CT scan exhibits a notable improvement in its alignment with the experimental findings, primarily attributed to its incorporation of printed morphology. However, it still tends to overestimate the post-yielding response. This discrepancy can be attributed to the utilisation of a simplified finite element and material constitutive model, which only accounts for a single-unit cell in the simulation. It is anticipated that the utilisation of the FEN material constitutive model in simulating the complete CT-reconstructed model will result in a higher level of concordance with experimental findings. Figure 14b displays the outcomes of numerical simulations, namely the distribution of von Mises stress [191]. The distribution of stresses in the two models exhibits a noticeable similarity, with somewhat higher stress levels reported in simulations based on CAD. This suggests that the CAD-based model has a greater capacity to bear additional pressure.

In the simulation based on the reconstructed CT scan, it is observed that there is a marginal rise in the stress distribution. This can be attributed to the presence of defects, which lead to variations in thickness and subsequently result in the redistribution of stress intensity [192]. The future of Finite Element Analysis in polymer based SLS holds great promise for enhancing design, optimization, and cost-effectiveness in the additive manufacturing industry. Additionally, optimization strategies should be considered to reduce the impact of these defects. Optimization strategies could include improving the manufacturing process, introducing additional quality control measures, or using different materials. Ultimately, this will ensure that the product meets its intended purpose and is safe for use.

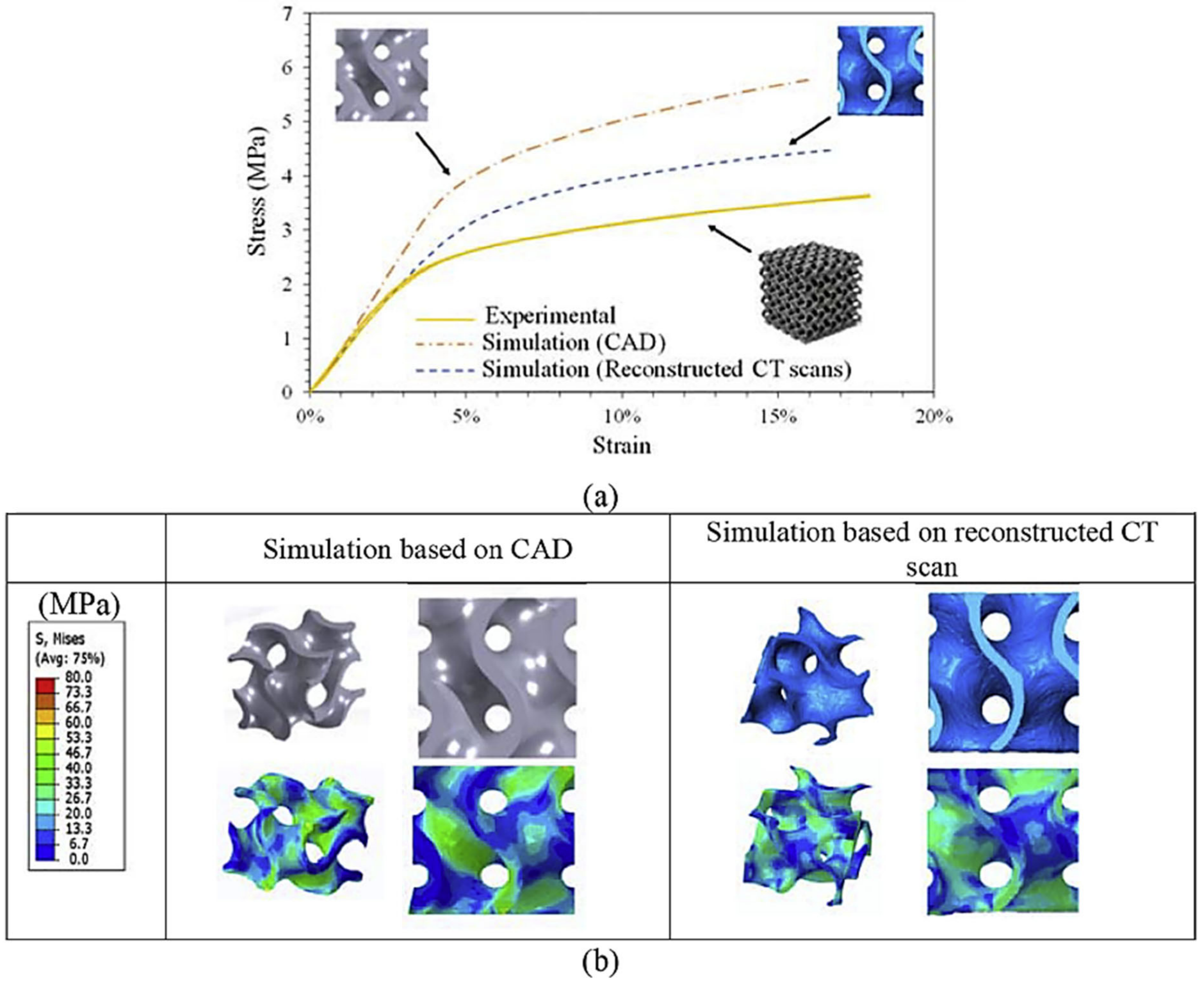

Fig. 14 **a** The comparison of stress–strain responses with experimental results, and **b** the analysis of von Mises stress distributions [191]

6 Summary

- This research focuses on polymer powders. However, the other materials that can be processed with the use of SLS process may be unable to achieve the requisite integrated performance.
- There have been limited literature available for the effect of orientation, scan length, scan speed, layer thickness and powder related as well as machine related parameters on the polymer parts. However, the sintering mechanism for polymer powder is clear but the research or facts presenting the effect of particular parameter on the challenges like mechanical properties, dimensional accuracy, microstructure as well as surface roughness are not clear. Therefore, SLS process parameters are still in a scope of optimization to enhance the applicability of parts.
- Mainly the research dealing microstructure and surface roughness of laser sintered parts refer to metallic powders. There is a significant difference in the mechanism of processing polymer and metallic powders with the use of lasers. Therefore, analysis of microstructure and surface roughness of polymer parts still requires more understanding and clarity.
- The limited understanding for SLS processing parameters not only affects mechanical properties, dimensional accuracy, microstructure, and surface roughness, but also limits the applicability of polymer-based parts. Current researchers, on the other hand, are mostly focused on challenges (mechanical properties, dimensional accuracy, microstructure, and surface roughness) with limited number of parameters; how to effectively regulate all parameters and factors via optimization, generation of simulation models and experimentally remains a fundamental question.

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Declarations

Conflict of interest The writers claim that there aren't any conflicts of interest.

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