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SELECTIVE LASER SINTERING – BINDING MECHANISM AND ASSISTANCE IN MEDICAL APPLICATIONS

ABSTRACT

Rapid prototyping technology (*RP*), based on designing and computer aided manufacturing, is widely used in traditional branches of industry. Due to its ability to accurately and precisely manufacture designed elements of various dimensions and complicated geometry, this technology is more and more frequently applied in the field of biomedical engineering. Selective laser sintering (*SLS*) is a universal *RP* technique, utilizing a laser beam to sinter powdered materials and create three-dimensional objects. Data for producing parts for tissue replacement come from medical imaging capabilities and digital presentation of test results. This paper presents the following: general classification of *RP* methods, the concept and methodology of performing laser sintering, sintering mechanisms, and the application of elements manufactured using this technology in biomedical engineering, particularly for the production of scaffolds used in tissue cultures, skeletal and dental prostheses in dental implantation, manufacturing of custom-made implants that are individually adjusted to the patient, and for production of training models on which a team of surgeons can train a surgical technique.

Keywords: laser sintering, sintering process, powder metallurgy, applications in biomedical engineering

INTRODUCTION

Design work often requires the creation of a physical, three-dimensional model of the designed element. Traditional methods of preparing prototypes and models are often very expensive and time-consuming [1]. Rapid Prototyping technology proves to be very helpful in this situation.

Rapid prototyping is performed by incremental forming, which is defined as a set of methods based on *CAD/CAM* technologies in which data collection, processing, and the manufacturing process are assisted by computers [2]. The concept of incremental forming is based on dividing a virtual 3D model into a series of two-dimensional layers, which are then produced in a specialized prototyping device [3]. The term "additive technique" may be used to refer to rapid prototyping and incremental forming, because in contrast to traditional methods, e.g. machining, rapid prototyping does not deal with the production of objects by removal of material, but by building objects layer by layer. There are many methods of incremental forming of physical models. The following figure among the *RP* methods that have been technically refined [4, 5]:

- stereolithography,
- selective laser sintering (SLS),
- solid ground curing (SGC),
- fused deposition modeling (FDM),
- laminated object manufacturing (LOM),
- ink jet printing (IJP),
- three dimensional printing (3DP).

The *RP* methods enumerated above are adapted for work in three-dimensional technology and are based on the addition of material in points (discrete or continuous), layers, or surfaces[6]. Elements manufactured by means of incremental technologies are distinguished by high accuracy of shape and dimensions as well as by good surface quality. *RP* methods are diverse due to the essence of their action, the course of the process that is conducted within the framework of a specific method, and the materials used in them. Fig. 1 presents a classification of rapid prototyping methods according to the type of material used [7].

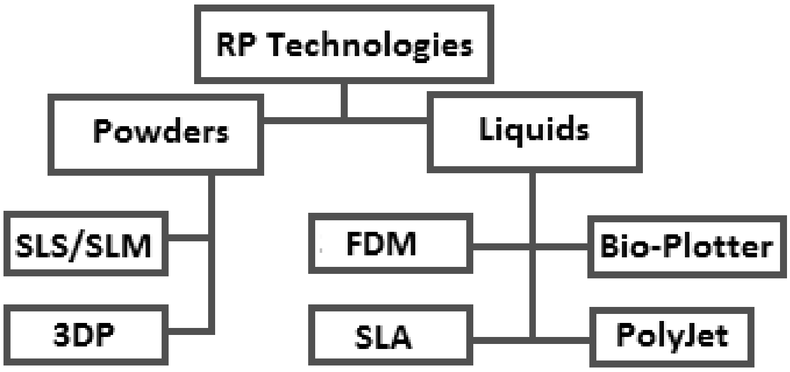

Fig. 1. Classification of RP technologies according to type of material used [7]

SELECTIVE LASER SINTERING

One technology for incremental manufacturing of models and prototypes is selective laser sintering, based on joining consecutive layers of powder using a laser beam [8]. The advantage of this method is the capability of obtaining a model of any shape without the necessity of bringing the material to a liquid state [9].

The entire laser sintering process takes place in the working chamber of a machine equipped with a computer that controls the production process (Fig. 2). Specialized software enables control and adjustment of the pressure value and atmosphere present inside the chamber, depending on the material that is used [10, 11]. This process is performed using infrared laser radiation from a CO_2 (10.6 μm) or Nd:YAG (1.06 μm) laser [12, 13]. Selective laser sintering is based on spreading a thin layer of powder on a table whose position on the Z axis can be adjusted. This layer serves as a substrate for the object that is being created. The laser beam travels over the surface of the powder according to pre-input and properly configured information concerning consecutive layers in the cross-section of the object's spatial image [14]. Selection of the appropriate laser beam parameters allows for melting or sintering of powder particles in strictly defined areas. Next, the structure of the platform, along with the table, is lowered by a set height (usually equal to the thickness of one layer; 30-100μm) relative to its previous position, and another thin layer of powder is spread [15]. Excess powder is diverted into a collection box found outside of the platform on which objects are constructed, after which the blade for removal of excess material returns to its initial position. The laser scans the cross-section once again. This process is repeated until a cohesive object is obtained according to the data contained in the generated digital file.

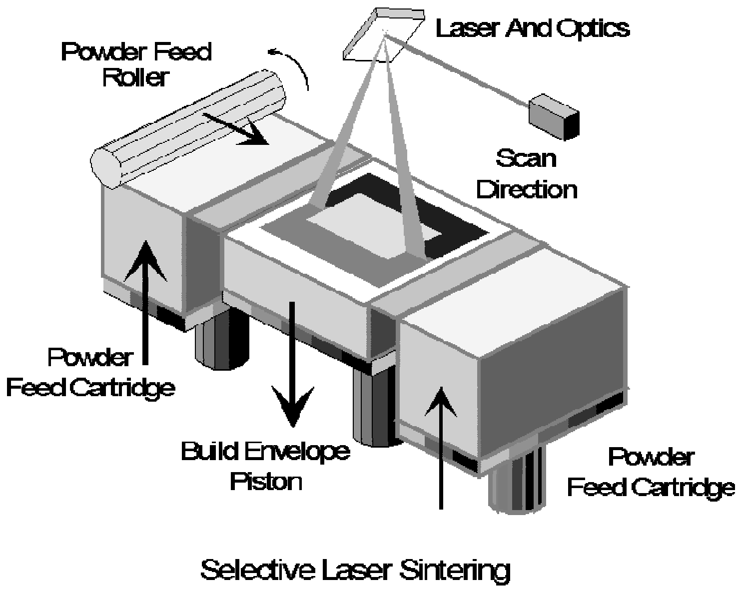

Fig. 2. Schematic of the SLS Process [16]

MECHANISMS OF THE SINTERING PROCESS

Two types of laser sintering can be distinguished within the framework of the SLS Rapid Prototyping method: indirect and direct [17].

Indirect selective laser sintering (ISLS, Fig. 3) utilizes metallic powder coated with a polymer 5μm in thickness. The laser beam sinters the polymer layer, and metallic powder grains remain unchanged. An object obtained using this method is characterized by low strength properties and high porosity (even above 50%), which is why it is necessary to subject it to further thermal treatment [18].

Thermal treatment is divided into two stages: polymer removal and infiltration. High temperature causes evaporation of the polymer. A further increase in temperature leads to the formation of necks between metal particles (sintering). The next step is infiltration, which is based on filling pores remaining after polymer evaporation with metal of a low melting point or on further sintering until full density is achieved [19, 20]. In addition, if pores are filled with a different metal, infiltration allows for the production of composites with desired properties [21].

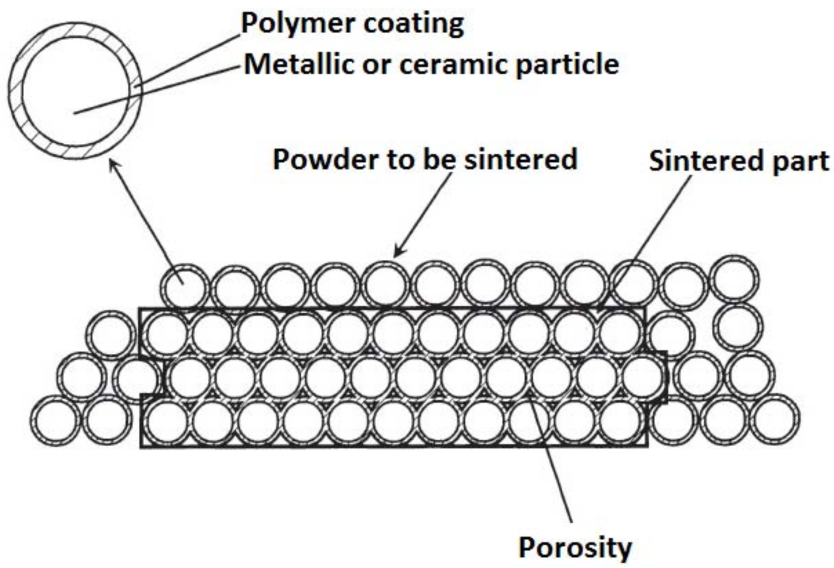

Fig. 3. Diagram illustrating indirect sintering [22]

In the case of direct laser sintering (DSLS), a high-power laser beam acting on a metallic powder substrate leads to its direct sintering [23]. An advantage of this type of selective laser sintering is that it eliminates costly and time-consuming thermal treatment. DSLS technology makes it possible to apply a mixture of different powders with different properties. This enables sintering of specialized materials with good and unique properties: cermets or alloys based on cobalt, nickel, and titanium [24]. These materials have strictly defined applications, which is linked to the high temperatures employed during the process, stresses, and rigorous conditions having an influence on oxidation or corrosion [25].

Sintering is a high-temperature consolidation process (thermal consolidation) to which loosely spread powder is subjected, and as a result, the system's free enthalpy is reduced as temperature is increased, causing reduction of porosity and an increase of material density [26,27]. These are macroscopic manifestations of sintering arising from the changes occurring inside the sinter. In the sintering process, mechanical connections between powder particles are transformed into metallic bonds of greater strength. When analyzing the theoretical aspects of the sintering process, driving forces and matter transport mechanisms must be accounted for [28,29,30].

Sintering may take place in a solid phase and with the involvement of a liquid phase [31]. The quantity of the liquid phase is restricted by preservation of the shape of the product during sintering (Fig. 4). Ordinary ceramic sinters or other simple metallic materials are typically obtained in the solid phase during sintering.

SOLID-STATE SINTERING

Solid-state sintering (SSS) is a thermal process occurring at temperatures at which melting of material takes place [32]. Various chemical and physical processes take place over the course of SSS, of which the most important is the diffusion process. This causes the formation of connections between adjacent powder grains in the form of necks.

The main advantage of SSS is the wide range of materials that can be processed in this way, under the condition that the temperature generated by the laser beam is sufficiently high to supply the kinetic energy required for hardening of the material by way of molecular diffusion [33]. Despite the fact that solid-state sintering is a long process, pre-heating of the substrate makes it possible to increase the diffusion of atoms and to achieve an acceptable laser scanning rate [34].

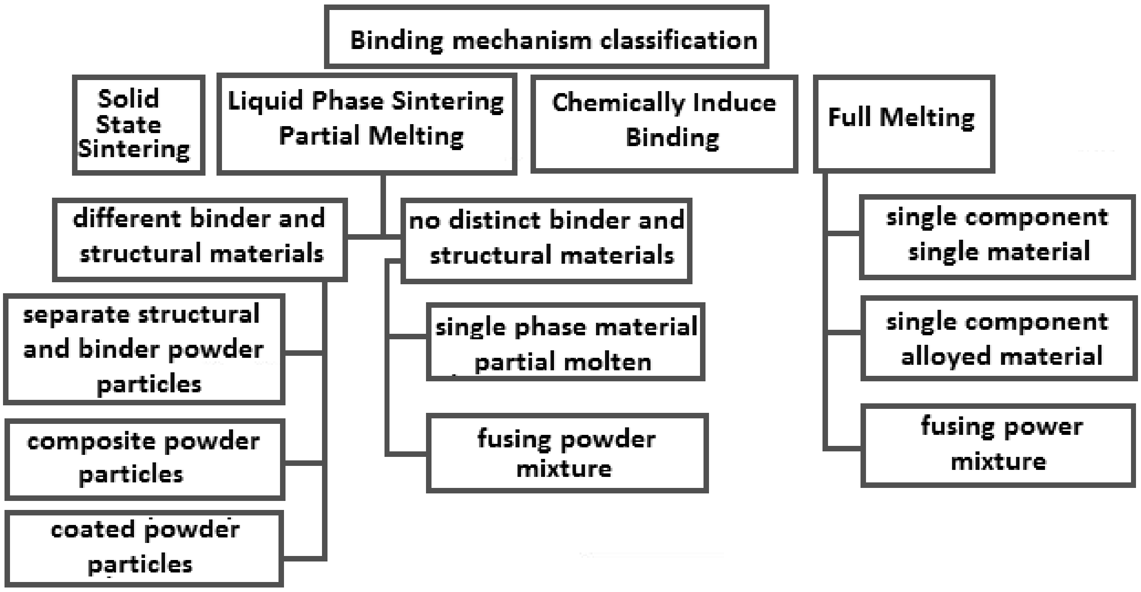

Fig. 4. Laser-based powder consolidation mechanisms [17]

CHEMICALLY INDUCED SINTERING

The chemically induced sintering process is premised upon using thermally activated chemical reactions between two powder types or between powder and atmosphere gas to manufacture the product of these reactions for bonding of the molecules of the material [35]. This mechanism is primarily used in the case of ceramic materials. An example of a reaction between powders and gas is laser sintering of SiC in the presence of oxygen, where SiO_2 is formed and binds together a SiO_2 and SiC composite [29]. Thanks to the addition of energy from the chemical reaction to the laser's energy, structures with a high melting temperature can be obtained at relatively low laser energies.

One of the characteristic features distinguishing this process is the porosity of the element. Thus, in order to obtain greater density, high-temperature furnace treatment or infiltration is necessary to improve the parameters required for most applications. Infiltration may involve the use of reactive elements and the formation of a new chemical composition. Unfortunately, costs and the time related to post-process processing limit the commercial application of this method in most machines [22].

LIQUID-PHASE SINTERING

Several types of technological processes are referred to by the name of liquid-phase sintering (LPS). Most of these technologies combine use of the structural material remaining after the entire duration of sintering and the material serving as the binding agent, brought to the liquid phase. In certain cases, the solid and liquid phase are the same material [34]. LPS is a basic mechanism of joining particles of a powder mixture during laser scanning of the substrate surface, based on bringing an ingredient with a lower melting temperature to liquid form while the second ingredient does not undergo a change in state (Fig. 5). Bonding of particles is based on capillary forces that can be very large.

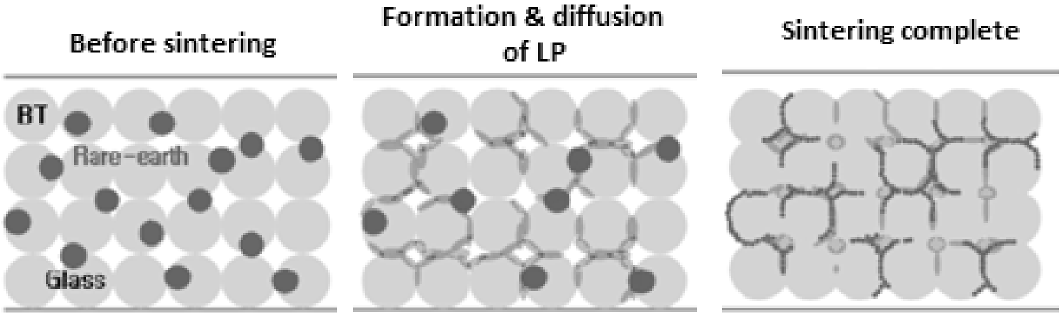

Fig. 5. Mechanisms of sintering [36]

Thanks to this method, objects of high density, often close to maximum density, are obtained within a very short time [36]. Because diffusion take place more rapidly in liquids than in solids, the presence of the liquid phase accelerates sintering as a result of faster binding and densification. Surface tension is a significant factor that is decisive to the degree of sinter. In the first step of this process, powder particles with a mixed composition are heated to a temperature at which the liquid phase begins to form. Because laser heating of the powder substrate takes place within an extremely short time, diffusion of the solid phase does not lead to densification before the first traces of liquid appear. As a result, we can distinguish three steps following the formation of the liquid phase: rearrangement, solution reprecipitation, and sintering [23].

METALLIC MATERIALS USED IN SLS TECHNOLOGY

As a rule, all materials that melt under the influence of a laser beam can be used in SLS technology. Today, selective laser sintering enables the use of a very wide range of materials in the form of powders, alloys, or mixtures. Metallic materials used in this technology include: steel, nickel-based superalloys, titanium and its alloys, refractory metals, nickel alloys with bronze, cermets, cobalt-chromium-molybdenum alloys, copper alloys [37].

Great efforts have been made to develop the availability of powders for use in the laser sintering process. The first problem that was encountered was the extremely short time of laser interaction with the powder substrate during scanning. Loose powder must be brought to a form with a permanent structure within just milliseconds [15]. This takes place over the course of object construction by means of sintering with utilization of liquid-phase emergence. When the laser travels over the surface of the powder spread over the platform, metal particles are melted, causing the formation of inter-particle necks. Obtaining stability of the geometry and dimensions of the product during sintering is another difficulty [8,36]. Because models are manufactured by means of sintering of consecutive material layers, contraction of parts may cause insufficient joining of edges and layers. The first attempts to selectively sinter single-phase metals were a fiasco because of caking. When a liquid phase forms as a result of the influence of a laser beam, melted powder immediately forms spherical structures with a diameter that is nearly identical to the diameter of the laser beam instead of bonding with the sintered powder below it [38]. This can be avoided by changing process parameters, i.e. increasing powder and reducing scanning rate.

In order to eliminate spheroidization tendencies of powder particles, a method utilizing biphasic metals was developed. Similarly as in the case of sintering of a liquid phase, the substrate contains at least two ingredients with distinctly different melting temperatures [34]. Over the course of the laser's point action on a powder layer, the more fusible material melts first. The formed liquid wets powder particles with greater melting temperature, joining to them. When using a combination of metals, particle bonding depends on the viscosity of the liquid, under the assumption that materials are chosen so that inter-particle wetting takes place. What is more, the tendency of caking is controlled by the viscosity of the mixture of solid and liquid phases, which increases as a consequence of particles maintaining their solid form in the accumulating liquid phase [36]. Thus, to avoid spheroidization, it is very important to adjust the amount of the solid phase. Because wetting is of key importance to bonding of the ingredients contained in the substrate, it should occur within the very short time of laser beam action.

For binary metal systems, to obtain optimal product density, the SLS process must be distinguished by the following characteristics [17]:

- for the solid phase:

- appropriate size of powder particles,
- high surface energy
- good laser coupling

- for the liquid phase:

- high surface energy
- low solubility coefficient of solid phase
- no volatile components.

APPLICATION OF SLS IN BIOMEDICAL ENGINEERING

The application of SLS in medicine developed at an astonishing pace from an early stage. This technology has found applications in surgery, orthopedics, dental reconstructions, manufacturing of skeletal prostheses in tissue engineering, and even for educational or research purposes [37,39]. What is more, it has gained widespread acceptance, acknowledgement, and is playing an increasingly significant role in solving complex cases [40]. The use of SLS technology for manufacturing of models used in bioengineering makes it possible to produce medical products according to expected and required dimensions and properties. The long-term stability of laser-sintered elements ensures that their geometry will be preserved for a long time. As of now, it is possible to sinter one or more types of powders with biocompatible properties acceptable to the human body while maintaining the appropriate strength and density [41,42].

In the case of scaffolds used in tissue engineering, despite the large amount of available techniques of obtaining them, when they are produced by selective laser sintering, they are characterized by the appropriate structural, porosity, and permeability parameters as well as the proper repeatability factor [43]. In addition, a positive aspect of using SLS to manufacture structures stimulating bone tissue growth is that it prevents the occurrence of stresses and the incidence of inflammatory states due to the lack of toxic solvents in the process, as is the case in conventional methods [44,45].

SLS is an excellent alternative to traditional techniques, such as casting, as a method of obtaining dental crowns and bridges [5,35,36]. Powdered Co-Cr alloy with a particle diameter of 3-14 microns is used for this purpose. The omission of activities like removal of material from and cleaning of molds is another advantage. The entire process boils down to the involvement of a 3D scanner and CAD software, which enable control of the virtual modeling process. Both the dimensions and thickness of a crown or cement, as well as the appearance of a bridge span, can be edited [46]. The above can also be standardized in this technological process. Moreover, the selective laser sintering process ensures high precision and quality of workmanship. It is worth noting that errors commonly occurring in traditional manufacturing techniques are eliminated. In the case of SLS, the production of a large product series poses no obstacle. It allows for the production of dental implants of high quality and density in an amount that is up to 20 times greater, which clearly displays its superior output [47]. In contrast to casting, it is more predictable in terms of deformation thanks to improved geometry control [16].

The use by surgeons of implant prototypes made from flexible materials has become a popular phenomenon in recent years. An example of this is titanium mesh, which is used to graft maxillofacial bones [48]. Despite the fact that this material is easily deformable, it requires the use of tools for proper adjustment and shaping of a model representing the geometry of the patient's bones [36]. Such "training" makes it possible not only to minimize the work performed during surgery but also to reveal previously unforeseen problems that may disrupt the work of a team of surgeons during surgery and to optimize the mesh, whose thickness and geometry may be modified based on a surgeon's guidelines.

Many prostheses now in use consist of modular components, which make it possible to adjust an implant to the needs of an individual patient. However, the fact that a significant percentage of patients have deformed joints and bones after overcoming an illness must be accounted for. In such a situation, it is difficult to select a module from a standard set that will represent the tissue geometry properly. Improved comfort and function can be achieved when components are matched on an individual basis, based on data obtained directly from examination of the patient by means of available imaging methods (computed tomography, magnetic resonance) [42]. The acetabulum of the hip joint can serve as an example, which, according to medical recommendations, is replaced by an artificial element over the course of prosthetic arthroplasty [38]. While a standardized process restores joint functionality, improper matching of the acetabular cup usually manifests as pain and restriction of joint mobility. SLS technology makes it possible to eliminate this problem by enabling precise representation of the geometry of the replaced tissue [49].

The application of metal powders brings clear benefits in SLS technology. Obtained elements are not perfectly smooth, and their characteristic slight roughness may be beneficial if the objective is to achieve the formation of a direct interface between the implant surface and the osseous tissue surrounding it in the process called osseointegration. Smooth surfaces can be obtained on joints and module connection points thanks to additional polishing or the application of an additional coat. By using additive techniques to build models made from metal powders, it is possible to produce an element of any geometry, size, and coarseness [50].

CONCLUSION

Additive model production technologies allow for the use of more complex CAD geometry. The necessity of assembling a working part from a large amount of small parts is eliminated, and a ready, disassemblable subassembly is obtained in a single process, in one machine pass (not including possible removal of supports and later finishing work). Importantly, these technologies enable engineers to make designs that are not limited by the manufacturing or technological capabilities available at plants. Engineers can now focus on developing new concepts without fear that their idea, in the form of a digital 3D model, will never be realized.

The main advantage of this technology is the relatively high strength of obtained parts as well as the wide range of materials that can be applied. Furthermore, the quality of obtained elements is very high, which is related to the fact that the laser sintering process takes place in a protective atmosphere of inert gas, yielding an elements devoid of admixtures and byproducts of combustion.

Rapid prototyping technologies are entering their third decade of commercial use. Over this time, many distinct changes have taken place, leading to improvements in the scope of surface quality, dimensional accuracy, mechanical properties, applicability, and to reduction of the manufacturing costs of elements produced using these methods. Achievement of high accuracy of designed models is a very significant problem. It is linked to the possession of a laser with the appropriate parameters. Considering the complexity of individual machines, their maintenance and operation may be linked to additional activities, maintenance, or operating methods. The applied software and its version is also an important factor. This is because the software allows for the application of advanced settings of the process's technological parameters - and thus, greater versatility of applications.

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