1. INTRODUCTION

Selective laser sintering (SLS) is an intelligent manufacturing process based on the use of powder coated metal additives, a process generally used for rapid prototyping and instrumentation. A continuous Laser beams are used or pulsating as heating source for scanning and aligning particles in predetermined sizes and shapes of the layers. The geometry of the scanned layers corresponds to various sections of the models established by computer-aided design (CAD) or from files produced by stereolithography (STL). After scanning the first layer, the scanning continues with the second layer which is placed over the first, repeating the process from the bottom to the top until the product is complete. SLS is known also as solid free and open shape manufacturing process, as a layer fabrication technology, rapid prototyping technology, a selective sintering of metal powders. The term "sintering" refers to a process by which objects are created from powders using the mechanism of atomic diffusion. Although atomic diffusion occurs in any material above absolute zero, the process occurs much faster at higher temperature which is why sintering involves heating a powder. Sintering is different from melting in that the materials never reach a liquid phase during the sintering process**.** It (SLS) is a powder-based layer-additive manufacturing process generally meant for rapid prototyping and rapid tooling. Laser beams either in continuous or pulse mode are used as a heat source for scanning and joining powders in predetermined sizes and shapes of layers. After the first layer is scanned, a second layer of loose powder is deposited over it, and the process is repeated from bottom to top until the part is complete. In this process a high power laser beam selectively melts and fuses powdered material spread on a layer. The powder is metered in precise amounts and is spread by a counter-rotating roller on the table. A laser beam is used to fuse the powder within the section boundary through a cross-hatching motion. The table is lowered through a distance corresponding to the layer thickness (usually 0.01 mm) before the roller spreads the next layer of powder on the previously built layer. The unsintered powder serves as the support for overhanging portions, if any in the subsequent layers.

Laser-Sintering means methods which manufacture solid parts by solidifying powder like materials layer-by-layer by exposing the surface of a powder bed with a laser or other energy beam [1].

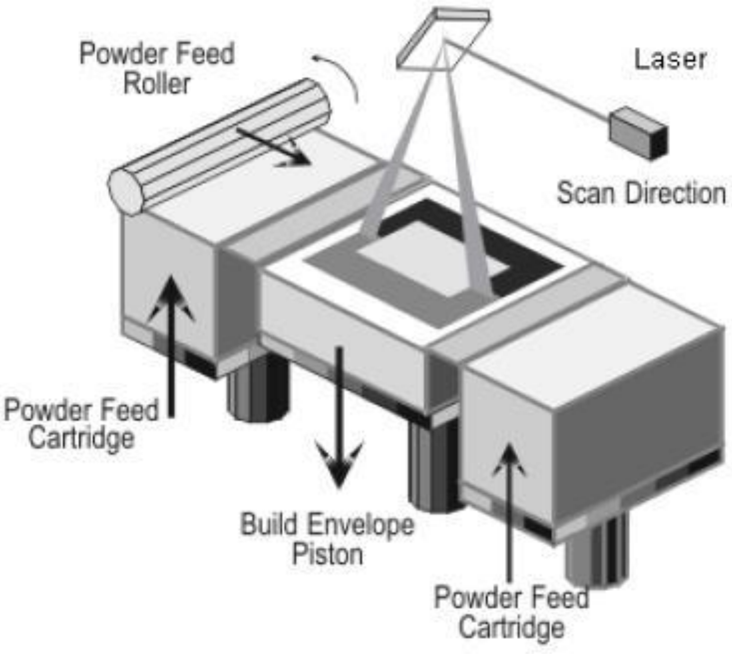

Fig.1. Components of SLS machine[2]

2. HISTORY

Manufacturing methods were first commercialised and the term Rapid Prototyping invented. Already in 1971 the Frenchman Pierre Ciraud filed a patent application describing a method for manufacturing articles of any geometry by applying powdered material, e.g. metal powder, onto a substrate and solidifying it by means of a beam of energy, e.g. a laser beam. Ciraud's descriptions and illustrations actually bear little relation to any of today's commercial technologies, but can still be seen as a forerunner of later 3D laser cladding technologies. The basic idea and the aim of his invention relate very strongly to today's developments in additive manufacturing: "The invention makes possible the manufacture of parts which can have extremely complex shapes, without the need for casting moulds". Moulding process for forming three dimensional articles in layers and which process may However this idea was not yet ready for commercialisation, for example because both lasers and computers were in their infancy. Six years later another independent, private inventor called Ross Housholder filed a patent application which included a description of a system and method which bore an uncanny resemblance to future commercial laser-sintering systems. The stated object of the invention was "to provide a new and unique be controlled by modern technology such as computers". In one embodiment "fusible particles are employed to form each layer which is then selectively fused by a laser beam to fuse an area in each layer which defines that portion of the article in the layers". Due to the extremely high cost of lasers at the time, Householder was only able to fully test a variation method which did not require a laser. His invention was not commercialised at the time and remained virtually unknown until it was discovered by DTM Corporation in the course of their own patent filings. DTM licensed the patent and used it for many years to protect and defend their business.

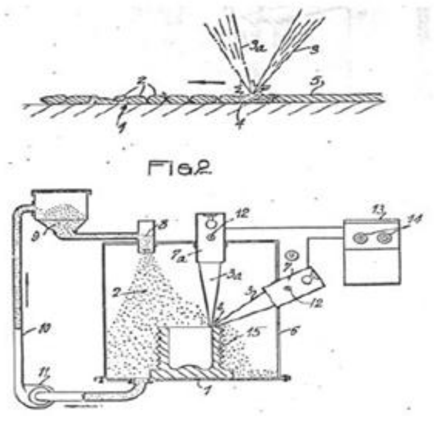

Fig.2. Ciraud's invention[3]

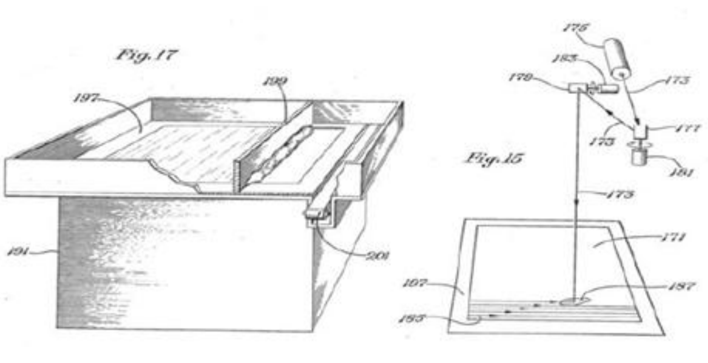

Fig.3. Housholder's invention[3]

Around 1986, a Masters student at the University of Texas (UT) called Carl Deckard started investigating a similar method to Hull's but using powder materials. Initially he called his method Part Generation by Layer wise Selective Sintering (PGLSS), later changing the name to Selective Laser Sintering (SLS). The resulting patent application in October 1986 described a "computer aided laser apparatus which sequentially sinters a plurality of powder layers to build the desired part in a layer-by-layer fashion". The described apparatus was essentially identical to Housholder's idea, but in this case real experimentation was done using a 100 Watt laser ("chosen because of lower dollar-per-watt cost") instead of CO_2 in continuous mode with ABS polymer powder. The first proper commercial system for laser-sintering was the Sinterstation 2000 from DTM Corp. of Austin, Texas, the result of the research and development by Deckard, Beaman and colleagues at UT and the commercialisation efforts of DTM. First systems were shipped in December 1992. The second commercial system for laser-sintering was launched by EOS GMBH of Munich, Germany, first shipped in April 1994.[1]

3. PROCESSES IN SLS

3.1. Pre-processing

The deposition of powders and the mechanism of sintering depend totally on

(a) The density of the powder,

(b) The shape and size,

(c) The flow rate.

For better sintering of powdered metal layers, the density should increase. Ordinary particles produce porous layers of high density, appropriate size and appropriate composition. This can be achieved by optimizing the particle shape and surface, prior to optimizing the performance and the SLS process, the powder sintering ability must be improved by selecting proper process parameters viz., material, laser, and scan environmental parameters. Describe about the process parameters that are important from the SLS point of view. Sometimes the material and laser parameters are varied for the reason that they are machine dependent.

3.2. Scanning Strategies

Hatch pattern for building part layer by layer choice for selecting a path for laser movement lies in the selection of the hatch pattern, the default value of the hatch pattern in the DMLS EOS machine is direction of scanning rotated of 67° between consecutive layers as shown in fig e. There are four choices for hatch pattern selection and they are along x, y, both in x-y or alternating in x-y as shown in Fig. 4. Fig 4a shows the scanning done along the x axis and Fig. 4b indicates scanning done along y. If both x and y options are selected then there will be double exposure on the layer, once along x and then along y as shown in (Fig.4c).

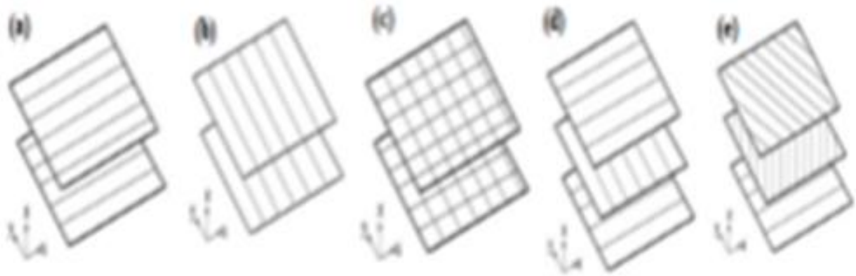

Fig.4. Different hatch patterns or scanning strategies[4]

3.3 Post Processing (Hybrid Direct Laser Fabrication)

Some of the direct laser fabrication processes like DLF, LENS, and DMD, where the objective is to fuse the powder to full density across each layer. SLS can produce complex shaped metal components with a part density exceeding 92 percent of the theoretical density. This is the fractional density at which porosity typically changes from interconnected or surface-connected to close. The powder in the interior of each layer cross-section can be optionally laser sintered to an intermediate density typically exceeding 80 percent of the theoretical density. Use of the compound fabrication method conceived as a rapid, low-cost replacement for conventional metal. The microstructure and mechanical properties of hybrid fabrication (SLS processed and hot isostatically pressed) post-processed material correlate well with those of conventionally processed material.[4]

4. PRINCIPAL PARTS OF SLS MACHINE

4.1. Laser

Laser is the main source to carry out the process which develops energy to sinter the powder particles. The energy source laser is either pulsed or continuous wave laser. Laser power along with scanning speed is one of the important parameter in the laser sintering process as it affects the overall mechanical properties of the produced part for example hardness, strength, porosity. CO_2 Laser, Fibre Laser can be used. Now a day, Fibre lasers are becoming most popular due to their high power, excellent control, less maintenance and reliability. The power requirements will depend on the raw material, speed of scanning etc.

4.2. Powder Feeder

SLS uses a powder feeder mechanism which lays a powder bed of a predetermined thickness over the base plate on which part is to be built. It is one of the essential components of any SLS based rapid prototyping machine. The layer of powder has to be very accurate and consistent over the complete process assuring the uniformity of part throughout the geometry. Researchers have used various techniques to deposit a layer for their experiments such as roller arrangements, scrapper blades etc. There are some techniques like 1. Classical deposition 2. Pressure gradient deposition 3. Ultrasound deposition 4. Spread method.

4.3 Enclosed Chamber for Controlling the Environment

SLS process involves diffusion of the atoms of one particle into atoms of adjacent particle. The heat energy involved is very high which will be near the melting point of the materials. At this high temperature, there is lot of chances of oxidation of surface which is in contact of the air. To control the oxidation, an inert gas atmosphere is provided. Vacuum gives the additional mechanical stability to the part if provided.[4]

5. Physical Description and Simulation

5.1 Physical Phenomenon

The SLS process involves several physical phenomena. These include:

- Heat generation and transfer (the heating of the powder bed and the cooling of the sintered sample);
- Microstructure evolution (porosity evolution and phase changes);
- Fluid effects (molten binder flowing in the solid lattice)

Mechanical issues (non-uniform distribution of thermal strains during the cooling stage may cause residual stresses and distortions of parts produced). In these coexisting physical phenomena, the thermal problem is dominant. The other problems, caused directly or indirectly by this thermal process, occur at different processing stages. Knowing the temperature distribution and evolution is essential to understand the SLS process. On the other hand, the temperature distribution and evolution is influenced by other phenomena.

5.2 Energy Input and Absorption in SLS

Sintering takes place if the powder bed is irradiated by the moving laser source up to the temperature at which the binder melts. After the laser has moved away, the sintered sample cools down. The thermal process in SLS may be summarised in four main stages:
1. Energy input and absorption.

2. Heating of the powder bed.

3. Binder melting and sintering.

4. Cooling of the sintered sample.

In the energy transformation stage, the light energy of the laser beam is converted into thermal energy that causes heating of the powder bed. Modelling of this stage requires the description of the interaction between the laser beam and the powder material. It is evident that not all energy contributes to the heating of the powders. A parameter quantifying “energy absorption” should be defined. On the other hand, unlike an opaque continuous medium, the powder bed allows a certain penetration of the light energy of the laser beam into the powders though multiple reflection.[4]

6. MATERIALS USED IN SLS PROCESS

The SLS process flexibility allows a variety of materials. Some of these materials make the SLS process superior to other rapid prototyping techniques, where the material properties depend on the process. Among these materials, the most common are: wax, paraffin, polymer-metal powders, or various types of steel alloys, polymers, nylon and carbonates. Polycarbonate powders were initially used as starting materials for both experimentation and modelling in the SLS process. It appears that the use of special materials for rapid prototyping is growing and the quality of products is visibly higher. The sintering achieves higher performance if you use a powder mixture consisting of two groups of materials:

- Thermoplastic materials (nylon, polyesters, waxes, some nylon or polycarbonate mixtures especially);
- Completion materials whose mechanical properties and thermal properties determined decisive use of new products (metal, non-metallic and composite).

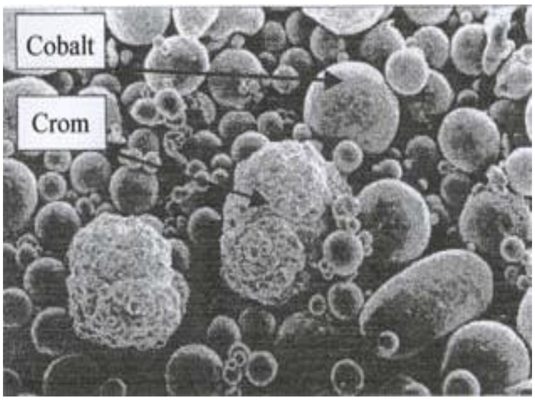

Fig.5. Co-Cr powder mixtures[5]

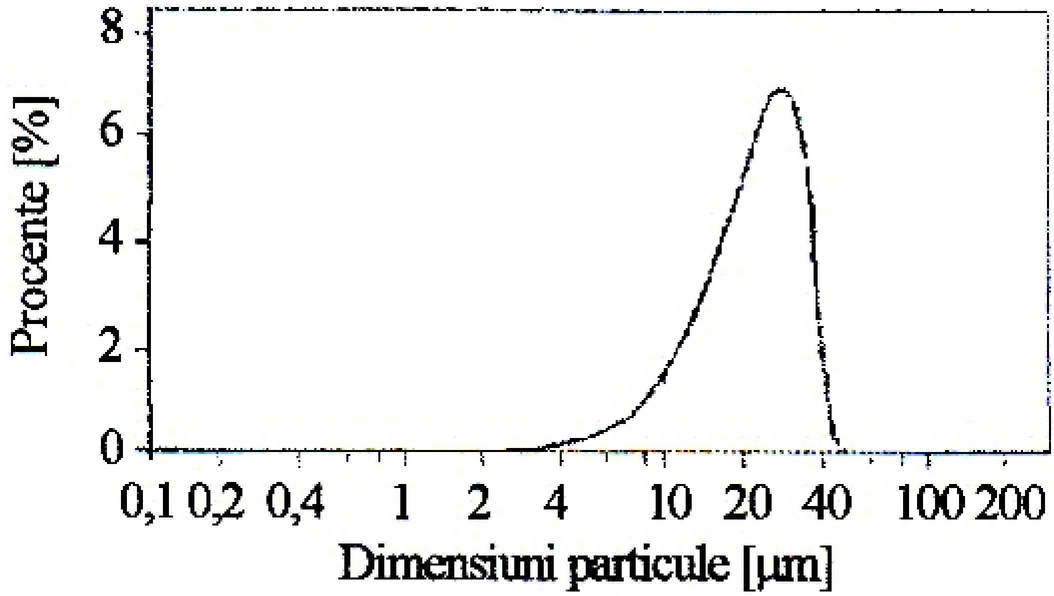

Fig.6. The particle size diagram[5]

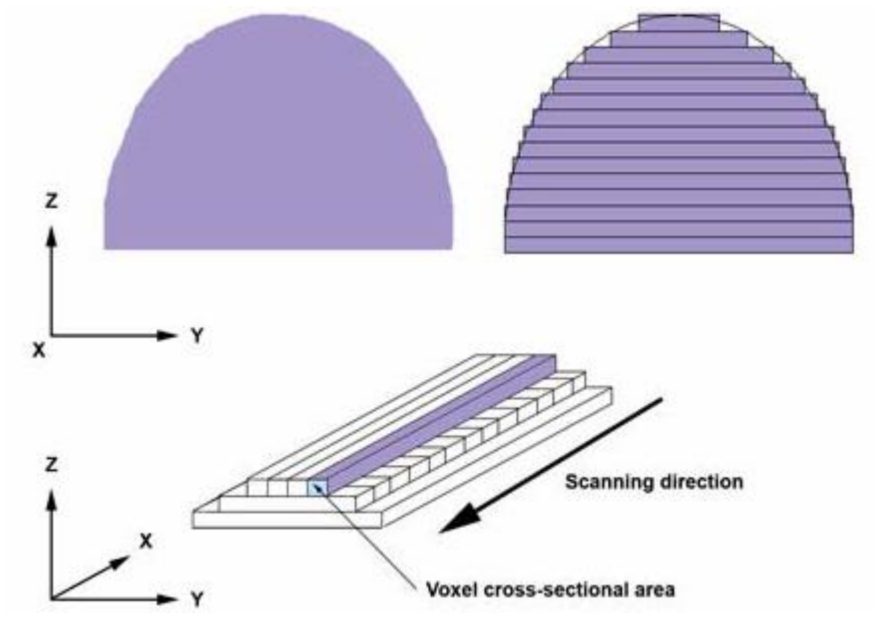

Fig.7. A view with emphasis on individual layers of the solidified powder bed[5]

The explanation is more complex because the solidification range of materials is especially diverse. It is essentially based on stereo lithography processes exposed to the same mechanism: the installation of chemical bonds that form macromolecular linear chains, or three-dimensional tree. For these situations state transitions, which involve a significant local heat input, they can be accelerated by inhibiting initialized and controlled substances, and energy intake may be given by concentrated heat sources on the desktop, laser radiation etc. These sources must be adapted and adjusted on the fly, so as to give extra heat necessary to achieve the melting temperature, which provides thermo-kinetic conditions favourable for the development process by establishing the macromolecular chains and a partially crystalline structure, with the transition of the liquid state to the solid state, reinforced, which marks the sintering product.

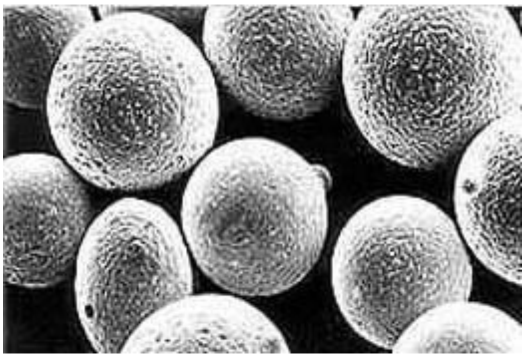

Fig.8. Micrographic appearance of pure metal powder

In terms of energy, the powders used in the in powdery have a wide range of melting temperatures which require a different input of heat from the concentrated source of energy. Choosing the necessary activation energy is possible by selecting rapid heating schemes in accordance with the dynamics of the sintering process. In SLS, parts can be made out of common engineering thermoplastics such as polyamides, polycarbonates, ABS to metals parts of steel, brass, bronze, titanium. Some of these materials make the SLS process advantageous over the other rapid prototyping techniques. Among these materials, the most common are: wax, paraffin, polymer-metal powders, or various types of steel alloys, polymers, nylon and carbonates. Polycarbonate powders were initially used as starting materials for both experimentation and modelling in the SLS process.

6.1. PA 12 (Polyamide)

Being a solid material, polyamide powder has the attractive feature of being self-supporting for the generated product sections. This makes support structure redundant. Polyamide allows the production of fully functional prototypes or end-use parts with high mechanical and thermal resistance. Polyamide parts have excellent long-term stability and are resistant against most chemicals. They can be made watertight by impregnation. The PA material used by Materialise is certified as biocompatible and food-safe under certain conditions.

6.2. Alumide (Polyamide Aluminum-Filled)

Alumide is a blend of aluminum powder and polyamide powder, which allows metallic-looking, non-porous components to be machined easily and is resistant to high temperatures (130°C). Typical applications include parts for wind tunnel testing in the automotive industry, small production runs, jig manufacturing, education and illustrative models with a metallic appearance.

6.3. PA-GF (Polyamide Glass-Filled)

Polyamide powder filled with glass particles (PA-GF) has a much higher thermal resistance (up to 110°C) than polyamide, and is typically used in functional tests with high thermal loads. This material exhibits excellent stiffness, high density and tensile strength, combined with low specific weight. As a result, PA-GF is ideal for demanding conditions where stiffness, temperature performance or wear resistance is the key.[5]

7. EXPERIMENTAL DETAILS

7.1. Bonding-adhesion mechanisms: when laser energy is absorbed by the material, the powders are bound by the following mechanisms:

- Viscous flow bonding effect of curvature,
- Particle wetting,
- Sintering in solid state,
- Liquid phase sintering,
- Melting.

Bonding the viscous flow is dominant in materials with suitable temperatures and depends on the viscosity, while the effect of curvature is the driving force in nano-crystalline materials. Laser sintering is conducted in a short period of time (milliseconds) not enough time for bonding to take place because of the diffusion of the solid layer. For this reason, the bonding of the powders is caused by the melting of the powder components with low melting points or complete melting of the entire mass. The sintering by melting a powder part is the most common and is carried out using particle systems in a combination of components with high and low melting points. In this situation, the laser beam attacks the local powder layer inducing only the melting of the solid with a low melting point that, after subsequent wetting, bonds the components with high melting points. Wetting the space between particles can be made by bringing together two phases, to prevent the emergence of the "formation of lumps" phenomenon. The sintered portion (fig. 9) shows clearly the circular forms, and agglomerations formed.

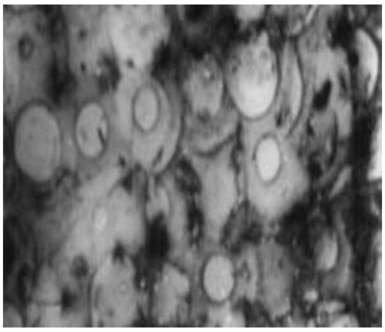

Fig. 9(a)[6]

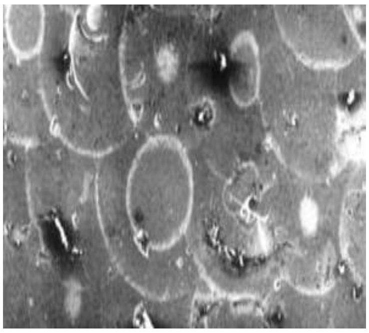

Fig. 9(b)[6]

Fig.9. Optical micrographs (a) electron scanning micrographs (b) sintered particles made up of iron and graphite.

In the actual fusion process, it was found that the complete melting of the powder causes problems such as warped surfaces and inadequate size of the finished piece.

7.2. Pre-Processing: The deposition of powders and the mechanism of sintering depend on the density of the powder on the sintering mechanism, the shape and size, and flow rate. The deposition on the mould (pattern) has a significant effect on the tension and on the bending of the part. For a better sintering of powdered metal layers, the density increases. This can be achieved by optimizing the particle shape and surface. For formation of dense layers, an electrostatic technique is used. Prior to optimizing the performance and SLS process, the powder sintering ability can be improved by thermal pre-treatment.

7.3. Experimental Parameters: That vary in SLS process are: powder size, scanning speed, powder density, frequency pulsars, and energy intensity laser scan size, scan of the surface temperature of the piece, laser performance, size distribution, particulate mixture and the volume of related material. For sintering, are taken into account other factors such as: working speed, building height, volume play. In addition, the manufacture and assembly orientation are important parameters for the optimal use of space and reducing execution time.

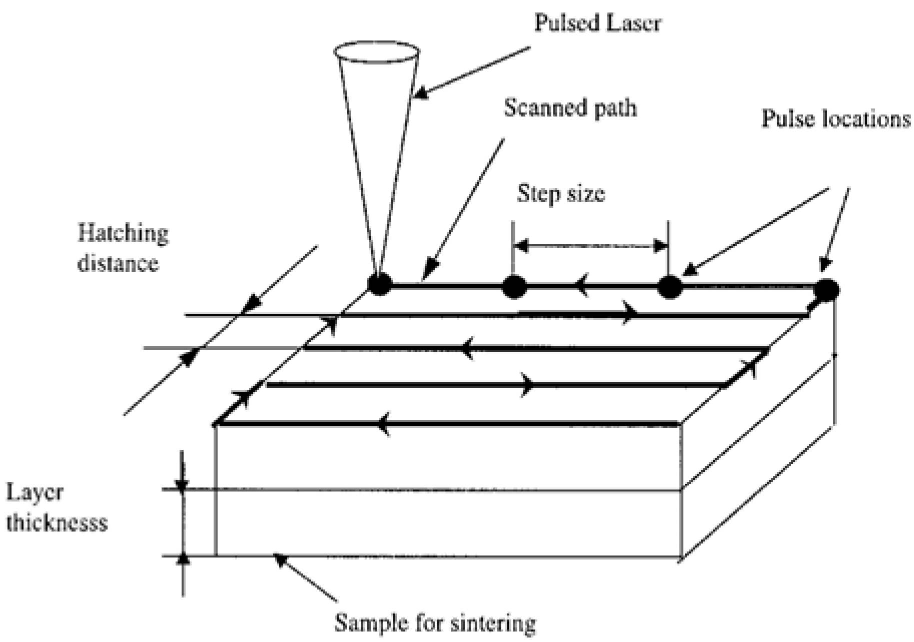

Fig.10. Schematic representation of the parameters of the SLS process.[6]

Experimental parameters role measurable properties of the sintered parts are: yield strength, elongation, Young modulus, hardness, surface roughness, shrinkage, thickness, and porosity, degree of wear, tensile strength, depth and speed of scanning sintering. Shrinkage is measured to determine the accuracy of the piece. The double laser beam technology, improves the ductile character of the metallic material obtained when the part is melted and solidified by the laser wave and CO2 laser reheated, with an appropriate delay time. When the scanned area increases, the porosity of the surface is improved and side pores form. In addition, when the peak effect of the laser beam was examined it was established that the solid piece and the maximum temperature of the powder have been affected more than the peak during laser radiation.

7.5. Post-Processing Defects: These are observed at concentrations of SLS powder, lumps, cracks due to pressing, twisting layers, cohesion and adhesion weak, porous or uneven surfaces which cause contractions, stress and porosity, low mechanical strength, rough surface and lack of accuracy and precision scale product. Therefore, it was found that SLS products post processing is needed, an operation which improves the integrity and compactness, mechanical properties, surface roughness of the structure while reducing the porosity.[6]

8. APPLICATIONS

Using select metals, it may be possible to generate core and cavity inserts for injection moulds. Because of the unlimited design potential of the process, these moulds may have water cooling channels and bubblers that are curved to accommodate the core and cavity surfaces. This would allow for a uniform temperature distribution across all mould surfaces, which is not easily obtainable with conventional mould building techniques.

8.1. Investment Casting Wax

The investment casting wax used in the process is an investment casting wax that The BF Goodrich Company purchases then powders in a patented process. This material has been in use for over 18 months and has gone through several improvements. The patterns made from this investment casting wax go directly into the investment casting process and can follow the procedures normally used for patterns generated via moulding wax. Thus the problems of long burnout cycles associated with photopolymer resins are eliminated. Other benefits of the SLS process with investment casting wax include:

The average tolerances range of wax patterns made in the SLS process range from ±0.002 to ±0.010 inches (±O.04 to ±0.25 mm). This meets the accuracy requirements for most investment casting applications.

Most parts made of wax in the SLS process have very complex geometries and are typically produced in very small quantities, typically less than 10 pieces. Some sample applications include:

Aerospace parts produced in titanium or other exotic alloys which are difficult to machine. The use of the investment casting process with the SLS process to quickly produce wax patterns allows for the rapid prototyping of parts which would normally take months to manufacture.

In the transportation industry, wax patterns are used to quickly produce functional metal prototypes for use on the engine or drive train. These pieces would be time consuming to prototype via traditional methods.

In medical prosthetics industry, custom made prosthetic implants can be quickly made in investment casting wax from CAT scan data.[7]

8.2. Another examples

- Casings
- Spare parts
- Machine parts
- Packaging (prototypes)
- Eyewear
- Jewellery
- Awards
- Surgical guides
- Anatomical models
- Orthopaedic appliances

9. NEW APPLICATIONS

- Prosthetic devices that can be custom made and used directly from the SLS process.
- Prototype moulds made of polycarbonate in the SLS process may be used in a variety of processes. These include moulds for wax injection which will produce patterns for investment casting, thermo forming tools, and patterns for sand casting. The thermoforming or vacuum forming moulds are used for materials with a forming temperature of less than 1700C (338°F). Materials that are formed below this temperature include polypropylene, polyethylene, polystyrene, and ABS.

9.1. Nylon

The latest material being added to the line of SLS materials is Nylon. This material was selected based on its performance in early testing. It offers improved toughness and strength over polycarbonate and will expand the number of functional applications.[8]

10. ADVANTAGES AND LIMITATIONS

10.1. Advantages: The main advantage is that the fabricated prototypes are porous (typically 60% of the density of molded parts), thus impairing their strength and surface finish.

- Variety of materials.
- No post curing required.
- Fast build times.
- Limited use of support structures.
- Mechanical properties of Nylon & Polycarbonate parts.

10.2. LIMITATIONS

- Rough surface finish.
- Mechanical properties below those achieved in injection moulding process for same material.
- Many build variables, complex operation.
- Material changeover difficult compared to FDM & SLA.
- Some post-processing/finishing required.[8]

11. NEW MATERIALS DEVELOPMENTS

When a material is selected for use in the SLS process, safety is a primary concern. The first step in the safety process is to review the MSDS sheets to ensure that the material is safe for the operator to handle. If the material is non toxic and safe, then it is reviewed to ensure that it will not cause a safety hazard in the machine. Once safety criteria are met, then the material will be tested via a single layer test to begin to understand how it sinters on a layer basis before multi-layer tests begin.

Further testing will include a 10 hours normal run test that will be used to collect gas data and determine if any gasses are being generated in a normal running mode.

Another test performed on a new material is called an upset test which is designed to determine what happens to a material exposed to high temperatures in the SLS process. This 90 minute test is performed by running the heaters at a high temperature with no nitrogen flowing through the system. The laser power is set at 100% to further degrade the material. Again, gas samples are collected and analyzed to determine if any harmful materials are begin emitted from the system.[9]

12. CHARACTERISTICS OF SLS PRODUCED PARTS

The measurable properties of sintered parts are yield strength, elongation, Young's modulus, hardness, surface roughness, line width, layer thickness, shrinkage, porosity, wear rate, density, tensile strength, sintering depth and scanning speed. The surface of an SLS part is powdery, like the base material whose particles are fused together without complete melting. The temperature dependence of the SLS process can sometimes result in excess material fusing to the surface of the model. SLS parts, because of the supporting powder, sometimes do not need any support. SLS parts can be easily machined compared to SLA and FDM parts. SLS parts are ideally used for form, fit and function and direct manufacturing applications. SLS parts are consistent, stable and durable and provide excellent prototypes and end-use parts for industries and applications that apply demanding and functional testing, giving you the flexibility to modify, optimize and evolve designs on the fly.[9]

13. CONCLUSIONS

- Since its emergence, the SLS has attracted attention from both researchers and users. As a result, various aspects of the processes and materials used for SLS sintering have been studied and there have been established that this is a modern and at the same time also a rapid means for prototyping and manufacturing.
- The SLS process is a viable time and money saving method for generating complex prototype parts in the plastics and metals industries based on the materials employed in the system.
- The ability to use a variety of materials and the future ability to expand the variety of materials which will work in the process. Current materials include investment casting wax, polycarbonate, and nylon. Future materials will include additional thermoplastics and the addition of metal and ceramic parts made with binders in an indirect sintering process and the direct sintering of metals and ceramics in a high temperature SLS process.
- In the plastics industry, the process can be used to generate functional models from three dimensional CAD models to visualize part form, verify fit, and test some aspects of the function. These functional models are an excellent aid for concurrent engineering because they clarify the communication between the designer, manufacturing, and marketing departments.
- Prototype tooling may be generated by a variety of techniques using SLS generated part patterns and mould patterns. These prototyping techniques include generating the mould pattern using a powdered polycarbonate material. These mould patterns may be used for wax injection applications. Among various techniques of rapid prototyping Selective Laser Sintering is the most flexible process that accommodates large variety of materials being processed. Laser sintering does not, however, lend itself to the production of near-net-shape objects to close tolerances and a high quality surface finish. Another obstacle that these processes face is the presence of micro structural defects (e.g., voids, impurities, or inclusions) in the final product. Such weaknesses can lead to catastrophic failure. Further work necessary for major success in particular application areas is ongoing or still to be done as part developed by sintering cannot be maintained full density which leads to the post processing techniques to be introduced to process it. One important technique which researchers have failed to identify is the severe plastic deformation (SPD) technique.[10]

REFERENCES

[1]. C. R. Deckard and J. J. Beaman, “Recent advances in selective laser sintering”, Proceedings, 14th Conference on Production Research and Technology, Michigan, USA, 1987.

[2]. Ciraud, P Housholder, R., "Molding Process", US patent 4,247,508, filed December 3rd, 1979, published January 27th, 1981.

[3]. S. Singh, A. Sachdeva, and V. S. Sharma, Investigation of Dimensional Accuracy/Mechanical Properties of Part Produced by Selective Laser Sintering, International Journal of Applied Science and Engineering 2012.

[4]. S. Kolosov, G. Vansteenkiste, N. Boudeau, J.C. Gelin, E. Boillat, Homogeneity aspects in selective laser sintering (SLS). Journal of Materials Processing Technology 177 (2006).

[5]. D.L. Bourelletal. - “Selective Laser Sintering of Metals”, Proceedings of ASME, New York: American Society of Mechanical Engineers, 1994.

[6]. Debasish, D, Fritz, B. P, David. R, Lee. W. “Layer manufacturing: Current status and Future Trends”, ASME, 1, 2001.

[7]. DTM Corporation Luke L. Kimble Market Development Manager July 29, 1992

[8]. Luke L. Kimble,” The Materials Advantage of the Selective Laser Sintering Process”, DTM Corporation, July 29, 1992.

[9]. IOSR Journal of Mechanical & Civil Engineering (IOSRJMCE) e-ISSN: 2278-1684. 5th National Conference RDME 2016, 10-11th March 2016. M.E.S. COLLEGE OF ENGINEERING, PUNE.

[10]. D.L. Bourelletal. - “Selective Laser Sintering of Metals and Ceramics”, International Journal of Powder Metall., 28(4)/1992.