A Review on Effect of Process Parameters on Surface Quality and Properties of Parts Realized by Selective Laser Sintering Process

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Abstract: This paper presents the survey of effect of different process parameters on surface quality and properties of parts fabricated by selective laser sintering (SLS) process. SLS is one of the Additive Manufacturing (AM) technique used for 3D printing of metal powders. AM is a layer based material additive process and can produce 3D parts directly from Computer Aided Design .stl data automatically without using any traditional tooling. Additive Manufacturing is an umbrella term given to all technologies that manufacture parts by adding material in layers, as opposed removing material in more traditional subtractive processes like CNC milling, turning, WEDM etc. As one of the advanced Rapid Prototyping and Manufacturing (RPM) processes, the SLS process not only save a lot of inventory but realize the components of almost any complexity in a wide range of metallic materials in quickest possible time. It offers rapid, cost-effective and low-volume manufacturing of physical parts. The various process parameters that affect the quality of final fabricated product are laser power, hatching distance, build orientation, layer thickness, scan speed, laser beam diameter, hatc/h length, scanning pattern and power particles size. From this the effect of various parameters on properties of final part were discussed below.

Keywords*: Additive Manufacturing, Selective laser sintering, Selective laser melting, Surface quality and properties, Process parameters.*

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1. INTRODUCTION

Rapid manufacturing (RM) is an advanced manufacturing technology first commercialized in the mid-1980s. It wasoriginally known as rapid prototyping (RP) and later grew to include rapid tooling (RT). Additive manufacturing (AM) is the current accepted term that includes all the technologies using layers to produce a part. There are more than 30 AM techniques, involving direct and indirect methods. Most of the technologies used in AM processes have a similar objective and use the same basic approach, but when looked at closely and in detail they vary considerably.Several studies have demonstrated that part mechanical properties and quality depend on the type of AM technology, the base material, the layer thickness, the laser type, build strategy, and post-processing.[1]

The American Society for Teasing & Materials (ASTM) committee F-42 standardized AM terminology and develop industry standards. According to their first standard, ASTM F2792-10, AM is defined as “The process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing technologies".AM technologies produce parts through the polymerization, fusing or sintering of materials in form of predetermined layers. By AM means, you enable the direct realization of geometries which are almost impossible to produce using other machining or moulding processes. The processes do not require predetermined tool paths. Features like draft angles or undercuts and internal channels can be designed and more easily obtained.Within the last 20 years, AM has evolved from simple 3D printers used for rapid prototyping in non-structural resins to sophisticated rapid manufacturing systems that can be used to create functional parts in different engineering materials directly without the use of tooling. Most work to date has been conducted using polymer materials, but the development of AM processes such as Selective Laser Sintering/Melting, Electron Beam Melting and Laser Engineered Net Shaping enabled to build parts by using metallic materials, metal matrix composites and ceramic materials. Additive manufactured parts are now utilized in aerospace, automotive, medical fields and also in consumer products and military. Additive manufacturing or 3D printing is receiving unprecedented attention from the mainstream media, investment community, and national governments around the world.

1.1 Principles of Additive Manufacturing

The basic principle of this technology is that a geometric model, initially generated using three-dimensional Computer Aided Design (CAD) system can be manufactured directly without the need of process planning. The layers of all AM parts are created by slicing CAD data with specialist software. All AM systems work using this principle; however, the thickness of the layers is dependent on the parameters and the system used.The layers of an AM part are built up one on top of another in the z-axis. As one layer has been processed, the work platform and substrate plate is lowered by one layer thickness in the z-axis and a new layer of material is recoated by using a number of different methods. With resin-based systems the parts submerge in the resin by one layer thickness and a traversing edge flattens the resin before the material is processed. With powder based systems, powder is deposited and spread using a traversing edge or a roller, or the part material is deposited through a print cartridge or a nozzle, which only deposits the support and part material required.

The time that it takes to recoat each layer with new material can be equally long, or even longer than the time it takes for the layer to be processed. For this reason, the most efficient way to produce parts is to build multiple parts together so that the material recoating time remains the same as building just one part. For optimum build efficiency, nesting software has become available to orientate and position parts within a virtual representation of the AM system's build envelope. Currently available examples of nestingsoftwares include VisCAM RP (Denmark), and Smart Space that is used within Magics (Materialise, Belgium). Some parts made using AM technologies require a support structure for fixing the part into position on a substrate plate during the build process. This support structure also prevents the part layers from lifting away from their axis as a result of material shrinkage. All AM systems use a different type of support structure that are designed to be most effective with a specific material or technique that the system uses to build parts. The most commonly used support structures are thin, scaffold-like structures with small pointed teeth for minimizing the amountof part contact so that they can be broken away from the part easily using hand tools.

This scaffold-like support style is used in AM systems like Stereolithography (SL), SLS, SLM and Fused Deposition Modeling (FDM). FDM can also produce supports in a soluble material that can be dissolved in a water-based solution after the parts are produced. Three-Dimensional Printing (3DP) sometimes requires a larger support structure to be used, and in some cases the downward facing surfaces of the parts are completely encased in support material that can be removed by breaking away or using a high-pressure water jet.

1.2AM Benefits & Value

Customization

3D printing processes allow for mass customization — the ability to personalize products according to individual needs and requirements. Even within the same build chamber, the nature of 3D printing means that numerous products can be manufactured at the same time according to the end-users requirements at no additional process cost. Drastic reduction in product design and development time. Errors in product design can be identified and corrected in early stage of design. Tooling for plastic injection molding, die casting, metal forming and rubber-molding processes can be fabricated in a short time.

Complexity

Parts with complex geometry can be produced directly from CAD data without the need for jig, fixture or tooling. The advent of 3D printing has seen a proliferation of products (designed in digital environments), which involve levels of complexity that simply could not be produced physically in any other way. While this advantage has been taken up by designers and artists to impressive visual effect, it has also made a significant impact on industrial applications, whereby applications are being developed to materialize complex components that are proving to be both lighter and stronger than their predecessors. Notable uses are emerging in the aerospace sector where these issues are of primary importance.

Tool-Less

For industrial manufacturing, one of the most cost-, time- and labour- intensive stages of the product development process is the production of the tools. For low to medium volume applications, industrial 3D printing — or additive manufacturing — can eliminate the need for tool production and, therefore, the costs, lead times and labour associated with it. This is anextremely attractive proposition that an increasing number or manufacturers are taking advantage of. Furthermore, because of the complexity advantages stated above, products and components can be designed specifically to avoid assembly requirements with intricate geometry and complex features further eliminating the labour and costs associated with assembly processes.

Sustainable / Environmentally Friendly

3D printing is also emerging as an energy-efficient technology that can provide environmental efficiencies in terms of both the manufacturing process itself, utilizing up to 90% of standard materials, and, therefore, creating less waste, but also throughout an additively manufactured product's operating life, by way of lighter and stronger design that imposes a reduced carbon footprint compared with traditionally manufactured products.[11]

2. SELECTIVE LASER SINTERING / MELTING

Laser sintering and laser melting are interchangeable terms that refer to a laser based 3D printing process that works with powdered materials. The laser is traced across a powder bed of tightly compacted powdered material, according to the 3D data fed to the machine, in the X-Y axes. As the laser interacts with the surface of the powdered material it sinters, or fuses, the particles to each other forming a solid. As each layer is completed the powder bed drops incrementally and a rollersmoothes the powders over the surface of the bed prior to the next pass of the laser for the subsequent layer to be formed and fused with the previous layer. Parts produced with this process are much stronger than with SL, although generally the surface finish and accuracy is not as good. Laser sintering can process plastic and metal materials, although metal sintering does require a much higher powered laser and higher in-process temperatures.

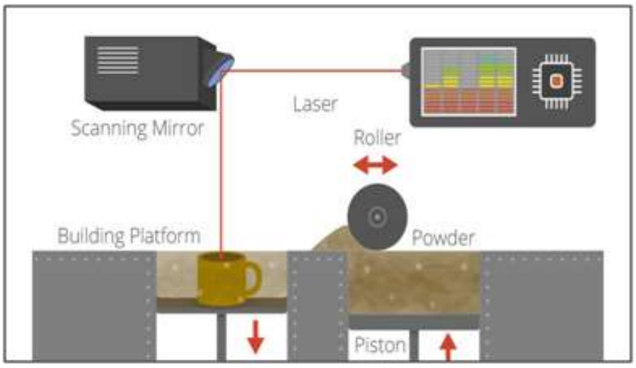

Fig-1:Selective laser sintering

2.1 Difference between Selective Laser Sintering and Selective Laser Melting

In the beginning the general principle behind both DMLS and SLM was patented by Pierre Ciraud and later Russ Householder. Carl Deckard who later went to found DTM then actually made the first SLS machine followed by EOS. EOS later together with partners commercialized DMLS. Then a whole bunch of Germans got together in a group to work on the technology. They then split up. Trumpf got the patent for single component metals. EOS obtained almost all the relevant DMLS patents. The technology called SLM was developed by two scientists of the group that would go on to found Realizer and SLM Solutions. ConceptLaser uses the term LaserCusing and has patents on the technology while the technology is remarkably similar to SLM lets say and was developed by another member of the group.

Selective Laser Sintering and Direct Metal Laser Sintering are essentially the same thing, with SLS used to refer to the process as applied to a variety of materials—plastics, glass, ceramics—whereas DMLS refers to the process as applied to metal alloys. But what sets sintering apart from melting or "Cusing" is that the sintering processes do not fully melt the powder, but heat it to the point that the powder can fuse together on a molecular level. And with sintering, the porosity of the material can be controlled.

Selective Laser Melting, on the other hand, can do the same as sintering--and go one further, by using the laser to achieve a full melt. Meaning the powder is not merely fused together, but is actually melted into a homogenous part. That makes melting the way to go for a monomaterial, as there's just one melting point, not the variety you'd find in an alloy. To nutshell it, if you're working with an alloy of some sort, you'll go SLS or DMLS; if you're working with say, pure titanium, you'll go with SLM." So in lay terms, SLM is stronger because it has fewer or no voids which helps prevent part failure but is only feasible when using with a single metal powder.[11]

3. PROCESS PARAMETERS IN SLS PROCESS

Process parameters are the defined variables that influence and control the SLS process. A number of parameters, some user defined and others defined by geometry or material considerations, affect the quality of parts fabricated. The response of the DMLS process is usually described by the geometry and mechanical properties of the object produced. Physical properties such as density, strength and degradation are all influenced by the quantity and timing of energy delivered to the part surface.

Other responses that must be considered are the production speed and geometric accuracy of the final part. Such responses may be related to the process parameters by examining how the parameters determine the amount of energy delivered to the surface. The SLS process is characterized by some important process parameters that determine the quality of the sintering part. That were discussed below.

3.1 Scan Speed and Laser Power

Before the fabrication, two important process parameters, scan speed and laser power, need to be decided based on the laser system and powder material properties. High laser power and slow scan speed are normally used in the metal sintering.Normally, a higher laser power and slower scan speed also bring higher part strength because more energy is absorbed by the loose metallic powder. It results in a higher density in the built part. But over-sintering will occur when the energy is too high. The resulting properties will then decrease sharply. The higher laser energy will bring a larger fused zone each time but will affect the part accuracy. In general, the sintering layer surface roughness will increase with increasing laser scan speed. Therefore, it is important to make a trade-off between the scan speed and laser power setting.

3.2Layer Thickness

The layers of all AM parts are generated by slicing a set of CAD data, by the use of a specialist software. The thickness of the layer is dependent on the considered system. Its typical range available in commercial systems is from 16 up to 200 micrometers. If the value of layer thickness is too high, no optimal adhesion between the single layers can be realized because the curing depth is not high enough, furthermore, mechanical tension can be generated through this layer which can lead to detachment of the layer below. If the selected value is smaller, a tearing-off of a structure can happen during the recoating process, since the sintered particles get struck between it and recoater blade.

3.3 Part Orientation

The orientation of 3-D digital model is defined as the normal direction of sliced layers. Part orientation is important because it greatly affects most of the final properties.

3.4 Laser Beam Offset and Scaling

The diameter of the sintered zone is usually larger than the laser diameter and is called as spot diameter or effective laser diameter. In order to compensate the dimensional error due to spot diameter, the laser beam should be offset from the boundaries of the cross-section of the object and is called beam offset. The beam offset values for contour and hatch lines are different.

In the SLS system, the beam offset can be entered separately for contouring and hatching. For the powder at the edge of the boundary to be completely ex-posed to the laser beam during the contouring, the value of the beam offset, should be set to the half of the contour spot diameter. If the beam offset for contour is less or greater than half the effective beam diameter, then there is the possibility of sintering powder outside the layer edge or not sintering part of the intended edge region, which would disrupt the dimensional accuracy of the part.

3.5 Hatch Spacing

Hatch space is the distance between two neighboring hatch lines. It decides the beam overlap area of continually sintering hatch lines that is relevant to the energy distribution.

3.6 Scan Path Pattern

The scan paths are important to the final sintering quality. Geometrically, two popular path patterns are widely used in RP. One is a contour (spiral) path pattern that comprises of a set of contours parallel to the layer boundary with different offset values. The other is a parallel path pattern that comprises of a series of parallel hatch lines along a fixed direction.

4. LITERATURE SURVEY

Jordi Delgado et al. (2011) investigated the effects of how scanning speed, layer thickness, and building direction, as process parameters, affect the part quality and mechanical properties of products manufactured by DMLS with DS H20 powder and SLM technologies with CL 20 powder. Findings were evaluated using ANOVA analysis. According to the experimental results, the quality for DMLS parts found sensitive to build direction. It shows plane parallel to building platform tend to have smoother finish compared to the plane normal to the building platform. An increase in layer thickness tends to weaken the parts in terms of tensile strength and elongation, with no effect on bending strength. For the SLM process, the build direction has no influence on mechanical properties. [1]

F. Calignano et al. (2012) carried out investigation of the surface roughness of aluminum samples produced by DMLS. A model based on an L18 orthogonal array of Taguchi design was created to perform experimental planning. Some input parameters, namely laser power, scan speed, and hatching distance were selected for the investigation. The upper surfaces of the samples were analyzed before and after shot peening. . Scan speed was found to have the greatest influence on the surface roughness. The Taguchi method uses S/N ratio to measure the variations of the experimental design. The equation of smaller-the-better was selected for the calculation of S/N ratio since it yields the lowest values of surface roughness. It was found that S/ N ratio is minimized when the scan speed is 900 mm/s, the laser power is 120 W & the hatching distance is 0.10 mm. Shot peening makes it possible to significantly reduce the surface roughness with glass beads. Different values of pressure were analyzed. The best results were obtained using a pressure of 8 bar (Ra reduced by up to 83 %). [2]

S. Dingalet al. (2007) investigated seven input parameters, namely, laser peak power density, laser pulse on-time, laser scan speed, stepping distance (distance traveled between pulses), interval–spot ratio (ratio of laser scan line interval and laser spot diameter), size range of iron powder particles, and powder layer thickness using taguchi L8 OA. Density, porosity, and hardness were considered for the characterization of the sintered samples. It is observed that a higher particulate size range gives rise to a lower value of porosity and vice versa. If the powder is fine-grained, the relatively smaller inter-particular gaps prevent a major part of the laser light from reaching into the depth of the powder layer such that the laser heating is mainly concentrated at the surface. Hence, inside the layer, the major part of the heating could be through the conduction of heat energy from the surface of the powder layer leading to slow non-uniform melting, higher radiative and convective losses. This phenomenon has a high probability of producing insufficient melting, which is one of the major reasons for pore or void formation. Density and porosity show a high level of correlation that indicates that most of the pores are closed in nature. Conventional sintering mechanisms are active in laser sintering as well. [3]

A. Simchiet al. (2006) studied the densification and microstructural evolution during direct laser sintering of metal powders Fe, Fe–C, Fe–Cu, Fe–C–Cu–P, 316L stainless steel, and M2 high-speed steel. It was found that as the laser energy input increases (higher laser power; lower scan rate; lower scan line spacing; lower layer thickness) better densification is achieved. Besides the fabrication parameters, the powder properties strongly influence the densification kinetics. Finer particles provide lager surface area to absorb more laser energy, leading to a higher sintering rate. The chemistry and the shape of the particles also affect the densification in DMLS process. The results showed that laser scanning strategy and sintering atmosphere influence the densification. t was found that when melting/solidification approach is the mechanism of sintering, the densification of metals powders (D) can be expressed as an exponential function of laser specific energy input (ψ) as $\ln(1 - D) = -K\psi$. The coefficient K is designated as “densification coefficient”; a material dependent parameter that varies with chemical composition, powder particle size, and oxygen content of the powder material. [4]

M.W.Khaing et al. (2001) studied about processing and characterization of EOS parts. The condition of rapid tooling parts depends on powder composition and solidification conditions. They studied the design of metal prototypes which are fabricated by EOS’S DMLS. The EOS material system is a mixture of nickel, bronze and phosphide material. The dimensional accuracy, surface roughness, impact toughness, hardness and strength of EOS parts are measured. They concluded that EOS DMLS process was able to produce 3D metal parts with very fine details, but the sintered parts were relatively soft, rough and porous. Optimization of process parameters and the working accuracy of the optical units were crucial to improve part quality and accuracy. Powder handling and humidity control of the working area are important for better process control. Also the experience and skill of the operator plays an important role in building a good part. Nickel plating would be an option to improve the hardness and wear resistance of the parts. [5]

Nitishkumar et al. (2016) were made an attempt to study and optimize the physical build process parameters which governs the final part quality. They studied the influence of three parameters namely Laser power, Temperature and Part Orientation for the dimensional accuracy and micro-hardness of part made in Selective Laser Sintering technique by using the Taguchi technique and an orthogonal array of experiment was developed which has least number of experimental runs with above three process parameters and also made by analysis tools such as ANOVA (Analysis of Variance). The result shows that the parameters such as Laser power, Temperature and Part Orientation have influenced much on the quality of SLS prototypes. Among these three parameters the Laser power and Temperature have the major influence over the dimensional accuracy and Temperature has the major influence for the micro-hardness of SLS prototype. [6]

Anoop Verma et al. (2014) suggested an algorithm for overall optimization of the DMLS process and validated with a set of examples. DMLS process takes time to build parts of even small-moderate size. A common solution to reduce the part build time is to sinter the parts with maximum allowable layer thickness. However, doing so will make staircase effect more prominent and lead to the poor surface accuracy of the part. The sub processes, namely, part orientation, layer thickness identification, and laser scanning directions, are optimized with an aim to build the parts with: (a) minimum amount of time and (b) minimum surface inaccuracy. Suggested algorithm results shows that on an average, compared to uniform slicing with the maximum layer thickness, the proposed method improved the result by 28.39 %, while in case of uniform slicing with the minimum layer thickness, 34.21 % improvement was found. Optimization of laser scan movement ensures minimum layer build time, which results in great savings in terms of time for fabricating the whole part. This results in reducing fabricating cost without affecting the accuracy of the part.[7]

A.B. Spierings et al. (2010) studied influence of three different powder granulations size on density, surface quality and mechanical properties in additive manufacturing of steel parts. A recent study confirmed that the particle size distribution of a metallic powder material has a major influence on the density of a part produced by selective laser melting (SLM). Although it is possible to get high density values with different powder types, the processing parameters have to be adjusted accordingly, affecting the process productivity. The scan surface quality and mechanical properties of three different particle size distributions and two layer thicknesses of 30 and 45 mm were compared. The scan velocities for the different powder types have been adjusted in order to guarantee a part density = 99.5 percent. The results of this study indicate that the particle size distribution influences the quality of AM metallic parts, produced by SLM. Therefore, it is recommended that any standardization initiative like ASTM F42 should develop guidelines for powder materials for AM processes. Furthermore, during production, the granulation changes due to spatters. Findings shows that by using an optimized powder material, a low surface roughness can be obtained. A subsequent blasting process can further improve the surface roughness for all powder materials used in this study, although this does not change the ranking of the powders with respect to the resulting surface quality. [8]

Manickavasagam Krishnan et al. (2013) investigated effect of process parameters namely laser power, scan speed and hatching distance on macroscopic properties (hardness and density) of AlSi10Mg parts produced by DMLS. The aim of the analysis is to find out optimum process parameter and that provides better macroscopic properties of AlSi10Mg parts. Optical microscopy observations are carried out to link the microstructure to macroscopic properties. The results indicates that among the process parameters investigated, hatching distance is the most significant parameter influencing the mechanical properties of the parts fabricated by DMLS process. A reduction of hatching distance results in an increase of energy density and possible curling effect. On the other hand, the increase in hatching distance reduces the overlapping of melt pools within the layer and increases porosity. The scanning speed is also a significant parameter affecting hardness and density. Reducing the scanning speed the energy density increases and the melt pool becomes wider, thus increasing the overlapping of scan lines. The effect of the scanning speed is more evident when the hatching distance is also increased. The experimental outcome led to determine the process window ranges from 1.2-1.8 J/mm2 of energy density for AlSi10Mg in DMLS process. The combination of 195 W laser power, 700 mm/s scanning speed and 0.17 mm hatching distance yields highest density. [9]

Subrata Kumar Ghosh et al. (2014) studied development of an in-situ multi-component reinforced Al-based metal matrix composite by direct metal laser sintering technique. The different mixtures of Al, TiO2 and B4C powders were used to initiate and maintain the self-propagating high-temperature synthesis by laser during the sintering process. It was found from the X-ray diffraction analysis and scanning electron microscopy that the reinforcements like Al2O3, TiC, and TiB2 were formed in the composite. The scanning electron microscopy revealed the distribution of the reinforcement phases in the composite and phase identities. The variable parameters such as powder layer thickness, laser power, scanning speed, hatching distance and composition of the powder mixture were optimized for higher density, lower porosity and higher micro hardness using Taguchi method. Experimental investigation shows that the density of the specimen mainly depends upon the hatching distance, composition and layer thickness. On the other hand, hatching distance, layer thickness and laser power are the significant parameters which influence the porosity. The composition, laser power and layer thickness are the key influencing parameters for micro hardness. [10]

5. CONCLUSION

From the above literature survey it is studied that researcher tried to improve different properties of realized object using optimization of different process parameters. Optimization of process parameters and the working accuracy of the optical units were crucial to improve part quality and accuracy. Also the experience and skill of the operator plays an important role in building a good part. The study was done in past on materials like Stainless steel, Aluminum, Iron and Copper Alloy

1. The study indicate that the particle size distribution influences the quality of realized metallic parts It is observed that a higher particulate size range gives rise to a lower value of porosity and vice versa. If the powder is fine-grained, the relatively smaller inter-particular gaps prevent a major part of the laser light from reaching into the depth of the powder layer such that the laser heating is mainly concentrated at the surface. This phenomenon has a high probability of producing insufficient melting, which is one of the major reasons for pore or void formation.

2.It is also studied that a reduction of hatching distance results in an increase of energy density and possible curling effect. On the other hand, the increase in hatching distance reduces the overlapping of melt pools within the layer and increases porosity.

3. The scanning speed is also a significant parameter affecting hardness and density. Reducing the scanning speed the energy density increases and the melt pool becomes wider, thus increasing the overlapping of scan lines.

4. According to study, the quality for SLS parts found sensitive to build direction. It shows plane parallel to building platform tend to have smoother finish compared to the plane normal to the building platform.

5. An increase in layer thickness tends to weaken the parts in terms of tensile strength and elongation, with no effect on bending strength. Finer powder partial size and lower layer thickness is also helpful in minimizing the surface roughness. Proper combination of scan speed and laser power is required in correlation.

6. Study suggests that shot peening makes it possible to significantly reduce the surface roughness. Nickel plating would be an option to improve the hardness and wear resistance of the parts.

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