A Review on Effect of Process Parameters on the Density, Hardness and Porosity of The Part Fabricated by Powder Bed Fusion Techniques in Additive Manufacturing

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Abstract
Direct metal laser sintering is an additive manufacturing method which allows manufacturing of complex parts without using dies in short time. In this paper different methods and experiments conducted in the domain are reviewed and presented. A comprehensive review has been done and this paper presents the experiments and their results. DMLS and SLS has attracted more attention as compared to the other methods available in the additive manufacturing. DMLS and SLS method uses the LASER power source for the melting the metal and manufacturing the part. These methods are categorized under powder bed fusion methods which either by melting or by sintering the powder manufactures the component. Different metals are experimented and it was observed from the results that electric current, scan speed, laser frequency are some parameters which are affecting the density and layer thickness of the material.

Keywords: Additive manufacturing; Laser re-melting; Powder bed fusion, Process Parameter

1. Introduction

Manufacturing Companies are continually evolving and developing new methods for the manufacturing in order to achieve the better production quality along with the saving in time and cost of the production [1]. Additive manufacturing (AM), provides cost efficient and easy solution for fabricating the customized parts in minimum time. The advancement in the rapid prototyping is the additive manufacturing [2]. Certain industries like automotive, aerospace and medical are more attracted towards the AM due to some inherent advantages of AM over conventional manufacturing method [3–5]. Some inherent advantages of the AM are eliminating the need of the holding equipment, saving in the energy, cost and time. Additive manufacturing also gives good geometrical flexibility over conventional methods [6–9]. In powder bed fusion technique different alloys can be used and, in this method, there is a different kind of binding between the powder particles of the metal or alloy used [10]. Different binding in the powder bed fusion technique is summarized in the Figure 1.

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In powder bed fusion techniques Direct Metal Laser sintering (DMLS), sometimes also known as selective metal laser sintering, electron beam melting and fused deposition modelling are all popular methods for the additive manufacturing. Direct metal laser sintering and electron beam melting are the two processes among others which has attracted more researchers [11–14]. Direct metal laser sintering process uses a powerful energy source known as LASER and scans the powder in a line which results into melting of powder and making the molten pool. After cooling and solidification of the molten pool, a layer of the part is made. This way the layer-by-layer deposition of the metal will result into the finished complex three-dimensional part [15].
For successful implementation of the DMLS process, parameters involved in the process plays an important role [5, 16–19]. Speed of scanning, thickness of layer and powder, size of hatch, pattern and path of scan and power of laser are all the parameters which are of most important and have considerable effect on the process [1, 20–22]. Geometrical accuracy, processing time surface finish and mechanical properties of the part is directly affected by the parameters used in the process [23]. Due to direct effect of the process parameters on the final product, many researchers are attracted towards the study of the process parameters in direct metal laser sintering process

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[24]. Speed of scanning is one of the parameters which can be controlled to control the molten pool. More the speed, the molten pool will be longer and thinner whereas with lower scanning speed materials remain in the molten state for longer period of time. When the constant power is used with faster scanning speed, the resulting part will be thinner [24].

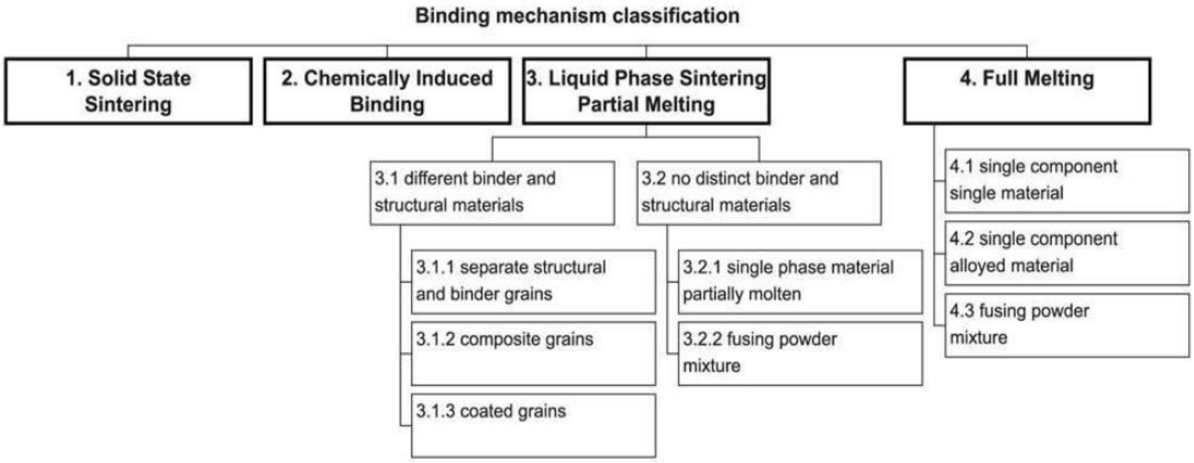

Figure 1: Summary of binding mechanism in PBF methods [15]

It is also observed that when the distance between the laser scan is reduced, there will be more surface roughness and the part will be denser [25]. With the increase in the scanning speed and power there will be increase in the surface tension and will lead to irregular structure of the manufactured part. It is also observed that when the scanning speed is increased there will be increase in the molten metal flow which will result in the intricate surfaces [26]. It is also observed that density of the manufactured part is affected by scanning speed and power of the laser [19].

2. Process Parameters in PBF Techniques

It is extremely important to decide the optimum process parameters for producing the parts with satisfactory mechanical properties in additive manufacturing. In powder bed fusion techniques these parameters are categorized into four categories viz. (1) Laser related parameters, (2) Scan related parameters, (3) Powder related parameters and (4) temperature related parameters. This all parameters interact mutually and are interdependent on each other. For instance, more laser power is required when there is material with higher melting point and bed temperature is lower. Again, the properties of the powder like shape, size and material type have an impact on the absorptivity which again influences the laser power requirement.

Generally, powder characteristics have considerable impact on the absorption of laser energy, powder bed density and also thermal conductivity of the thermal bed. Fine particles have good absorption characterises as compared to the coarse particles. To obtain better dimensional accuracy, surface finish and other mechanical properties there should be optimum selection of the laser power, scan speed, and scan spacing. Higher bed temperature or laser power results in the denser parts but recyclability and cleaning of the parts is difficult. When the part is produced with the lower laser power and lower bed temperature, there will be good dimensional accuracy but there will be comprise in the density of the part and there are higher chances of layer delamination. When laser power is kept higher and bed temperature is lowered, resulting part will have uneven shrinkage and residual stress will be induced in the part. This can lead to curling of the part.

There are certain parameters like scan speed, laser power and spot size whose combination will decide the energy input which is needed for sintering of the powder. Lower the scan speed means higher the time for laser to dwell in a particular location and it will give deeper fusion depth and also the larger diameter of the melt pool. To get the better sintering of the particles when laser power is lower, scan speed needs to be lowered so that laser has sufficient time to dwell in the location and make the sintering proper. Settings of laser power, scan speed, spot size and bed temperature will decide the size of the melt pool. To ensure the best mechanical properties, scan speed plays an important role and it should be selected carefully so that there is sufficient degree of melt pool overlap between adjacent fused material.

Powder characteristics as discussed above have considerable effect on the absorption properties and in turn will affect the part quality. It is preferable that powder packing density is higher so that better thermal conductivity of the bed is obtained and the mechanical properties of the part is as desirable.

3. Experimental Investigations on Effect of Process Parameters

In a study conducted by [3] titanium alloy was used for the fabrication of the medical implants. In an alloy of titanium there was 60% aluminium and 40% vanadium by weight. Powder of Ti–6Al–4V was mixed in the tumbling mixer of conventional type for one hour to achieve the homogenous alloy powder. Size of the particle was of 48 µm which indicates that 50 µm of layer height can be kept. In an experiment sintering process was done on the EOSINT under argon as an inert gas. Titanium plate of pure metal was used for the sintering process and this plate was kept on the heating plate at a temperature of 230˚C. Plate was prepared by sand blasting and acetone cleaning before using it in the process. Laser power of 195 W at constant rate was used. To test the limit angle of the material and the machine, the part was tested at an inclination of 0 to 45˚. In an experiment conducted by [19], 90%W-7%Ni-3%Fe (wt%) was used for the laser sintering. Objective of the study was to understand the effect of laser power, scan speed, laser trace width and scan pass on the density of the material. Among this parameters, laser power and scan speed hold more important and has more effect on the density of the final part. Relative density of the sample was defined by;

$$\rho = \frac{\rho_m}{\rho_T}$$

Where; $\rho_m = \text{measured density of the sintered sample}$
$\rho_T = \text{Theoritical density of fully dense sample}$

The samples were produced in the argon environment. Electrical discharge machining was used to remove the build plate from the sintered part. After removal of the part from the build plate, the samples were polished and studied under the scanning electron microscope. It was noted by [3], varying hatch distance and scan speed were taken into consideration for studying the effect on the test specimens. Hardness and final density were taken as a response to this varying parameter. Best results were 96.7% of final density and 515 HV of hardness was obtained and optimized parameter was studied. Other minor factors studied were inclination of the model and effect of the support structure.

In an experiment of [19], different scanning parameters were taken into consideration and density was taken as the response to those parameters under study. It was noted that density of the part is mostly affected by the scanning speed and laser power. Experiment was conducted by varying the trace width. From the results, it was found that the effect of the trace width on the density can create the variation up to 4% which was technically not so much significant.

In a study done by [25], it was studied about the effect of the scan speed and scan spacing on the densification of the part. CU powder with 40µm particle size was used. Continuous wave CO2 laser of wavelength 10.6 µm controlled by laser scanner was used to perform the experiment. Lens of focal length of 375 mm was used to focus the laser beam. Initially the loose mixture powder was loaded in the process cylinder and was levered by the blade which give the flat powder surface. Experiment was conducted in two batches. In first batch the hatch distance (Scan Spacing) was kept at 0.1mm and speed was varied from 20 to 500 mm/s. In second batch the scan spacing (Hatch distance) was varied to 0.3mm from 0.1 mm at interval of 0.1 mm and scan speed was kept at 100 mm/s. Laser power was kept constant at 100 W throughout the experiment for both the batches. Experiment was conducted in the ambient environment and pre heating was also not done here [25]. It was noted that [25], scan speed and hatch distance were considered and varied to study its effect on the densification of the fabricated part. Scan speed was varied from 100 to 500 mm/s and hatch distance from 0.1mm to 0.3 mm. It was observed that by reducing the scan speed and hatch distance there would be more dense part.

In an experiment done by [27] CL50WS hot work steel was used which was fabricated from the gas atomized powder. For conducting an experiment, a setup was used with ytterbium fibre laser system having peak power of 200 W and set up also had an inert gas chamber. For manufacturing the specimen 25mm thick substrate of H13 tool steel was used. Laser beam was directed on the substrate surface with 300 µm spot size. Closed environment was maintained in the working chamber and was filled with the Nitrogen gas and oxygen concentration was maintained to 1.8%. Experiment was planned using the Box-Behnken design to optimize the process parameter. In an experiment done by [27], shrinkage rate was studied with the effect of the varying scan parameters. Scan parameter taken into consideration are laser power, scan speed, layer thickness and hatch distance.

In a study conducted by [28], aluminium silicon alloy was used. Aluminium silicon alloy is more attractive due to their good fluidity, weldability, corrosion resistance low coefficient of thermal expansion [28]. Magnesium as an alloying element will promote the formation of the Mg2Si. Due to this, matrix will be stronger and enable the hardening process through different heat treatment and solidification methods. With this advantage, there is a limitation imposed on the design feasibility [29–34].

For automotive and aerospace industries, aluminium is more preferred due to the combination of all the advantageous properties such as low density, high strength and thermal capacity [33]. Due to smaller solidification range and near eutectic composition, aluminium alloys are easy to process with the laser [32]. Selective laser melting was used for conducting the experiment. In this method part building takes place inside an enclosed chamber filled with the inert gas such as (helium, Argon or nitrogen) to prevent oxidation. Infra-red heater keeps the powder at elevated temperature but below the melting point temperature of the powder [28].

Schematic of the SLM is given in the Figure 2. Optimized parameter was found by [28] for the maximum hardness of the fabricated part. Parameter under consideration were Laser power, scan speed and hatch distance. In a process of optimization, three approaches were used where any two of the parameters are varied and third one is kept constant. In this was the optimized parameter was found by the combination of the results. The surface plot for the hardness vs different parameter is shown below in the Figure 3.

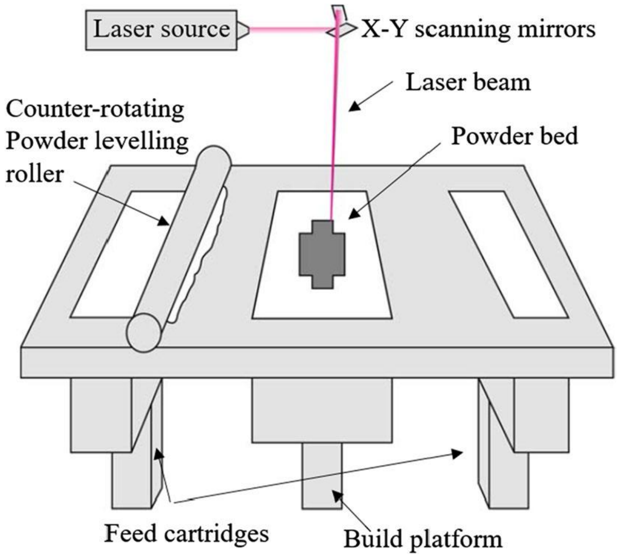

Figure 2: Schematic of SLM method [10]

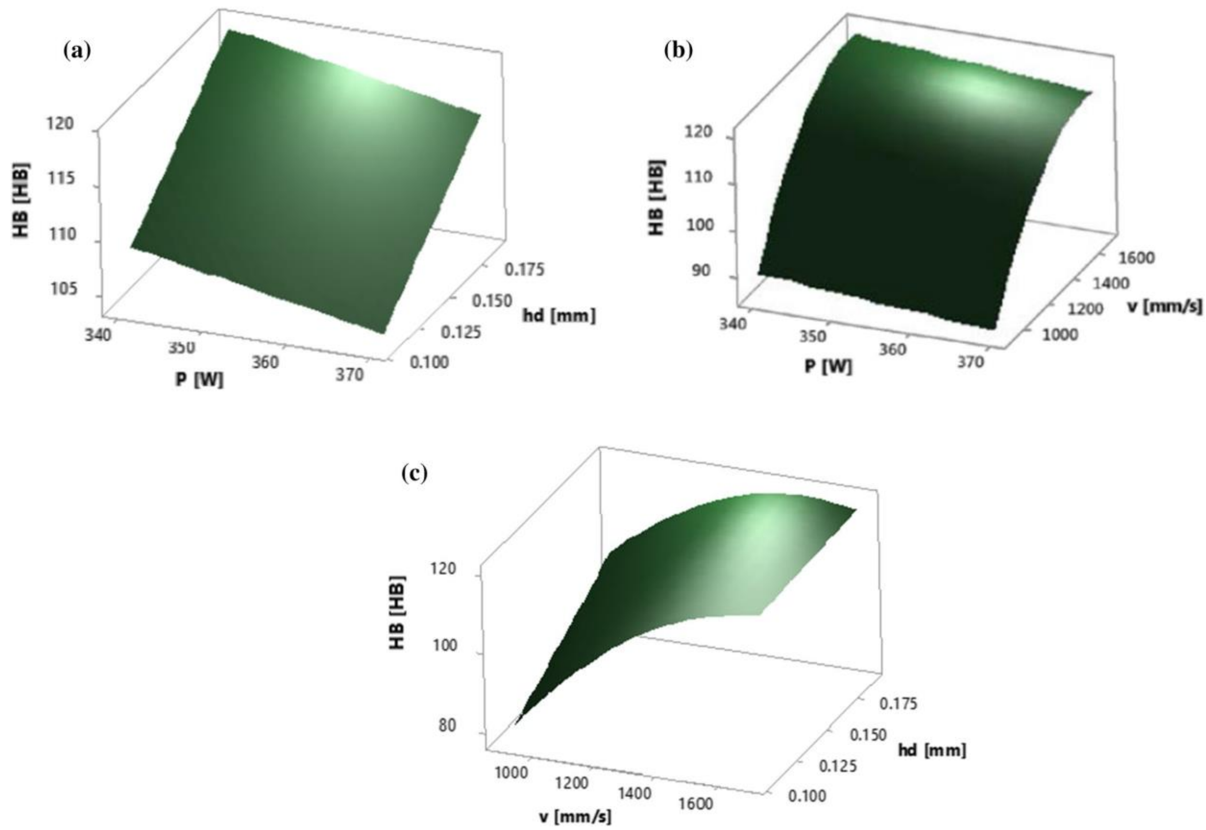

Figure 3: Surface plot of hardness vs: (a) hatch distance and laser power (Scan speed = 1300mm/s); (b) scan speed and laser power (hatch distance = 0.15mm); (c) hatch distance and scan speed (laser power = 355W) Adopted from [28]

experiment conducted by [35] Duraform PA (Polyamide) was used in the powder form. CAD model was generated using the CAD software and the STL format was exported to the laser sintering machine. The study was done to identify the micro-hardness of the part and dimensional accuracy.

Coordinate measuring machine was used to check the dimension of the part and for testing the micro hardness of the part Vicker's Micro hardness testing machine was used. Taguchi approach was used for designing the experiments. In this experiment [35], process parameter and its effect on the part fabricated by selective laser sintering method was studied. Objective of the experiment was to find the optimized parameter for obtaining the good dimensional accuracy and micro-hardness in the fabricated part. Parameters under study were scan speed, process temperature and part orientation. Nine experiments were performed and for dimensional accuracy, length and depth of the part was considered. For an evaluation of the process parameter, signal to noise ratio (nominal is best) was used where signal indicates the desired target whereas noise is an undesired value.

In an experiment done by [36], energy density related parameters were taken into consideration and their effect on the geometrical characteristics was studied. They used Stainless steel powder for conducting the study. As per the results they got in the experiment, laser power was the most dominant factor on geometrical characteristics and then layer thickness, scanning speed was there. The least affecting parameter was powder particle size.

In an experimental study of [37], laser power and scan speed were decreased while keeping the energy density constant. They used stainless steel powder the conducting the experiment. In their findings, they noted that porosity increased while density if the part decreased when this change was done in the parameters. In a study done by [38] it was observed that while increasing the laser power there is reduction in the porosity. For conducting the study [38] has used the iron powder with the customized laser sintering system.

In an experimental study of [39], it was observed that laser power has significant effect on the porosity of the part and increasing the laser power will reduce the porosity in the part and will also improve the tensile strength of the part. In an experiment conducted by [40], titanium alloy specimen was used in which the porosity was found to be decreased with the increase in the laser power. Combination of three different scan speed was used to identify the effect of the laser power on porosity of the specimen.

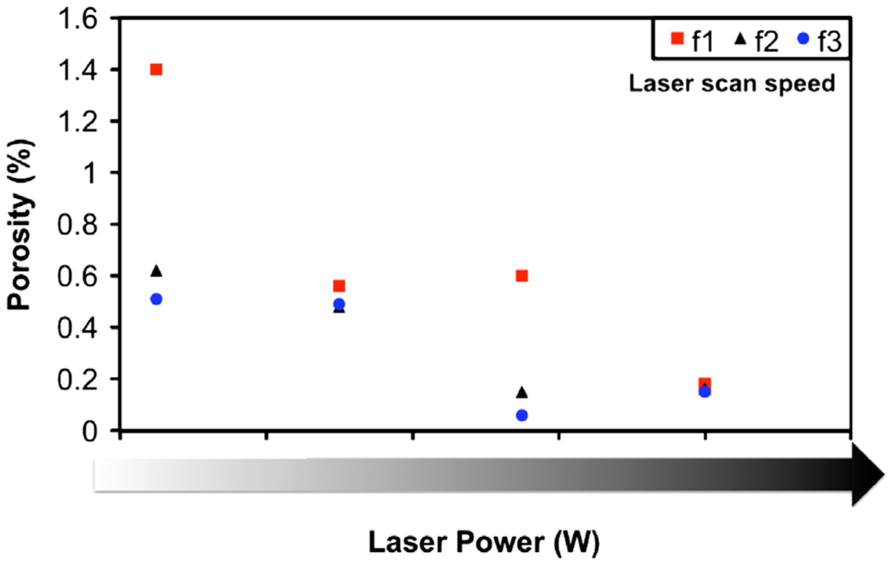

Figure 4: Figure showing effect of laser power on porosity with three different scan speed (f1< f2< f3) [40]

An experiment was conducted by [41], in which the hardness and density of the part decreased when layer thickness is increased. An experimental study was done by [42] in which part was made with titanium powder in the customized selective laser melting system. In their findings they observed that the density of the part decreased with the increase in the layer thickness. Similar results were obtained by [43], when layer thickness was increased porosity also increased and in turn it reduced the density of the part. When experiment was done using the iron powder and customized laser sintering system similar results were seen where increased layer thickness has resulted in increased porosity and in turn reduced the density and hardness of the part [38]. A study conducted by [44], iron-based material was used in two different system of additive manufacturing. In DMLS system there was reduction in the hardness of the part with increasing layer thickness whereas in the SLM there was no significant change observed in the hardness with respect to change in layer thickness.

When [41] performed the experiment with increasing the scan speed, it was observed that hardness and density of the part reduced. Similar results were obtained by [42], when scan speed was decreased there was increase in the density of the titanium alloy. When the results of the comparative study done by [44] was observed, it was noted that in SLM system of additive manufacturing there was reduction in the hardness with increase in the scan speed whereas in the DMLS system there was no significant change observed in the hardness with increasing scan speed. It was observed by [45] that with increasing scan speed there will be incomplete melting of the scan tracks and large pores will remain which will reduce the density of the part. Similar results were obtained by [39], in which stainless steel specimen was used and they also found that with increase in the scan speed there was increase in the porosity and decrease in the tensile strength of the specimen. Contrary to the previous results obtained, in the study done by [40] in which titanium alloy was used with selective laser melting method they found that the porosity decreased with the increase in the scan speed. Similar results were obtained in the experimental study of [37, 46] that with the reduced scan speed porosity of the part can be reduced and density of the part will increase. For Nickel alloy when scan speed was increased there was reduction in the hardness of the specimen [47].

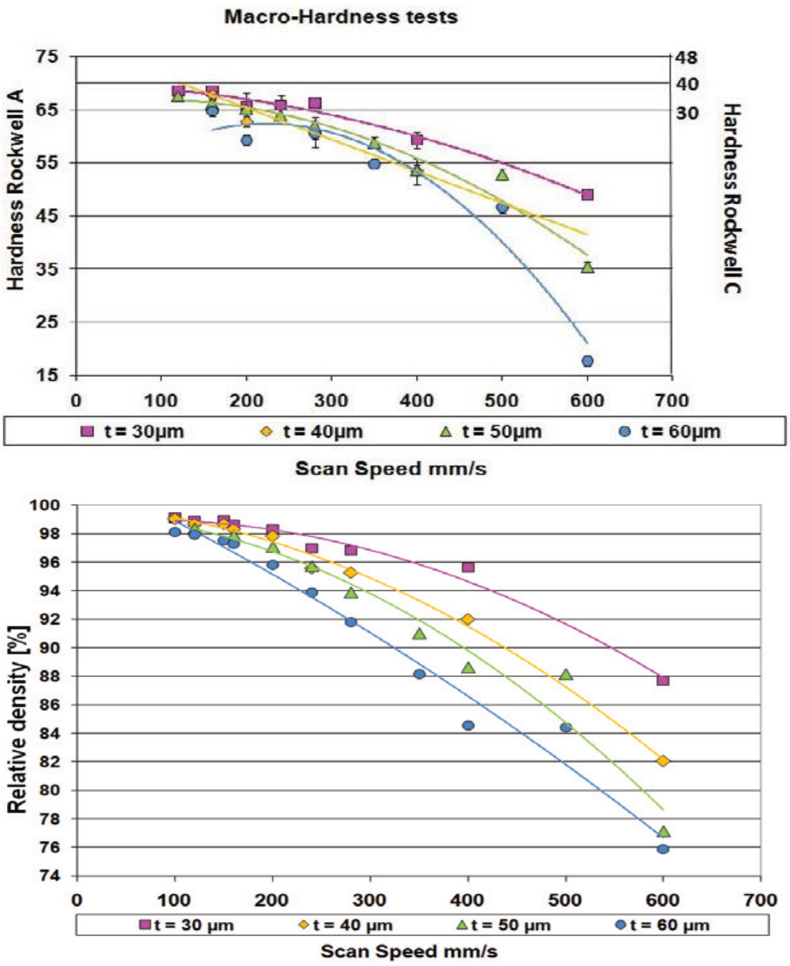

Figure 5: (a) Macro-hardness for samples with different scan speeds and layer thicknesses, (b) Relative density for samples with different scan speeds and layer thicknesses [41]

Figure 6: Effect of layer thickness on porosity for two parameter sets (A: 190W, 9S0mm/s and B: 100W, 5OOmm/s) [43]

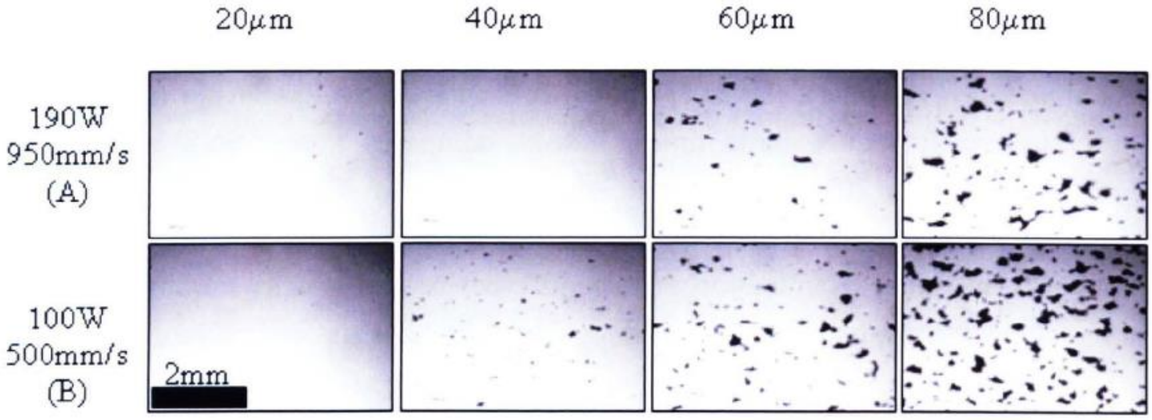

Figure 7: Effect of layer thickness on porosity of two power/velocity combinations [43]

It was observed by [45] in their study that with the increasing hatch distance there was incomplete melting of the scan tracks which leads to the large pores and reduced density of the part. It was noted in experiment of [42] where titanium-based alloy was used with the customized selective laser melting method that when hatch distance is reduced density of the part increases. In their study [39] has examined the influence of the energy related parameters on the porosity and tensile strength of the manufactured part. They observed that with the increase in the hatch distance, porosity increases and tensile strength decreases.

Table 1: Summary of the effect of the variation of Process Parameter on the density, hardness and porosity of the part.

Ref. No.	Method	Material	Process Parameter	Change in the Process Parameter	Change in Density	Change in Hardness	Change in Porosity
[38]	Custom SLS	Iron	Layer Thickness	↑	↓	↓	↑
			Laser Power	↑	-	-	↓
[41]	SLM	18Ni-300 steel	Layer Thickness	↑	↓	↓	-
			Scan Speed	↑	↓	↓	-
[43]	DMLS	IN718	Layer Thickness	↑	-	-	↑
[42]	SLM	Ti-6Al-4V	Layer Thickness	↑	↓	-	-
			Scan Speed	↑	↓	-	-
			Hatch Distance	↑	↓	-	-
[44]	DMLS	CL 20 (SS316L)	Layer Thickness	↑	-	-	-
			Scan Speed	↑	-	-	-
[44]	SLM	CL 20 (SS316L)	Layer Thickness	↑	↓	-	-
			Scan Speed	↑	↓	-	-
[45]	SLM	Ti-6Al-4V/CoCr-Mo	Scan Speed	↑	↓	-	-
			Hatch Distance	↑	↓	-	-
[46]	SLM	SS 316L	Scan Speed	↑	↓	-	-
[37]	DMLS	17-4 PH (SS)	Scan Speed	↑	↓	-	↑
			Laser Power	↑	↑	-	↓
[40]	SLM	Ti-6Al-4V	Scan Speed	↑	-	-	↓
			Laser Power	↑	↑	-	↓
[47]	SLM	Ni20Cr	Scan Speed	↑	↓	-	-
[39]	SLM	17-4 PH (SS)	Scan Speed	↑	-	-	↑
			Hatch Distance	↑	-	-	↑
			Laser Power	↑	-	-	↓

4. Conclusion

From the study of different work done in the domain, it is identified that the process parameters have significant effect on the mechanical properties of the part. Major four parameters are there which have significant effect and if those parameters are optimized then desirable mechanical properties can be obtained in the additively manufactured part. Laser power, scan speed, hatch distance and layer thickness are major parameters having significant effect on the mechanical properties of the part. There is strong interdependency between this four major process parameters and combination of correct adjustment of all this four will give the part with acceptable properties. Layer thickness and scan speed has effect on the build time whereas laser power and hatch distance will more affect the melting and sintering of the powder. Other parameter that are of little concern is orientation of the part during the process and the scan path. These parameters are not much considered as technically they don't have that much considerable effect like other major parameters considered. Effect of all four process parameters on the properties of the part is described individually below.

4.1 Effect of Layer Thickness

Increasing the layer thickness between the solidification phase can reduce the overall time and can help in speeding up the manufacturing process. Increasing layer thickness will definitely speed up the process but will also adversely affect the mechanical properties of the part. Too thick layer will result in incomplete melting of the scan tracks and result in the part with higher porosity. Increased layer thickness will also reduce the density and hardness of the part. Thick layer of the powder can be compensated with the lower scan speed and higher laser power.

4.2 Effect of Scan Speed

Scan speed is one of the important parameters and needs to be correctly adjusted as it will decide the overall time required for the manufacturing of the part. Too high scan speed will not give sufficient time to laser for the melting the powder. Whereas lower scan speed will increase the overall time required for the manufacturing of the part. Increased scan speed will reduce the density and hardness of the part. While keeping laser power higher and lower hatch distance it is possible to get higher scan speed. There are many experimental results stating that when the scan speed was increased there was insufficient melting of the scan track which resulted in the higher porosity of the part. There are also some cases in the experimental investigation where it was noted that for some material and some additive manufacturing method increasing scan speed has resulted in lower porosity, but these cases are negligible in number and in overall we can say that higher scan speed without proper adjustment of other parameter will result in increased porosity and lower density and hardness of the part.

4.3 Effect of Laser Power

To create the melt pool and ensure proper melting of the powder correct laser power is must. Lower laser power will result in incomplete melting of the metal or will not make proper penetration of the laser through the layer of the powder. Increasing laser power too much will cause the excessive heat and will cause the vaporization and gas traps within the layers of the powder which will cause porosity in the part. For metal sintering higher energy is needed as compared to the polymer, so for the metal sintering higher laser power is generally preferred. Scan speed is kept slower which brings the higher strength and makes the part denser because more energy is absorbed by the loose particles. Higher laser energy may sometime result in over-sintering and can create a larger laser spot which may lead to effect the accuracy of the part. Surface irregularities also increases with increasing scan speed and will result in the intricate surface as mentioned by [26]. It is also observed that laser power has the least impact on the tensile strength but with increase in the laser power tensile strength of the part also increases when most influencing parameter like hatch distance and scan speed is correctly adjusted.

4.4 Effect of Hatch Distance

Hatch distance must be kept less than the laser beam diameter and if not kept then the bonding will be not good as the particles will not absorb the required energy. While keeping other parameters constant, larger hatch distance allows the particle to absorb more energy and gives the more mechanically strong part. Larger hatch distance will increase the build time. When the build time is the key concern, this is the most important parameter affecting it is the layer thickness. Strength of the part has reverse relationship with the layer thickness. When there is decrease in hatch distance overlap of each laser pass will increase and can cause burning of the outer edge of the laser track. When hatch distance is increased, overlapping of the laser would not be enough and will cause incomplete melting of the powder. It is observed in several studies that with improper increase in the hatch distance will cause part with lower density and higher porosity.

Nomenclature

AM	Additive Manufacturing
PBF	Powder Bed Fusion
DMLS	Direct Metal Laser Sintering
SLM	Selective Laser Melting
SLS	Selective Laser Sintering
SS	Stainless Steel
17-4 Ph SS	Stainless steel Alloy
Ti-6Al-4V	Titanium Alloy
18Ni-300 steel	Nickel Steel Alloy
IN718	Nickel Alloy
CoCr-Mo	cobalt–chromium–molybdenum alloy
CL 20 (SS316L)	Stainless Steel Alloy
↑	Increasing
↓	Decreasing

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