PHYSICAL BEHAVIORS OF MATERIALS IN SELECTIVE LASER MELTING PROCESS

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Abstract: *The quality and strength of a product fabricated by selective laser melting (SLM) process depend upon the physical behaviors of materials occur at the time of fabrication. Hence, it is necessary for the researchers to know the physical behaviours and the processing parameters which influence those behaviors to fabricate a high-quality product. Numerous thermal and physical behaviours occur in the SLM process where thermal behaviors affect the physical behaviours of materials during fabrication. The notable physical behaviours are melting of powder, molten pool formation, solidification, amalgamation, separation, vaporization, spattering of powder and liquid material, Marangoni effect, capillary effect, vortex, gaseous bubble entrapment, keyhole formation, metallic vapor entrapment, explosion of the molten pool, instability of the pool, presence of powder particles without melting, partially melting powder particles, re-melting, excess heating, reheating and cooling, microstructural phase transformation, bending and shrinking. The physical behaviors are highly influenced by the manufacturing parameters namely energy density, laser power, scanning speed, hatch spacing, layer thickness, and scanning strategy. The behaviours can be regulated by controlling the mentioned processing parameters. This chapter has emphasized the physical behaviours of materials as well as the processing parameters which influence those behaviours and their effects on the product quality.*

Key words: *Selective laser melting, physical behaviors of materials, manufacturing parameters, product quality*

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1. Introduction

Selective laser melting (SLM) is a fabrication process in the metal additive manufacturing technology where powder metal is used to fabricate complex designed product as entrusted Computer-aided design (CAD) model (Grigoriev et al., 2017; Liu et al., 2015). Due to high manufacturing flexibility including optimum manufacturing time and cost and a functional and customize designed products can be produce without or with less post-processing, the manufacturers choose SLM process for fabricating the parts of industrial applications especially in aerospace, automobile and biomedical implantation (Kostevsek et al., 2018; Leordean et al., 2015; Stef et al., 2018; Thijs et al., 2010). In SLM technology metallic power particle are used to melt by laser energy to form the tiny melt pools for fusion and amalgamation during solidification (Pal et al., 2018). The melting process is continued track by track and layer by layer until the product is finished as entrusted CAD model (Dilip et al., 2017). About 5 to 45 micrometers diameter spherical powder particles and about 20 to 200 micrometers layer thickness are used considering the product quality (Brandt, 2017; Shi et al., 2016). The raw material could be one type of metallic or alloyed powder such as pure titanium (Ataee et al., 2018), Ti-6Al-4V (Pal et al., 2018; Vilaro et al., 2011), 316L stainless steel (Liu et al., 2015), Stainless Steel PH1 (Pal et al., 2016), CoCr (Demir and Previtali, 2017), etc. or multiple types of metallic powders are used for in situ alloying during SLM process (Grigoriev et al., 2017; Simonelli et al., 2018). The focus diameter of the laser ray can be tens to 200 micrometers.

Several kinds of thermal and physical zones occur during the fabrication process. The fabrication process is started by depositing a powder layer by the powder re-coater. Then, the laser ray starts action and melts the powder particles to form a tiny melt pool. Afterward, the laser moves forward to melt the powder particles ahead. The melt pool amalgamates surroundings and itself during the solidification. Thus, the process is done track by track parallelly. After scanning the defined area, the re-coater deposits the powder on the actioned layer and thus the process continues similarly until the part is finished to build up. At the actioning zone along with its surroundings several thermal and physical zones occur, and these zones have great influences on the occurrence of physical behaviors of the materials. The mechanical properties, as well as product quality, directly depend upon these physical behaviors of the materials, which can be controlled by the processing parameters. The heat transmits by conduction, convection, radiation and the heat taken away by metal evaporation from the action zone to its surrounding area (Chen et al., 2018; Spears and Gold, 2016) (shown in Figure 2) which also effect the physical behaviors as well as microstructural phase transformation of the part.

The melting-fusion-amalgamation process is done rapidly (Pal et al., 2018). The heat at the action zone increases rapidly by the laser. Hence an unequal heat distribution occurs inside the powder particles. Rapid heating causes spattering of powder particles, evaporation of material, keyhole effect, the explosion of melt pool, and a higher level of mixing of inert gas into the melt pool. After the powder particles are being melted, they form a tiny melt pool, and the pool also solidifies rapidly. The melt pool causes adhesion of powder particles surrounding its wall. Vorticity, viscosity, different shapes

and sizes of the melt pool, and partially melted powder particles can be seen inside the pool.

Fig. 1. Several influencing processing parameters which effect the physical behaviors of materials in SLM fabrication process

There is a chance of physical instability of the melt pool (Thijs et al., 2010). An uneven heat transmission occurs from the melt pool toward its surroundings because of the presence of different types of materials surrounding the melt pool. These materials are powder particles, latest scanned solid part, preceding solid layers and inert gas above. These uneven heat conductions cause bending, separation, gaseous bubble entrapment, Marangoni effect (Chen et al., 2018) and uneven shrinkage.

Remelting occurs at the time of adjacent track scanning and upper layer scanning. The architecture of the microstructure is depending upon cooling rate, numbers of the heat cycles, i.e., reheating and recooling (Yang et al., 2016), and the numbers of melting of a zone (Dilip et al., 2017).

In the SLM process, several manufacturing process parameters as shown in Figure 1, influence the physical behaviors of materials. The physical behaviors depend upon five domains namely laser parameters, scanning strategy, process temperature, environmental condition, and material properties. The laser parameters rely on laser power, focus diameter, pulse duration, and pulse frequency. Scanning speed, the distance between two parallel tracks, the pattern of scanning, and scanning timing of an area are under scanning strategy. Changing one of these parameters can influence the scanning strategy. The process temperature includes the temperature of build tray, powder bed, powder re-coater, and an inert gas at the time of fabrication along with the input energy per volume, i.e., volumetric ED during fabricating of a part. As the support structure plays a vital role in heat conduction from the part to the build tray, therefore product segment temperature, as well as cooling rate of the action zone, depends on the support structure too (Hanzl et al., 2017). The inert gas, oxygen level, gas flow rate and the chamber temperature influence the environmental condition. Eventually, the physical behavior of the material depends on the properties of the material, which includes its particle size, shape and size distribution. Moreover, the powder layer thickness and the powder bulk density in the action layer. The material properties also belong to its metallurgical properties such as specific heat, heat conduction rate, melting temperature, etc. The material of the built tray is also a considerable material by which the heat conduction rate from fabricating a part to build tray can be regulated. Among all of these processing parameters, ED and its technological parameters namely laser power, scanning speed, hatch spacing, and layer thickness are the key factor to regulate the physical behavior of a specific material.

Severe product quality related issues has been arrised in the recent years which leads to unwanted product defects. Improvement in these fields are now necessary to overcome these quality related problems. Therefore, this chapter has focused on the physical behaviors of the materials which occur in the time of fabrication in SLM technology. The occurances of normal desired as well as unwanted phenomena of the materials has been clearly described here. The most influencing processing parameters and their influences on the physical behaviours of the materails also have been elaborated by which the unwanted phenomena can be kept under control considering the raw material properties and the productivity.

2. The technological parameters which affect the physical behavior of materials

Laser ray provides the thermal energy to the action zone, and powder particles present in the action zone absorb the thermal energy (Thijs et al., 2010). After that, the powder particles melt to form a tiny melt pool. Thus, melting occurs track after tracking wise. The amount of input energy directly depends upon the value of laser power and the timing of input. Lower scanning speed plays longer timing of heat input, thus the input energy is indirectly dependent upon the scanning speed. The distance between

the central points of two consecutive laser scanning tracks is called hatch spacing or hatch distance. For a normal process, it is required to overlap between two consecutive laser scanning tracks, which is known as track overlapping. Therefore, higher track overlapping causes lower hatch distance. Moreover, higher track overlapping causes higher heat at a specific area, therefore, hatch distance is inversely proportional to the heat input. The powder particles would do the absorption of heat, and more powder particles need more heat to come to a certain thermal point. Thus, the ED at the action zone is inversely proportional to the layer thickness. Therefore, the volumetric ED (E) depends upon the technological parameters namely laser power (P), scanning speed (v), hatch spacing (h) and layer thickness (H) and which can be expressed by the Equation (1) (Pilipović et al., 2014; Thijs et al., 2010).

$$E = P/vhH \quad (1)$$

The ED plays as a key factor where the melt pool volume, proper/improper melting of the allowed powder particles and viscosity of melt pool depends on the value of ED. Low ED may indebt for the improper melting of the powder particles or unable to melt all of the powder particles at the action zone. High ED may lead to vaporization of metal, explosion and burning by excess heating. The variation of the process parameters leads to different local solidification conditions which evidently affected the microstructure and product quality (Chen et al., 2018; Dilip et al., 2017; Liu et al., 2008). The scanning speed indirectly leads to the solidification and cooling rate. A higher scanning speed provides higher thermal shocking to the powder particles.

Higher layer thickness causes a staircase on the surface of a product and physical instability of the pool. Lower layer thickness is more provocative for the thermal cycles in the preceding layers (Yang et al., 2016) which leads to the changes of microstructure. Higher layer thickness reduces manufacturing time and cost.

3. Thermal and physical zones

This chapter has focused on two kinds of physical behaviors depending upon the occurrences. One is normal behaviors of the materials as the desired process, i.e., melting of powder, tiny melt pool formation, and solidification, which have been discussed in this subchapter. Other physical behaviors of the materials are considered under irregular and uncertain occurrences which have been described in the next subchapter. In the normal behaviors of materials, eight zones are observed at the action zone during fabricating a product denoted as inert gaseous zone, powdered zone, melted zone, re-melted zone, mushy zone, solidified zone, heat affected zone, and vapor zone, which have been shown schematically in the Figure 2 (Dilip et al., 2017; Ladewig et al., 2016). Except for the vapor zone, all others are expected to behave gently to build a high-quality product. If these zones are not stable and not transform from one zone to another zone gently, then the defect occurs in the product. Therefore, the mentioned zones are crucial for understanding and the zone can keep under control by the processing parameters, thus a flawless product, as well as desired mechanical properties, can be achieved.

Before starting the fabrication process, the fabrication chamber is filled with the inert gas such as Nitrogen or Argon, which acts as a shielding by reducing unexpected reaction of gaseous particles with the materials as well as the unwanted phenomena such as burning and explosion. A continuous flow of inert gas is maintained in the chamber. The properties of the product could be led by the gas flow rate as well as the use of kind of gas (Anwar and Pham, 2017). The spattering of material may be reduced by the proper uses of the gas such as pressure, temperature, and the type of inert gas. The higher flammable materials such as Magnesium have a high burning rate in the SLM process, and the burned material can be flow-out from the chamber using a proper flow of gas. The gaseous zone also contains oxygen and oxygen could lead to reducing the surface tension of the melt pool by oxidation. The inert gas is also present in the interparticle gap of powder, and thus there is a chance of mixing of inert gas into the melt pool. The inert gas is required to remove gently with the help of processing parameters to reduce porosity and explosion of materials at action zone. The inert gas also helps to remove the heat from the melt pool and product segment by convection

Fig. 2. A schematic model of the thermal and physical zones in SLM technology

The powder re-coater spreads the powder particles tray layer by layer on the build after having each layer scanned by the laser as defined area. Therefore, from the powder zone defined area only being melted for forming a product. The powder particles have another supportive role too where the powder bed provides direct support to the area where the supportive-area does not exist in-between the supportive points during the first layer scanning on the support structure. The downside of an inclined surface gets support by the powder bed. The powder bed conveys minimal heat by conduction.

The behaviors of the materials depend upon the bulk density of the powder bed. The sizes of melt pool depend upon the bulk density of the powder at the action zone as well as powdered layer thickness for a fixed value of the processing parameters. Properties of the powder particles such as specific weight, specific heat, heat conductivity, chemical properties, shape, and size have a great influence on the product quality along with the processing parameters. Therefore, the different materials need different combinations of the processing parameters to meet the desired product quality and productivity.

The laser provides the thermal energy, which melts the powder particles and forms a tiny melt pool. Thus, the laser scans track by track on the defined area to melt the powder particles. During melting of the powder particles, the interparticle gap is disappeared and thus the thickness of the layer shrinkage as to the desired layer thickness. The sizes, i.e., width, depth and overall volume of the melt pool depend upon the values of the technological parameters. A melt pool has the responsibility to amalgamate three sides well along with itself during solidification. The sides belong to scanned preceding layer, adjacent previous scanned track and hind side of the pool. The sides of the melt pool can be found in Figure 2 and Figure 3.

Melting of existing loose powder particles present in the action zone along with partial melting of preceding layer denoted by “remelted zone” in Figure 2 and the preceding track as denoted by “remelted zone” in Figure 3 forms a melt pool. The ED influences the depth of the melt pool for a fixed layer thickness which thus decides the amount of remelting of the preceding layer. The amount of remelting of the preceding track depends upon the track overlapping. The remelted zone helps to connect the previous solidified zone to the melt pool, and thus a solid structure is formed to build up the product.

Fig. 3. A schematic top view of the physical zones and sides of a melt pool in SLM

The materials present at the neighboring zone of the surface of the melt pool absorb heat and become soft and pulpy. It contains a mixture of partially melted materials and exists in-between the melt pool and solid/powder material as shown in

Figure 2 which denoted as mushy zone (Chen et al., 2018). Comparatively lower heat available at the mushy zone and it solidifies fast because of the existence of colder material in the outer surface side of it. It has a high capability in adhering powder particles onto it because of high viscosity and very rapid cooling rate.

The melt pool cools down after moving out of the laser form the action zone and then forms a solidified zone. The solidified zone could be remelted during upper layer and next track scanning to be connected with these sides. The metallurgical properties of the solidified zone depend upon the solidification rate along with cooling rate. Pore formation and distortion of the part depend upon the stability of the melt pool as well as cooling rate, and these phenomena can be controlled using a proper combination of the technological parameters.

The heat transmits up to hundreds of micrometers from the melt pool and creates the heat affected zone. The powder at the front side of the melt pool is being heated, and thus it could be prepared from the thermal shock of rapid heating by the laser as well as due to heating of the next action zone the existing inert gas expands and remove partially from the interparticle gap. Therefore, there would be a lesser chance of spattering of powder particles as well as an explosion by the expansion of the entrapped gas. The preceding layer affected by the heat and changes its microstructure. Though hind side of the pool is cooled down and solidified, remain presence of heat and additionally it gained heat from the acting zone which causes heat affected zone and provokes bending and separation.

Laser ray melts the powder particles and the preceding layer and track at the action zone rapidly, and the heat does not transfer rapidly toward melt pool's surroundings. Thus, the temperature rises to the boiling point and started evaporation. Higher ED provokes higher evaporation of the metal and causes a cloud, which protects a bit to enter the laser beam into the action zone (Ladewig et al., 2016).

4. Unwanted physical behaviors of materials

Several types of unwanted physical behaviors of the materials occur during fabrication of an SLM product. The unwanted physical behaviors are spattering of material, keyhole effect, balling effect, separation, vaporization, Marangoni effect, capillary effect, vortex, gaseous bubble entrapment, metallic vapor entrapment, explosion of the molten pool, instability of the pool, presence of powder particles without melting, partially melting powder particles, excess heating, bending and shrinking. These unwanted phenomena decrease density and increase porosity. Here the porosity is included architecture, volume, containing, numbers and the place of pores. The pores could be very irregular in shape having the inner surface with critical corners, trench, and ripple. The corner edge initiates microcracks, the trench and ripple act as a stress concentrator and thus initiate cracks. There is no suitable volume; the pore could be from nanoscale to a few hundred micrometers. A pore could contain one or more of these materials, which are raw powder particle, partially melted powder particle, fragile metallic materials, inert gas, and vacuum. The formation of the pores is very uncertain as the unwanted phenomena cause uncertainty and thus the pores occur any place and any number in the product. A pore can occur on the surface; thus,

it increases the surface roughness and well as surface area. If a pore contains raw or partially melted powder particles, it improves the density and not improves the product quality or mechanical strength. Other physical behaviors such as remelting, cyclic reheating and cooling, and different cooling have the effect on the microstructural phase transformations. Thus, the mechanical properties of a product can be countercontrolled by controlling these physical behaviors, which can be regulated by the processing parameters and mostly by the technological parameters. It has been seen that the architecture of the microstructure differs along vertical and horizontal direction (Yang et al., 2016). Therefore, the mechanical properties along different directions are different (Hanzl et al., 2015).

4.1 Spattering of materials

The spattering of materials is the biggest unwanted phenomena occurs in the SLM process (Anwar and Pham, 2017; Wang et al., 2017) as such the spattering occurs in many laser material processing techniques such as laser drilling (Low et al., 2001), cutting (Lee et al., 2017) and welding (Kaplan and Powell, 2011). The spattering phenomenon disorders the materials and thus its causes an inequality distribution of materials as well as an impurity of the materials. There are several reasons and several types of materials to be spattered-out or spattered-in at the action zone which are shown in Figure 4. Several types of material spattering occur, which are powder particle spattering, molten metal spattering and a mixture of partially melted powder particle with the molten metal. The reasons for the spattering are gas flow, recoil pressure of laser, thermal shock, expansion of gas, and the recoil pressure of metallic vapor. The spattering behaviors, as well as the amount of spattering, can be controlled by the several processing parameters, where the technological parameters and their combinations have the great impact on this phenomenon. The metallurgical characteristics such as specific heat, heat conduction properties, melting point, boiling point, molten metallic viscosity, and density of the metal also effect the spattering behavior of the material. The powder particle shape and size are also involved in the characteristics of spattering. Most of the spattering look like sparking, which can be observed in the welding process (Liu et al., 2015; Wang et al., 2017).

Fig. 4. Several types of the spattering of materials occur in SLM process

The laser starts the action and heats the action zone very rapidly. Thus, the inert gas expands rapidly at the action zone. The rapid expansion of gas, which exists in the interparticle gaps, causes spattering of powder particles. These powder particles are

also gained heat; therefore, these particles spatter as hot spatter powder particles. If a powder particle does not gain heat equally, the surface of it enlarged, and thus the particle loses equilibrium, which gives momentum into the particle. Moreover, the inert gas at the action zone warms up at a high level as well as the metal also starts vaporization. The hot air, a mixture of inert gas and metallic vapor, goes up and the surrounding cooler inert gas transfers into the action zone which creates a cyclone. This cyclone ejects the powder particles from the action zone and provides motion upward, thus, the action zone loses material. The movement of the air can push the powder particles toward the action zone too. The cyclone also entrains cold powder particles and thus brings some powder particles from surrounding to the action zone or blows the powder particles. Therefore, the cyclone dismisses the equality of distribution of the powder particles which forms some mounded and valley zone and more-or-less material at the action zone. These types of the movement of the powder particles depend also with their specific weight as well as the density of a particle. For instance, high density material such as stainless steel has lower movement compared to lower dense material such as titanium and its alloys (Tiyyagura, Kumari, et al., 2018). Such wise, magnesium has very low density (Reddy et al., 2016; Reddy Tiyyagura et al., 2019) which moves with a higher amount, and the huge movement of the powder particles can be observed during the SLM process.

Fig. 5. The schematic diagrammes of the spattering of materials and the defects caused by spattering, (a) various types of spattering, (b) the effects of different sizes of spattered particles, (c) void formation caused by massive spattering, (d) remaining pore at the massive spattered zone.

The gas exists in the gap between the powder particles, could be entrapped in the melt pool and then it could try to expand, which causes an explosion in the melt pool. The recoil pressure could also be created by the metallic with the help of keyhole effect. A high recoil vapor pressure causes an explosion in the melt pool. These explosions cause spattering of the molten metal and mixture of a partially melted particle with molten metal. If the ED is higher, there is a chance of vaporization in a higher rate, and thus, rapidly formation and expansion of vapor cause a high explosion which causes a higher degree of spattering (Liu et al., 2015). During slow speed of the scanning, the gas can get time to expand, and some gas removes from the powder. Therefore, there is a lesser chance of spattering of powder particle as well as an explosion by the entrapped gas is lesser for slower scanning speed. Higher scanning speed induces lesser energy in the action zone as well as the melt pool solidified faster. Thus, the slower scanning speed creates smaller melt pool which causes the unmelted zone at the beneath of two consecutive tracks as shown in Figure 6(a). The gas exists this unmelted zone could expand and creates large spattering. The lesser track overlapping also causes this phenomenon (Wang et al., 2017). Higher track overlapping induces high energy at the overlapping area as shown in Figure 6(b), which thus be affected similarly as high ED (Bai et al., 2017). The entrapped gas by the melt pool in the preceding track could expand and causes explosion and spattering of material. The laser also put recoil pressure (Han et al., 2017) which adds the value of material spattering. High ED reduces the viscosity of the molten metal and causes a high vortex in the melt pool which provokes a high rate of spattering.

However, the spattering caused by the explosion, keyhole effect and vortex are three types, which are jet spattering, big spattered particles, and small spattered particles. The jet spattering of material is caused by the high recoil pressure of metallic vapor. The jet spattered material can be fragmented into several pieces to reduce surface tension and causes droplet spattered particles. Two or more hot and molten spattered material could be marge together and form a large material. These spattered particles redeposited onto the powder bed. If a spattered particle is small or smaller than the layer thickness, the spattered particles melt and dissolve into the layer during the next scanning as shown in Figure 5(b). If a spattered particle is large, it may not melt well during next scanning which is illustrated in Figure 5(b). Therefore, the large spatter particle remains as a mixture of small and big separated particles which shows brittle nature. This large spattered particle may improve the density of the product but not provide such mechanical strength. The massive spattering of materials from the action zone causes a lack of material in the melt pool which thus eventually causes void after solidification of the pool as shown in Figure 5(c). If this void depth is small, this void can be solved out and filled up with the right process during the next upper layer scanning as shown in Figure 5(d). If the void depth is high, the void is filled up by the powder particles and the laser energy cannot melt well all the powder particles existed in the void. Thus, massive spattering forms a big void as shown in Figure 5(d) and the voids are very irregular in shape having a critical corner. This type of voids contains inert gas, nonmelted and partially melted powder particles. Therefore, these voids improve a little density but act like total void space. Spattering during to surface causes uneven surface which includes powder particles and small and big plashed particles.

4.2 Keyhole effect

Keyhole effect is well known in the laser welding technology (Fabbro, 2019), and it creates a pore having a corner point and smooth surface wall. The laser ray imposes on the powder bed, some laser rays reflect out from the top surface of the powder zone, and some laser rays penetrate the powder bed. The laser ray penetrates the powder and mostly scatters at the bottom portion of the layer. Therefore, the bottom part of the powder layer gains a higher temperature than its upper part.

The high temperature at the bottom part causes evaporation and thus forms a keyhole in the melt pool. The laser ray also enters the keyhole and scatters at the lower part of the melt pool which causes a high temperature at the bottom part of the pool and forms more vapor. Two forces occur between the keyhole vapor and molten metal which are recoil pressure by the vapor pressure and surface tension by the molten metal. If the surface tension is higher than the recoil pressure, the vapor at the bottom part of the pool is trapped by the molten metal. Higher scanning speed leads to the higher solidification rate of the melt pool as well as higher scanning speed induces lesser energy, thus the higher viscosity of the melt pool occurs and therefore the vapor entrapped by the liquid metal. Higher ED lowers the melt pool viscosity and releases the surface tension. Therefore, higher ED helps to reduce keyhole void formation. After solidification, the entrapped vapor remains as void space. Most of the keyhole void takes conical shape as the shape of the melt pool is conical, and there is a high chance having a corner point of the void (Liu et al., 2016; Pal et al., 2018).

4.3 Entrapment of gaseous bubble

There is a high chance of mixing the gaseous bubble into the melt pool from the interparticle gaps. Then the gaseous bubble moves with the vortex, which occurs in the melt pool due to thermal differentiation. A gaseous bubble could break into several small pieces. The melt pool solidifies from the bottom part to the top part and it happens due to the heat transfer rate is higher to the beneath part than toward the above part of the melt pool. This solidification phenomenon occurs due to existence of the solid part at beneath part of the melt pool where the heat conduction rate is faster than the side part of the melt pool where mostly powders zone and last scanning zone (hind zone) exist. The powder zone has comparatively very lower heat conduction rate than solid zone. The melt pool can release the heat by radiation at first and then by convection, which is lower heat transfer rate than conduction.

The vortex position also moves up with the solidification of the melt pool from bottom to top. In a similar way, the gaseous bubble moves up and stays as a pore at the upper part of the layer after solidification of the melt pool. The size and shape of this pore are small and spherical and the wall of this pore also smooth. These pores reduce the density of a product as well as decrease a bit of mechanical strength. If the processing ED is higher then the viscosity of the melt pool becomes lesser and thus there is a chance of ejection of the gaseous bubble with the help of buoyancy force by the liquid metal. The gaseous bubble can stay as an open por during scanning of the top surface of the product. Interestingly, most of these pores again mixed up with the next upper pool during upper layer scanning and go up of the next pool. Thus, most of the gaseous bubble remove from the product.

Previously entrapped gaseous bubble provokes explosions of the melt pool during the expansion of the gas. During scanning with high ED, there is a high chance of explosion by the entrapped gaseous bubble.

4.4 Improper melt pool formation

There are several reasons for occurrence of improper melt pool formation. The melt pool could smaller or bigger, thermally and physically unstable, contain partially melted powder particles and gaseous bubble. Small melt pool occurs due to high scanning speed, low laser powder, and low ED. A high scanning speed not provides sufficient time to melt all the powder particles belong to the action zone due to rapid solidification. Low laser power induces less thermal energy and thus melts insufficient of the powder particles. Low ED is being considered as insufficient energy exist in a volumetric zone to melt all powder particles as well as preceding layer and track so that the product segment can be well connected.

If the melt pool is small, then there could exist an unmelted zone at the beneath of two melt pool of two adjacent tracks which can be observed in Figure 6(b). A melt pool gets thermal instability due to unequal heat transformation toward a different side of the due to the existence of different zone in different sides of the pool as shown in Figure 2 and Figure 3. If a melt pool gets thermal stability during longer time, the action zone can fuse the materials well. A melt pool will get thermal stability by slow scanning speed. Physical instability of the melt pool occurs when the viscosity becomes low. Higher ED lowers the viscosity of the melt pool. Improper powder particles distribution such as low powder bulk density provokes stabilization of the melt pool. High scanning speed, low ED and long hatch spacing cause improper melting of the powder particles. Due to the high scanning speed, solidification rate is higher so the powder particles do not get enough time to melt well. A low ED does not provide sufficient energy to melt the materials well. Long hatch spacing unable to melt all the powder particles exists in between two consecutive tracks as shown in Figure 6(a).

4.5 Effect of track overlapping

The amounts of track overlapping have the great impact on the physical behavior of the materials including melting, spattering, defects, bending, separation, microstructural changes, and pore formation. As discussed above, lesser track overlapping which causes longer hatch spacing has an inconvenient impact on the melting of all desired materials. Thus, a gap with unmelted zone remains at the beneath portion in between the two conical melt pools of two adjacent tracks as illustrated in Figure 6(a). Thus, it forms a critically shaped pore included with partially and nonmelted powder particles.

The melt pool separates during shrinkage and makes a microcrack in-between the partially melted powder particle and melt pool zone. Thus, a microcrack remains in the pore caused by low track overlapping which provokes a big drawback in mechanical strength of the product (Pal et al., 2018). Therefore, the pores happened due to less track overlapping contain partially and nonmelted powder particles which improve the density of a product but basically act as void space.

Fig. 6. Effect of different track overlapping in the SLM process

A shorter hatch spacing or higher track overlapping can melt all the required materials at the action zone which thus reduces porosity and improves product quality. There is also a drawback of a high track overlapping where due to high track overlapping, the overlapping zone accumulates a high ED and starts spattering of molten metal which has been shown in Figure 6(b). Evaporation of metal occurs in the overlapping zone as well as the entrapped gas from the preceding track causes explosion.

4.6 Shrinkage, separation, bending and cracks

Separations occur between two layers and track, melt pool and partially melted powder particles. Due to the lack of proper melting of the preceding layer and track and fusion, the melt pool unbales to bonds of two adjacent layers or track (Konečná et al., 2016). During solidification and cooling down the materials shrink and thus, cause these separations. Liquid-solid separation occurs by a smooth shift of the viscosity where the liquid shrinks higher than the solid material. The shrinkage phenomenon is also depended upon the thermal stability of the melt pool by which the crystallinity time is being affected (Childs and Tontowi, 2001).

Therefore, slower scanning speed leads to more shrinkage of the product segment. The high thermal gradient and residual stress cause bending of the part segment (Mercelis and Kruth, 2006; Le Roux et al., 2018). Olakanmi (Olakanmi, 2013) showed that during cooling of a melt pool from center to the colder surface of melt pool, thermal gradients develop which leads to the balling up of liquid material to minimize the surface energy. The ball surface cools faster than its center points which cause microcracks on the surface of the ball. A high ED causes high thermal gradient as well as enlarge the product segment higher which cause microcracking.

4.7 Oxidation and burning

The presence of oxygen causes oxidation of the materials. Oxidation reduces the surface tension of the melt pool (Guo et al., 2017). High ED can cause a high rate of burning of the material. Burning is also depended upon the material properties such as a huge burning occurs during fabrication of magnesium product (Tiyyagura, Mohan, et al., 2018).

5. Conclusions

This chapter has critically reviewed and elaborated different aspects of physical behaviors of materials occur during the SLM fabrication process of any metallic product. The desired normal phenomena as well as unwanted phenomena which occur during fabrication of the materials. These phenomena can be regulated by the processing parameters where the technological parameters included in ED acts as the key factors, by which the mechanical and metallurgical properties of the product can be enhanced. By studying this chapter, it is possible to gather knowledge about the physical behaviors of the materials occur in the time of fabrication process and its regulations by controlling the processing parameters considering productivity. Thus, the porosity of the product can be reduced as well as pores architecture can be transformed from critical shape to spherical shape having smoother inner surface which will enhance the quality of the SLM product. The mechanical strength along with microstructural properties can be regulated by knowing the physical behaviors of the materials stated in this chapter. Henceforth, this chapter provides a clear picture of the SLM process which will lead the researchers in a right direction to achieve the desired properties of the product to meet the productivity as well as quality for the manufacturer.

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7. References

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