Bulletin of the JSME Vol.8, No.1, 2014
*Journal of Advanced Mechanical Design, Systems, and Manufacturing*

# Consolidation characteristics of ferrous-based metal powder in additive manufacturing

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**Received 20 May 2013**

**Abstract**
Selective Laser Sintering/Selective Laser Melting (SLS/SLM) is one of the most promising additive manufacturing (AM) techniques that are widely accepted by the industrial community. This is due to its high flexibility in processing different types of material under various conditions. However, the capability of the end product to have a desirable quality comparable to traditional processing techniques is still not achievable. Consolidation characteristics and the influence of processing parameters are important in determining the SLS/SLM part quality. In this paper, the consolidation process of ferrous-based metal powder is examined by monitoring the real-time consolidation process. A high-speed camera was utilized with telescopic lenses in order to monitor the interaction of laser and material within the powder fusion zone (PFZ). Based on the study, the line consolidation can be classified into five different consolidation types. The line consolidation characteristics were analyzed according to the line consolidation width, PFZ, consolidated agglomerate diameter and metal particle splattering behavior. The influence of laser power and scan speed on these characteristics was analyzed. It was also found that the line consolidation width, PFZ, consolidated agglomerate diameter and splattering were increasing with the increase of laser power. In contrast, with the increase of scan speed the result was vice versa. These phenomena can be explained with respect to the heat transfer behavior that took place during the interaction between the laser beam, metal powder and substrate surface. The consolidation mechanism that occurred during consolidation is also reported.

***Keywords*** : Selective laser sintering (SLS), Selective laser melting (SLM), Consolidation, Additive manufacturing (AM), Metal powder, Layered manufacturing

## 1. Introduction

Selective laser sintering/selective laser melting (SLS/SLM) is one of the most promising additive manufacturing (AM) techniques that are widely accepted by the industrial community compared to other competing AM technologies. This is due to its high flexibility in processing different types of material under various conditions with relatively reasonable material properties (Kruth, et al., 2003),(Kumar, 2003). SLS/SLM is actually a direct fabrication of near net-shape products that is accomplished through the layer-by-layer manufacturing technique. During the SLS/SLM process, a thin powder layer is deposited, and a laser is irradiated to the powder surface successively until the final part is produced based on the CAD data. The part is a consolidated material whereby its mechanical properties and appearance are influenced mainly by powder materials and fabrication parameters. During the iterative process of powder deposition, laser irradiation and molten powder solidification, the metal powders are consolidated to form solid

Paper No.13-00073
[DOI: 10.1299/jamdsm.2014jamdsm0009]

metal parts based on the CAD data transferred to the AM system. This capability has improved the lead time from design to manufacture in comparison to the classical method. However, currently, the end product produced via the SLS/SLM system still does not meet some of the stringent quality issues and requirements necessary to be adopted as a good alternative to the conventional method. The capability of the end product to have a desirable quality comparable to traditional processing techniques is still not achievable (Hopkinson and Dickens, 2006),(Kruth, 1991). This is caused by some of the common characteristics associated with consolidated part-mechanical properties such as porosity, low strength, high residual stresses, poor surface roughness and others. SLS/SLM involves the consolidation of metal powder to solid under the influence of high heat generated from laser irradiation within a very short time. As a result, the powder and consolidated structure experience repetitive microstructural and mechanical behavior changes as sintering/melting and solidification alternately occur during layer-by-layer laser irradiation.

Consolidation characteristics of metal through SLS/SLM are relatively important due to its current application in mold design and manufacturing. However, outstanding mechanical properties and high accuracy requirements are vital characteristics that need to be improved for extensive application in mold manufacturing. The very basic element in developing a good quality consolidated part is by understanding the transformation process of metal powder to solid after being irradiated with a reasonable amount of heat. Understanding of the consolidation characteristics is essential in developing a good consolidated structure. This will enable control of the mechanism and method to be realized so that future development is possible. In order to improve these problems, it is important to understand the consolidation characteristics and mechanism during SLS/SLM.

A number of researches have reported the consolidation characteristics during SLS/SLM. Consolidation mechanisms of metal powder can be classified into solid-state sintering, liquid-phase sintering, full melting and chemical-induced binding (Kruth, 1991). The binding mechanism invoked in full melting is largely driven by the fluid behavior of the melt, which is related to the surface tension, viscosity, wetting, evaporation and oxidation (Kruth et al., 2007). The ability of metal powder to consolidate during SLS/SLM depends on many factors. These factors affect the quality of the material and mechanism involved in the formation of the consolidated structure. They can be categorized into processing factors and material factors. Material factors include the size of the metal powder, impurity, particle shape – which can be either sphere, dendrite or irregular – mixture, chemical composition, homogeneity, degree of agglomeration, and others. Whereas, factors that can be associated with its processing are laser parameters, processing environment, pressure, processing temperature, cooling rate, time, and others. There are more than 50 factors affect the SLS process (Van Elsen et al., 2008). However, among these parameters, the most important factors are laser power, layer thickness, laser-beam spot size, scanning speed and hatching size (Simchi and Pohl, 2003),(Dingal et al., 2007),(Chatterjee et al., 2003). Therefore, physical understanding and observation of the laser beam and material interaction, which occurs at high temperature with respect to these important parameters, are paramount in SLS/SLM research.

Theoretically, the high temperature at the laser-irradiated area on the metal powder during SLS/SLM can be associated with the theory of moving sources of heat (Rosenthal, 1948). The problem of a travelling point source of heat presented by Rosenthal has been the basis for heat flow study, especially in welding. It was reported that temperature distribution in a moving source of heat is dependent on the welding condition. The heat was more concentrated around the heat source, and the rise of the temperature in front of the heat source was much steeper than the fall of the temperature behind the heat source. There was also a lag of temperature distribution when the heat source was moved forward. Refinement of the theory has been largely used in other applications that involve movement of heat. In SLS/SLM, application of a laser as a source of moving heat has been studied theoretically (Van Elsen et al., 2007). Van Elsen reported the temperature distribution of a moving heat source and highlighted that the more the energy is concentrated, the higher the peak temperature. The peak temperature is located near the rear end of the spot size. The higher the speed of the heat source, the more the peak temperature is located at the rear end.

Experimentally, a comparison with real-time experimental data is relatively complex due to the nature of SLS/SLM. During SLS/SLM, the consolidation occurs on a micron-sized scale inside a confined area with a very high temperature, and energy intensity has caused earlier research involving real-time observation of the SLS/SLM process using a high-speed camera at the laser irradiation spot to be not very clear. Some of the earlier reports on real-time observation of SLS/SLM were discussed in (Bayle and Doubenskaia, 2008),(Hagedorn et al., 2011),(Lott et al., 2011) and (Chivel, 2013). It is also suggested that in-depth study is required of the mechanisms of the formation of single laser-melted tracks and of the instabilities of the molten pool so that the application of a wider range of commercially available powder is feasible (Yadroitsev and Smurov, 2010). Hence, a clear and real-time monitoring of the consolidation process in SLS/SLM is essential. The design of the experiment and preliminary observation of the research was previously reported by the author (Furumoto et al., 2012).

In this paper, the consolidation process on the first layer of laser irradiation of ferrous metal powder is examined by monitoring the real-time consolidation process in the SLS/SLM process. A high-speed camera was utilized with telescopic lenses in order to monitor interaction of laser and material and the transformation of metal powder to the consolidated structure. Since consolidation characteristics and the influence of processing parameters are important in determining the SLS/SLM part quality, laser power and scan speed were varied in order to study the influence of these parameters on the consolidation process during SLS/SLM. Based on this, the consolidation characteristics during SLS/SLM are reported.

## 2. Methodology

### 2.1 Experimental setup

In order to monitor the consolidation characteristics of metal in SLS/SLM, a special small-scale SLS/SLM machine was designed and fabricated. The experimental setup is shown in Fig. 1. The Yb:fiber laser beam was placed at a 45-degree angle from the surface so as to improve the visibility of the consolidation that occurred on the powdered surface. To avoid harmful reflected laser beam, a beam diffuser was used to reduce the reflected beam. A metal halide lamp was used in order to ensure sufficient lighting to the laser irradiation area and its surroundings. The consolidation process was carried out in a closed test chamber with a nitrogen-controlled atmosphere. This was to improve the quality of the consolidated part since oxidation was avoided during the process.

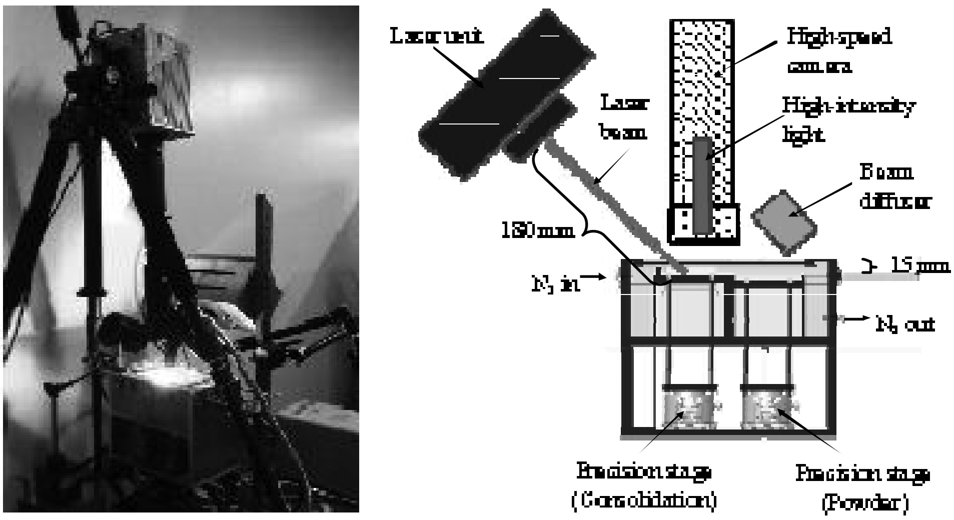


Fig. 1 Setup of line consolidation monitoring apparatus

Table 1 Experimental conditions

| | | |
|---|---|---|
| Laser | | |
| Type | | Yb:fiber |
| Wavelength | $\lambda$ | 1070 nm |
| Power | $P$ | 1- 40 W |
| Scan speed | $V$ | 1-100 mm/s |
| High-Speed Camera | | |
| Shutter speed | $s$ | 10,000 fps |
| Resolution | | 768 x 648 |

Table 2 Specification of metal powder

| | | |
|---|---|---|
| Type | | Fe, Cu, Ni |
| Average diameter | $d$ | 25 μm |
| Shape | | Irregular |
| Bulk density | $\rho$ | 4190 kg/m$^3$ |
| Absorption ratio | $A_r$ | 25% |
| Thermal conductivity | $K$ | 0.14 W/(m·K) |
| Layer thickness | $t$ | 50 μm |
| Layer number | | First layer |

[DOI: 10.1299/jamdsm.2014jamdsm0009]

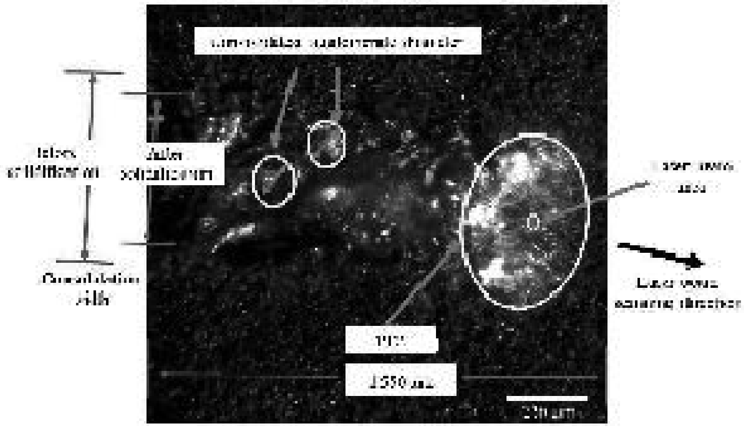

Fig. 2 Line consolidation characteristics and their nomenclature

The laser equipment used was LP-10 manufactured by SUNX Ltd. The laser beam was a continuous Yb:fiber which formed a Gaussian shape with the focal diameter of 45 μm. The laser power was varied from 1 to 40 W and the scan speed used was set from 1 to 200 mm/s. The high-speed camera used was a FASTCAM SA5 with a shutter speed of 10,000 fps. A filter was used with the high-speed camera in order to protect the camera from the scattered laser beam and enhance the visibility of the consolidation process within the PFZ. The filter was a laser-protective shield manufactured by Sigma Koki, YL-500P-Y1 with dimensions of 50mm x 50mm and a thickness of 3.5 mm. The filter was made from polymethyl metaacrylate and was able to absorb the wavelength of 1064nm, which then enhanced the visibility of the consolidation of metal powder through the high-speed camera during laser irradiation. The experimental condition used in the experiment is tabulated in Table 1.

The influence of laser power and scan speed on line consolidation characteristics were analyzed. The analysis was made with respect to characteristics defined in the study. These characteristics are consolidation width, consolidated agglomerate diameter, powder fusion zone (PFZ) area, splattering behavior and consolidation mechanism. The consolidation characteristics nomenclature used in the study is illustrated in Fig. 2. During laser irradiation, metal powder was heated producing molten powder. After the molten powder solidified, the shrinkage of molten powder towards the center of the line consolidation occurred, producing a smaller consolidated line. This is referred to as line consolidation width after solidification. The solidification has created a powder-free area between the consolidated structure and the metal powder that is not fused by laser irradiation. Consolidated agglomerate refers to a group of metal powder particles that coalesce, forming molten powder which then solidifies together, producing a ball-shaped agglomerate with various diameters at different processing parameters. Average values of consolidated agglomerate diameter produced at the same setting were recorded. Another line consolidation characteristic observed was powder fusion zone (PFZ). The PFZ in the SLS/SLM process is defined as the area on the metal powder being fused as the laser beam moves forward during laser irradiation. Throughout the experiment, the observation was made twice: that is, without filter and with filter. Measurement of the PFZ was made using the series of images from the high-speed camera without the filter. The boundary zone of the PFZ is defined by the existence of an elliptical brighter region. Since the shape of the PFZ is approximately elliptical, the area was determined based on the major diameter and minor diameter of the ellipse. The measurement was made using the high-speed camera software Photron FASTCAM Viewer. It is important to note that the PFZ observed in the experiment is approximately elliptical shaped due to the laser orientation being at 45 degrees from the laser-substrate surface.

### 2.2 Metal powder

The material used in the study was a ferrous-based powder material with the particle mean diameter of 25 μm. The metal powder was a mixture of steel, copper-phosphorous alloy and nickel with a weight percentage of 70%, 20% and 10% respectively. The powder was prepared through a gas-atomization method. The specification of metal powder used in the experiment is tabulated as Table 2. The metal powder was deposited on a cold-rolled steel substrate that had been sandblasted by #46 grain size. This was to improve the wettability of the molten powder. Similar to any SLS/SLM system, the metal powder was deposited under the influence of gravitational force and then was levelled using a squeegee blade. Throughout the experiment, the thickness of the metal powder was maintained at 50 μm.

 

## 3. Results and Discussion

### 3.1 Line Consolidation Structure

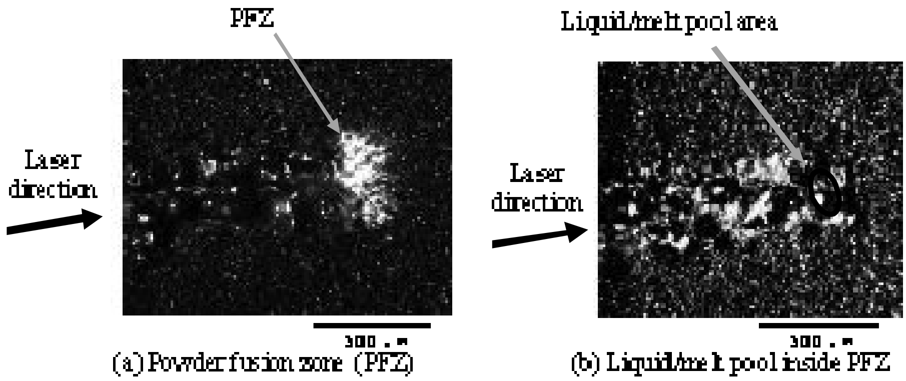


Fig. 3 Line consolidation during laser irradiation

Understanding line consolidation characteristics is important because during the SLS/SLM process the laser beam is irradiated line by line on the powdered surface. As the laser beam is continuously irradiated in a straight line, a line consolidation is formed. Figure 3(a) shows the PFZ on line consolidation, which can be seen on the high-speed camera when there is no filter used during laser irradiation. The figure clearly shows an elliptical shape of the PFZ caused by the irradiated laser beam on the metal powder. The approximately elliptical shape of the PFZ, which can be related to the moving heat source, was obtained from the experiment due to the laser orientation being at 45 degrees. The laser orientation was positioned in order to enhance visibility at the laser-irradiation area. Figure 3(b), on the other hand, depicts the line consolidation under the same setting when a filter was used. When there was no filter, consolidation within the PFZ was not clear due to very high brightness intensity. In contrast, with the application of the filter, the consolidation behavior and transformation of the metal powder to a consolidated structure that occurred within the liquid/melt pool area can be observed clearly. The liquid/melt pool is located inside PFZ. The figures also show a direct relationship between the major diameter of the PFZ and the line consolidation width. The major diameter of the PFZ was approximately the same as the line consolidation width before solidification.

### 3.2 Influence of Laser Power on Consolidation Characteristics

The influence of laser power on consolidation behavior was monitored at different laser powers ranging from 1 to 40 W at a scan speed of 50 mm/s and a thickness of 50 microns. Based on the analysis, it was found that the increase of laser power affected line consolidation width, where it was increasing with the increase of laser power. Similar behavior was observed after shrinkage of line consolidation width. This influence of laser power on consolidation width before and after solidification is presented in Fig. 4. The figure shows different line consolidation widths obtained at various laser powers.

As the laser beam was irradiated to the metal powder surface at low laser power, the amount of metal powder coalescing with its neighboring powder particles was very small. Heat that was generated by laser irradiation was not enough to liquefy high amounts of metal powder, but was only able to liquefy the outer layer of metal powder particles at the center of the laser beam. As a result, only the metal powder directly irradiated by the laser beam and those very close to the center of the laser-beam path coalesced. These metal powder particles coalesced to form consolidated agglomerates with approximately the same diameter, which were randomly distributed within the line consolidation width. Furthermore, the metal powder particles did not consolidate with the substrate at low laser power. The influence of laser power on the consolidated agglomerate diameter and the PFZ is graphically depicted in Fig. 5. The amount of metal powder coalescing with neighboring powder was increasing as the laser power was increased. Consequently, the diameter of consolidated agglomerate grew bigger due to more metal powder coalescing with each other.

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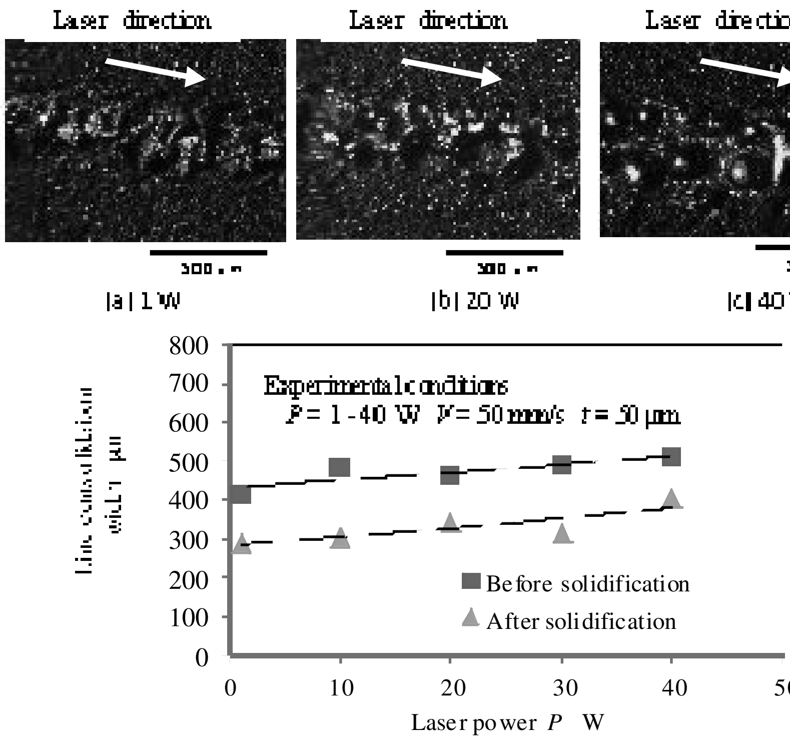


Fig. 4 Influence of laser power on line consolidation width before and after solidification

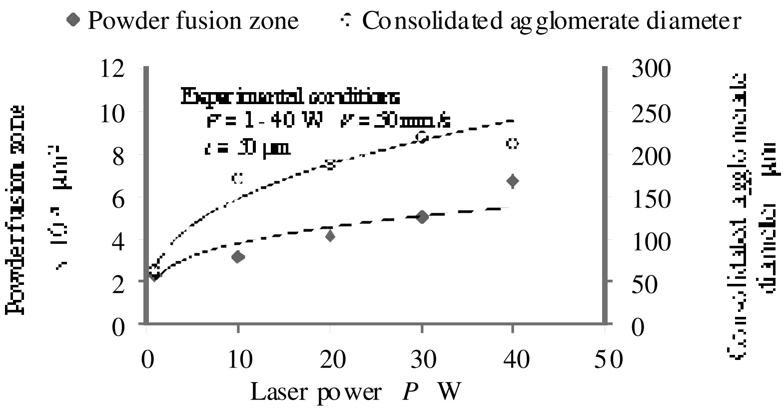


Fig. 5 Influence of laser power on PFZ and consolidated agglomerate diameter

In terms of PFZ observation, increasing the size of the PFZ was obtained with the increase of laser power. It was observed that as the laser beam irradiated on the metal powder a larger area of PFZ was formed. Even at the lowest laser power of 1 W, the size of the PFZ measured was approximately at 2.2 x $10^5$ $\mu m^2$, despite the actual laser-beam area of 2.3 x $10^3$ $\mu m^2$. The area increased significantly with the increase of laser power. A bigger PFZ was obtained as compared to the laser-beam area attributed to the heat transfer from the laser-beam area to surrounding metal along the line irradiation of the laser beam. At higher laser power, a very high thermal gradient existed between metal powder particles that were directly positioned at the center of the laser beam in comparison to the surrounding metal powder. In order to achieve thermal equilibrium, the heat was dissipated and transferred through the substrate surface. Accordingly, as the laser power was increased, better consolidation among metal powders and between metal powders and substrate occurred more prominently. At high laser power also, the PFZ was bigger, which resulted in bigger line consolidation width. Furthermore, splattering of metal particles and molten powder occurred around the line consolidation. A slightly higher amount of metal particle splattering was observed at higher laser power.

[DOI: 10.1299/jamdsm.2014jamdsm0009]

### 3.3 Influence of Scan Speed on Consolidation Characteristics

In contrast to the influence of laser power, the increase of scan speed resulted in narrower line consolidation width, smaller PFZ and smaller consolidated agglomerate diameter. The influence of scan speed on line consolidation width before solidification and after solidification is illustrated in Fig. 6. The phenomena can be linked to the heat transfer process that causes the PFZ around the irradiated area. At high scan speed, the amount of heat transferred to the powder surface was less compared to at low scan speed. The exposure time of each metal particle to laser irradiation that caused the reaction of metal powder to take place during the interaction between the laser beam and metal powder was very low. In contrast to low scan speed, the exposure time of the metal powder to the laser beam was high, causing highly localized heating within a small area. The heat was then transferred from the metal powder to the substrate surface and was further transferred radially, causing the PFZ to have a big diameter. Due to this, rapid heating and cooling of line consolidation occurred faster at high scan speed as compared to at low scan speed. Consequently, a smaller PFZ was monitored at high scan speed. In order to explain this behavior, Fig. 7 schematically illustrates the PFZ and the interaction between laser beam, metal powder and substrate during laser-beam irradiation. It is also important to note that the substrate had high thermal conductivity, $K_{base}$=56 W/(m·K) in comparison to the metal powder $K_{powder}$=0.15 W/(m·K). Therefore, during the heat transfer process, it is believed that the radial direction of heat transfer mainly occurred through the conduction process that occurred through the substrate material.

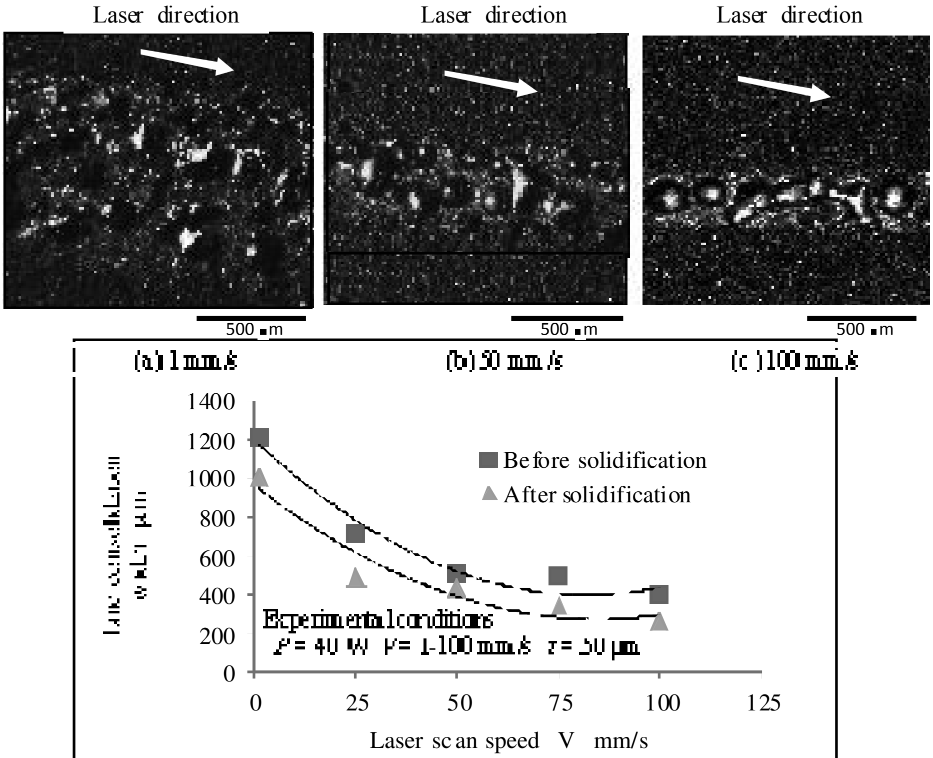


Fig. 6 Influence of laser scan speed on line consolidation width before and after solidification

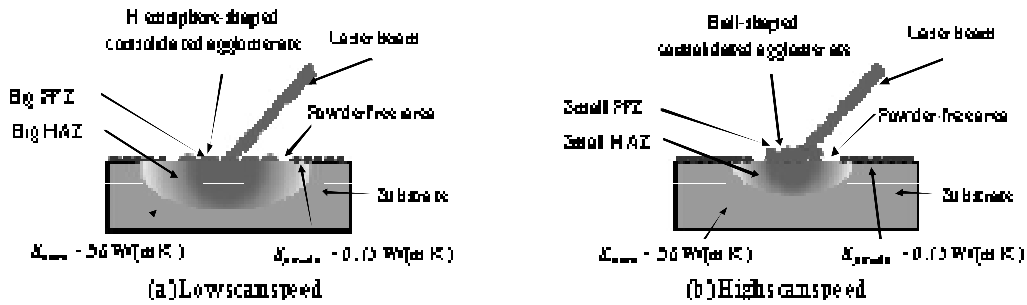


Fig. 7 Schematic of laser irradiation on substrate

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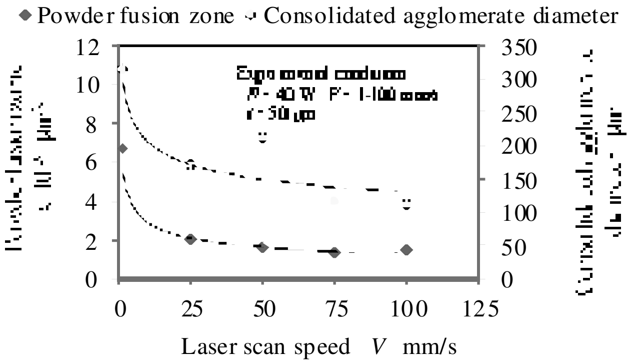


Fig. 8 Influence of scan speed on PFZ and consolidated agglomerate diameter

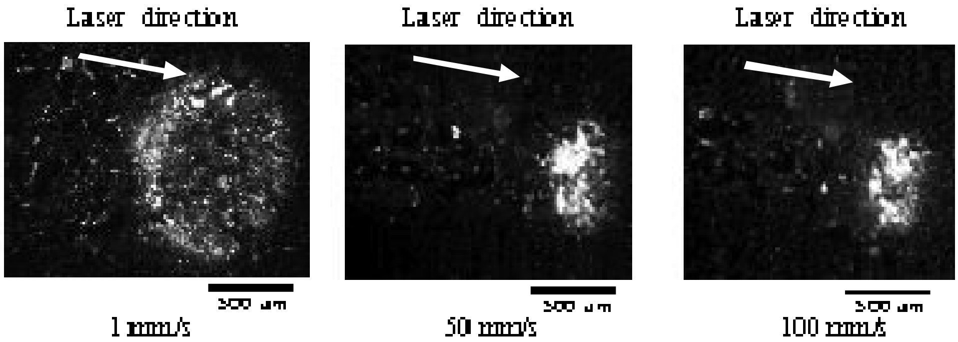


Fig. 9 Influence of scan speed on PFZ

The influence of scan speed on the PFZ and consolidated agglomerate diameter is illustrated in Fig. 8. The line consolidation with the PFZ images at 1 mm/s, 50 mm/s and 100 mm/s is shown in Fig. 9. The area was significantly large when the scan speed was 1 mm/s but reduced significantly with the increase of scan speed and was almost constant approaching 100 mm/s. In terms of consolidated agglomerate diameter, higher temperature on the irradiated spot caused more localized heating when the scan speed was low in comparison to high scan speed. At low scan speed, the metal powder melted as a high amount of heat was generated due to laser irradiation to the powder surface. With the increase of scan speed, less heat generated to the PFZ due to the reduced interaction time between the laser and metal powder. As a result, consolidated agglomerate diameter decreases with the increase of scan speed, as shown in Fig. 8. In terms of the splattering of metal powder and molten powder, significant splattering was observed with the increase of scan speed.

### 3.4 Line Consolidation Mechanism of Metal Powder

Understanding the consolidation mechanism of metal powder is of utmost importance in SLS/SLM as consolidation is the very essence of the development of 3D structures from metal powder in the AM system. Figure 10 shows the consolidation process recorded when the scan speed is 1 mm/s with a laser power of 40 W. The figure shows a series of images obtained using a high-speed camera at intervals of 6 ms. During the start of laser irradiation, the skin or the outermost layer of powder particles was initially liquefied. As more heat was absorbed by powder particles, the powder particles coalesced with their surrounding particles, forming hemisphere-shaped consolidated agglomerate. During consolidated agglomerate formation, surrounding powder particles were attracted together, as indicated in the direction of the arrow in Fig. 10(f). Since the speed was very low, a higher volume of metal powder was transformed to liquid. Due to the increase of molten powder-volume ratio within the PFZ, the formation of liquid/melt pool occurred. As a result, the viscosity of the liquid/melt pool increased. This caused the flow of molten powder to move under the influence of surface tension.

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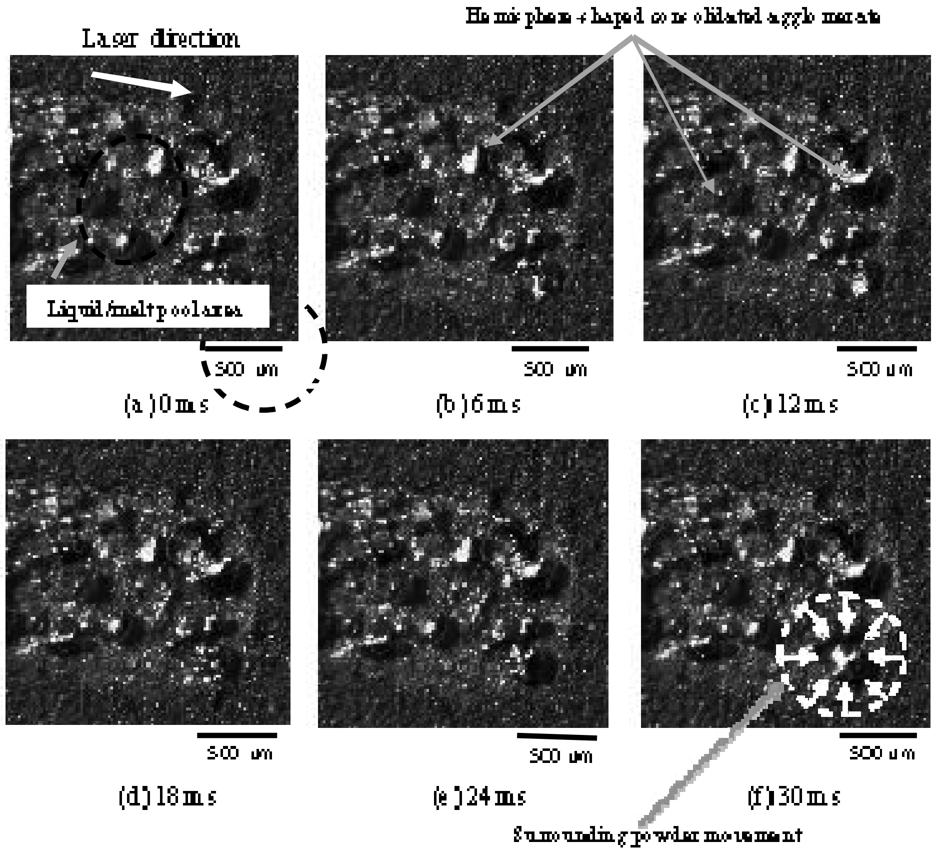


Fig. 10 Consolidation of metal powder at $P$ = 40 W and $V$ = 1 mm/s

Figure 11 shows consolidation transformation of metal powder when the laser power was set at 40 W and at a higher scan speed of 50 mm/s. The transformation of the metal powder to consolidated agglomerate was recorded at 2 ms intervals. With the increase of scan speed, there was less interaction time between the laser beam and metal powder within the irradiation spot. As a result, only a limited amount of the outer layer of the metal powder transformed to liquid due to the shorter exposure time of the metal powder to the laser beam. This contributed to the low-volume fraction of molten powder compared to the condition when the scan speed was 1 mm/s. At this point, it was observed that surface tension significantly caused the molten powder to attract the metal powder particles to its surrounding area to form consolidated agglomerates. As the volume fraction of molten powder was increasing and sufficiently high, the molten powder flowed more rapidly toward the center of the molten pool. Surface tension in SLS/SLM is created due to the attraction force that exists between molten powders. During the attraction of molten powder, the neighboring metal powder particles adhered to the molten powder surface and moved together.

Comparison of Fig. 10 and Fig. 11 shows that the flowing of molten powder toward the center occurred more prominently when the scan speed was increased. Other than that, the tendency of balling to occur increased at the higher scan speed. At the higher scan speed also, it was observed that wetting of the molten powder to the substrate surface was not as good as when the speed was set at 1 mm/s. At the scan speed of 50 mm/s, most of the molten powder still wet to the surface; however, at the higher speed some of the molten powder did not wet to the substrate surface and formed ball-shaped consolidated agglomerate. This ball-shaped consolidated agglomerate, which is also well known as balling phenomena in SLS/SLM, is one of the most common problems in SLS/SLM. The amount of heat generated on the powder surface was less, causing ineffective transformation of the metal powder particles to molten powder. As a result, spheroidisation of the liquid melt pool was formed. Although some molten balls formed at this speed tended to wet to the substrate surface, some of these solidified molten balls could be easily removed as the metal powder was cleaned from the substrate. Hence, when the scan speed was 50 mm/s, the tendency of balling of the molten powder was high in comparison to when the scan speed was 1 mm/s.

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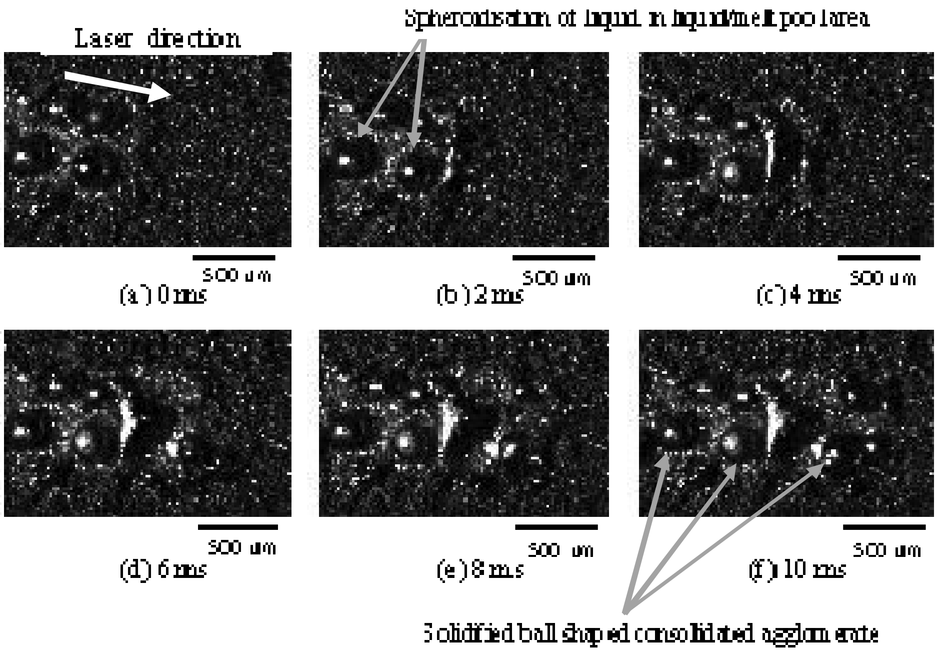



Fig. 11 Consolidation of metal powder at $P$ = 40 W and $V$ = 50 mm/s

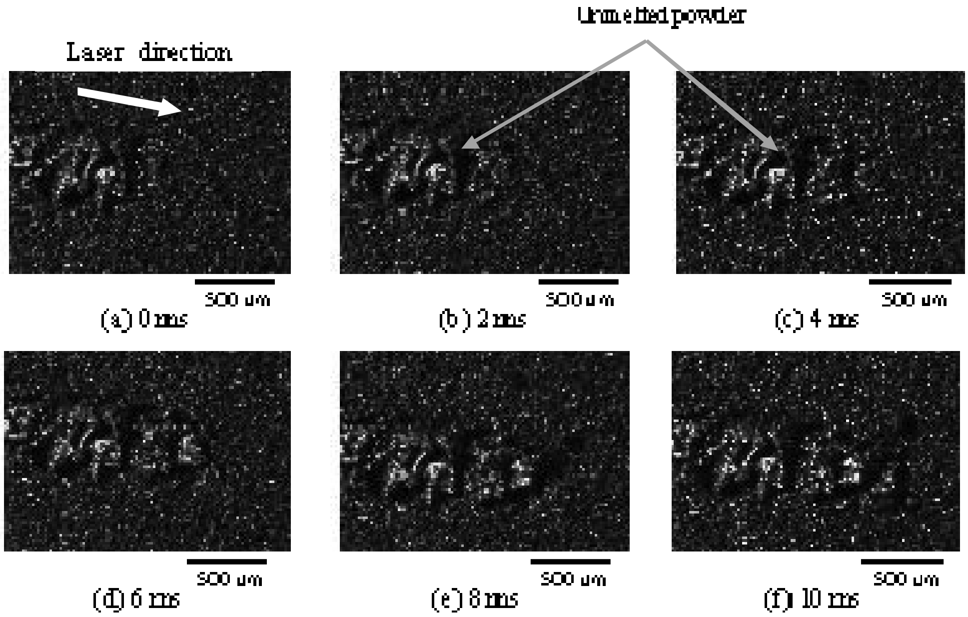



Fig. 12 Consolidation of metal powder at $P$ = 1 W and $V$ = 50 mm/s

In order to demonstrate the consolidation transformation process at lower laser power, 1 W of laser power was used. Figure 12 shows a sequence of metal powder consolidation at 2 ms interval when the lower laser power of 1 W and a scan speed of 50 mm/s was used. When the laser power was very low, only sintering took place between the metal powder particles since there was no significant amount of molten powder observed. It is believed that the agglomerate structure that was formed attributed to coalescence between powder particles when there were only small amounts of liquid film between powder particles after the metal powder particles were irradiated with the laser beam.

In SLS/SLM, not only is consolidation between powders important, but so is the adhesive property between successive adjacent line-by-line consolidation and between different layers. The study elaborates in detail on line consolidation, which is the basis of the development of 3D consolidated structures. However, in actual SLS/SLM, repetitive and successive line-by-line laser irradiation needs to be executed at the same layer and increasing layer

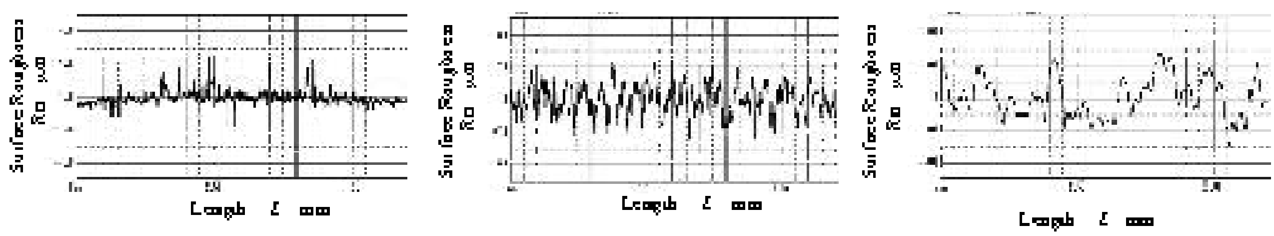
[DOI: 10.1299/jamdsm.2014jamdsm0009] 

numbers. Repetitive and successive line-by-line consolidation on the same layer at equal hatching distance formed area consolidation. With the increasing layer number, a 3D consolidated part was produced. Therefore, in area consolidation, instead of having only one single line during laser-beam irradiation, the laser was irradiated successively adjacent to each line at the distance of the hatching size. Large consolidation width caused the previously formed consolidated structure to be wider than the hatching size. As a result, during area consolidation the laser beam was actually being irradiated on the previously formed consolidated structure repeatedly with new metal powder continuously being added. Hence, the line consolidated structure overlapped and the melted powder bonded to the other adjacent lines structure. Successive lines on the same layer re-sintered/re-melted previously formed tracks and overlapped. This improved adhesive properties between line consolidations. The molten metal within the melt pool flowed and spread easily between the adjacent tracks. Hence, the molten powder filled the gaps between the tracks, consequently decreasing the porosity and escaping the previously trapped gas.

After area consolidation was completed, the consolidation stage was lowered down to allow a new powder layer to be deposited on the previous consolidation area. Later the consolidation process on the new layer started. In order to investigate consolidation behavior at different layers, observation was also performed on the consolidated surface. It is important to note that the average surface roughness of substrate surface, sandblasted substrate surface, and consolidated structure layer was 0.2046 μm, 2.4893 μm and 11.2862 μm, respectively. Previous studies showed that the width of the consolidated structure was influenced by the surface roughness on the substrate. The studies also suggested that the adhesion force of the consolidated structure is higher when a sandblasted substrate surface was used due to the improved wettability of the molten metal (Furumoto et al., 2008),(Furumoto et al., 2009). The roughness of different surfaces where metal powder was deposited is shown in Fig. 13.

Generally, consolidation behavior on the sandblasted substrate surface produced relatively smooth and faster movement of the metal powder in comparison to consolidation on a consolidated surface. This is owing to better surface finish. In contrast, during consolidation on the consolidated surface, the movement of the melt pool and its surrounding metal powder was relatively dependent and limited by the quality of the consolidated surface. As the laser was irradiated on the metal powder with the underneath layer being a consolidated material, molten metal flowed towards the pore filling of underneath layer. As a result, densification of consolidated material occurred.

Since SLS/SLM involves layer-by-layer consolidation, where there are continuous changes of thermophysical properties of materials that interact with the laser beam, investigations into thermal conductivity of these materials are important because they affect the consolidation process. Previous research on thermal conductivity of the same material in the powder, consolidated and bulk states showed that the thermal conductivities differ significantly. The thermal conductivity of the consolidated material varies from 6.2 to 8.3 W/(m·K) depending on the porosity of the consolidated material. The thermal conductivity measurements of the metal powder state and bulk material state are 0.15 W/(m·K) and 42 W/(m·K) respectively (Alkahari et al., 2012), whereas the thermal conductivity of the substrate is 56 W/(m·K). Therefore, there are large differences in the thermal conductivity values as the laser was irradiated on metal powder with different bottom surface conditions. As a result, during the heat transfer process in the SLS/SLM process, laser irradiation on successive layers in SLS/SLM exhibits different consolidation characteristics results caused by the variation of the thermal conductivity with the increase of layer thickness. However, as the number of the layers becomes sufficiently high, the thermal conductivity and surface roughness of the consolidated material become more important factors affecting the line consolidation characteristics compared to the thermal conductivity and surface roughness of the substrate.



(a) Roughness of substrate surface (b) Roughness of sandblasted substrate surface (c) Roughness of consolidated surface

Fig. 13 Surface quality of different surfaces

[DOI: 10.1299/jamdsm.2014jamdsm0009]

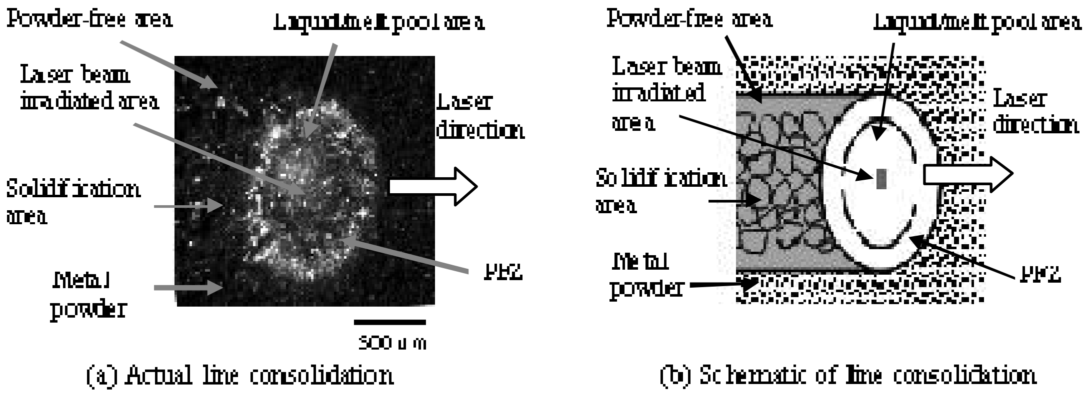



Fig. 14 Main area and stages in line consolidation stucture

The evolution of the consolidation process in SLM/SLS involved material state changes from solid state (powder) to semi-liquid state or liquid state (molten powder), then back to solid state (consolidated) after the solidification process can be observed in the study. An examination of the consolidation mechanism that occurred at various processing parameters in Fig. 10, Fig. 11 and Fig. 12 revealed that the metal powder particles experienced changes in their shape and structure as consolidated agglomerate was formed.

Based on the high-speed-camera images obtained under various processing conditions, similar behavior and consolidation mechanisms were revealed. Based on the observation, the consolidation process of metal powder during the SLS/SLM process can be divided into stages, which correspond to different areas on line consolidation. The metal powder underwent several stages of transformation due to high localized temperature during laser beam irradiation on the metal powder and the substrate interaction process. Figure 14(a) shows the actual line consolidation with the PFZ. The existence of the different areas within line consolidation, which reflect stages that occurred continuously during SLS/SLM, can be schematically illustrated in Fig. 14(b). During laser irradiation, the area on the metal powder can be divided into five different areas:

- Area 1 : Laser beam irradiated area
- Area 2 : PFZ
- Area 3 : Liquid/melt pool area
- Area 4 : Solidification area
- Area 5 : Powder-free area

Since the nature of SLS/SLM processes where the movement of the laser beam continuously travels and irradiates on the new powder surface, the schematic figure may represent the line consolidation area at any instantaneous position. As SLS/SLM involves layer-by-layer laser irradiation and powder deposition, each subsequent consolidation of a new layer on top of the surface causes the underneath layer to experience these different stages repeatedly until the 3D object is fabricated.

The laser beam irradiated area is the actual size of the laser beam diameter as it is irradiated from the laser source. The area is the main area that received irradiated heat from the laser source. Therefore, this area has the highest temperature compared to other areas. However, theoretically, the exact peak temperature location may be slightly nearer the rear end, depending on the speed (Van Elsen et al., 2007). The heat within the laser beam irradiated area was transferred radially to its surroundings on the substrate causing the PFZ. The PFZ was surrounded by more glittering areas. The glittering was caused by the reflection of the semi-solid metal powder particles as they started to melt, or as they started to solidify. It is important to note that the temperature at the edge of the PFZ was lower compared to the temperature at the center. At the center of the PFZ area a liquid pool developed and flowing of molten powder occurred. When the melting state was achieved, the area formed a melt pool. The flowing of the molten powder depends on the viscosity of the molten powder at that time. Hence, there is less glittering observed toward the center of the PFZ or inside the liquid/melt pool area.

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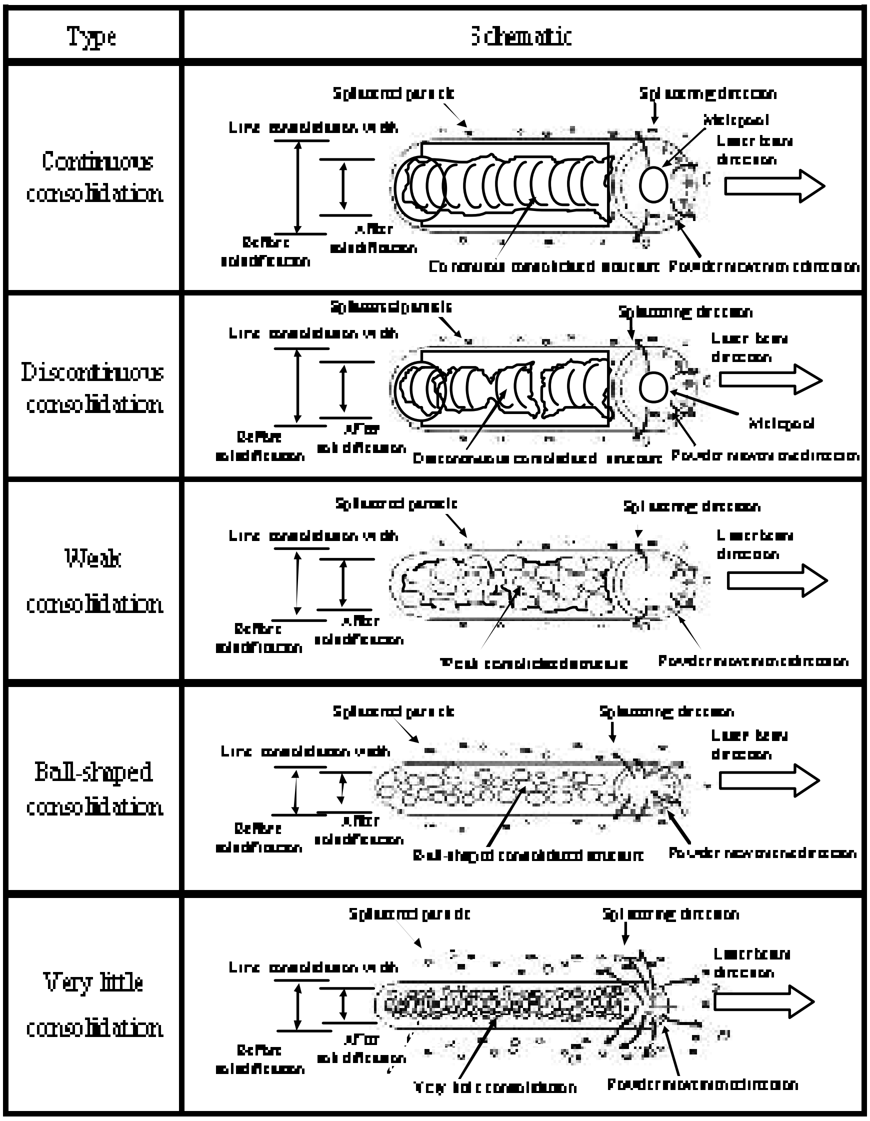


Fig. 15 Schematic presentation of line consolidation types

After the laser beam moved away from the irradiated spot, the line consolidation structure cooled down and the solidification process started. Solidification of the molten powder caused relatively little shrinkage of the molten powder as transformation from liquid to solid occurred. As a result, a powder-free area was formed. Within the liquid/melt pool area also, fast movement of the metal-powder particles was observed toward the center with the increased of scan speed. During these movements, collisions between metal powder particles occurred. Collisions that occurred between metal powder particles contributed to the splattering of the metal powder. An increasing amount of splattered molten powder occurred in a circumferential direction as the scan speed was increased. As a result, the amount of splattering that occurred in the vicinity of the line consolidation increased where the splattered metal powder particles tended to be displaced further from the line consolidation structure.

Generally, the line consolidation characteristics and types can be summarized schematically in Fig. 15. Changes in laser processing parameters resulted in changes in the line consolidation characteristics. As can be seen in the figure, changes in line consolidation characteristics were observed in terms of line consolidation width, PFZ, consolidated agglomerate diameter and splattering behavior. Based on the quality of line consolidation observed in the research, its relation to parameter can be classified as continuous, discontinuous, ball-shaped, weak and very little consolidation. Continuous consolidation is characterized by the formation of a continuous consolidated track. This form of consolidation is considered as good because the structures are connected to each other in a straight line, coherently forming a relatively dense surface which penetrates to the substrate surface. On the contrary, discontinuous consolidation is characterized by a discontinuous shape of the consolidated structure. The structures are relatively dense

[DOI: 10.1299/jamdsm.2014jamdsm0009]

but most are not continuously connected. Another type of line consolidation quality is weak consolidation. This is characterized by scattering and a small amount of sintered metal powder, which can be easily broken. The shape is relatively irregular due to the shape of the metal powder. Sintering between metal powder particles only occurs between the surfaces of the metal powder and occasionally coalesces with the substrate surface.

Ball-shaped consolidation is characterized by the existence of a high number of ball-shaped consolidated structures that are scattered randomly on the line-consolidation track. The ball-shaped structures are not connected to each other, resulting in a rougher surface. Some of these structures coalesced with the substrate surface, forming hemisphere shapes. At relatively low laser power and high scan speed, another type of line consolidation occurred, which is called very little consolidation. The existence of un-sintered metal powder particles, most of them unconnected, is the main characteristic of this type of line consolidation. Changes of the individual metal powder shape were observed due to the small amount of heat, but the energy density was not enough to cause coalescence between metal powder particles.

The mechanism and phenomenological analysis discussed in the study indicated that it is apparent that the quality of the line-consolidated structure is affected by the laser parameter used. This is because at different laser parameters the transformation of metal powder to molten powder exhibits different properties due to the energy irradiated to the metal powder, which is related to the viscosity, surface tension, laser absorption, wettability, roughness of the substrate, viscosity, and others. Generally, effective molten metal flow within the PFZ allows a relatively smoother surface of consolidated structure. Therefore, observation of the melt pool and optimization of processing parameters is crucial in determining the optimum conditions to ensure that solid and continuous consolidated structures can be manufactured. Kruth et al. suggested that for each new material a process map needs to be developed experimentally (Kruth et al., 2005). This is due to different property changes of the materials used during SLS/SLM processing. Variations of line consolidation quality have been reported by many authors using different materials (Kruth, Froyen, et al., 2004),(Khan and Dickens, 2012),(Olakanmi, 2013). In this study, the laser was varied from 1 to 40 W and the laser scan speed range was from 1 to 200 mm/s. The line consolidation quality is shown in Fig. 16.

Based on the study, it can be summarized that the transformation process of metal from powder state to consolidated agglomerate occurred as the laser was irradiated on the powder surface. The formation of consolidated agglomerates was highly influenced by the amount of heat on the irradiation spot, which then affected surface tension and flowability of molten powder. When the laser was beamed onto metal powder, localized high temperature occurred at the irradiation spot within a very short time. Sufficient thermal energy liquefied the outer layer of the metal powder first. Further heating further liquefied the successive outer layers and eventually changed the powder to molten powder. A rapid increase in the temperature caused high temperature gradient in the consolidated area. The high temperature stimulated physical changes and chemical reactions. The difference in the temperature between the edge and center of the liquid/melt pool also contributed to the consolidation characteristics where the flow of molten powder was observed. It is generally accepted that surface tension is dependent on temperature. As a result, the high temperature gradient induced surface tension on the irradiated surface. Since a number of groups of molten powder spread and coexisted simultaneously on the PFZ, the gradient of surface tension between these molten powders initiated the movement of molten powder within the PFZ.

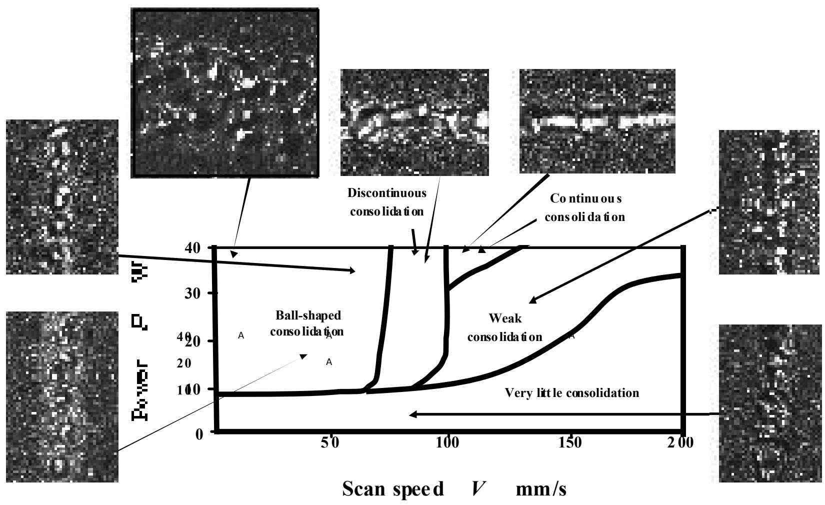


Fig. 16 Line consolidation quality

 

## 4. Conclusions

Consolidation characteristics of ferrous-based metal during SLM/SLS were successfully monitored and analyzed with the utilization of a high-speed camera. Based on the study, the transformation and mechanism of the consolidation of metal powder to a consolidated structure within a PFZ under the influence of a laser beam was elucidated. It was also found that:

1. The quality of line consolidation is important, as it is the basis of 3D consolidated structure formation. The line consolidation quality can be divided into continuous, discontinuous, ball-shaped, weak and very little consolidation. Monitoring of the sintering/melting mechanism that occurs within the PFZ enables the understanding of the consolidation process of metal powder to consolidated structure.
2. The PFZ is one important characteristic in the SLS/SLM process due to all microstructural and mechanical changes and the transformation of the metal powder to a consolidated structure occurring in this area. The result showed that the line-consolidation width was approximately the same diameter as the PFZ major diameter when the laser beam was irradiated in a straight line on a metal powder.
3. Line consolidation width, PFZ, consolidated agglomerate diameter and splattering increase with the increase of laser power. In contrast, with the increase of scan speed, the result is vice versa. The PFZ was found to decrease significantly and become constant as the scan speed approaches 100 mm/s. The tendency of balling formation is also higher with the increase of scan speed. This is due to a lack of wettability of the molten powder with the substrate surface. As a result, poor consolidation occurs between metal powders due to less interaction time between the laser beam, metal powder and substrate, which can prompt a reaction to take place.
4. Line consolidation width, PFZ, consolidated agglomerate diameter and splattering behavior are related to the heat transfer process that occurred during the interaction of the laser beam, metal powder and substrate surface.

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