Chapter 6

Results and discussions

6.1. RESULTS AND DISCUSSION: NUMERICAL MODELLING

This chapter presents the key findings on the physical phenomena happening in the laser melting process, based on the objectives presented in chapter 3 and from the results of the numerical and experimental studies elaborated in the chapter 4 and 5.

6.1.1. ENERGY DENSITY Vs PERCENTAGE OF DEVIATION

6.1.1.1. RESULTS

Energy density of the laser beam is calculated from Eq. (4.1) and the percentage of deviation in laser melted samples obtained from Eq. (4.20) represented in table 6.1. The effect of the energy density on the percentage of deviation in layer thickness before and after laser exposure were found out and represented in Figure (6.1). The result shows that the maximum percentage of deviation 60 % is obtained at energy density of 1 J/mm². However, the percentage of deviation does not pose a serious problem when the energy density is set at some higher level (2 J/mm²). Whereas it increases from 20 to 40 % when increasing the energy density from 2 to 4 J/mm². Also it further decreases while increasing the energy density beyond 8 J/mm².
Fig. 6.1. Energy Density Vs % deviation

Table 6.1 Percentage of Deviation values

<table>
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<tr>
<th>Energy Density J/mm²</th>
<th>Deviation %</th>
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<tr>
<td>8.33</td>
<td>40.973</td>
</tr>
<tr>
<td>1.785</td>
<td>28</td>
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<td>22.712</td>
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<td>2.142</td>
<td>27.236</td>
</tr>
<tr>
<td>2.5</td>
<td>3.879</td>
</tr>
<tr>
<td>10</td>
<td>20.566</td>
</tr>
<tr>
<td>4.761</td>
<td>26.155</td>
</tr>
<tr>
<td>2.5</td>
<td>19.919</td>
</tr>
</tbody>
</table>
6.1.1.2. DISCUSSION

The energy density versus percentage of deviation shows that at lower energy density, the percentage of deviation in layer thickness before and after laser exposure is larger (Fig 6.1). This is mainly due to the laser power and the scan speed, which define the energy density which improperly melts the powder. The percentage of deviation decreases with increasing scan speed as well as the laser power (Fig 6.1). There is a % of deviation for the same values of energy density 2.5 J/mm² this is mainly because of the laser power and speed. The energy density showing higher percentage of deviation having laser power 200 W and laser speed 12 m/min. whereas the same energy density with lower percentage having laser power 150 W and laser speed 12 m/min. The difference is mainly due to the higher laser power which over melts the powder bed and leads to higher percentage of deviation in track height. By increasing the energy density predominantly, the percentage of deviation will be reduced. Moreover by increasing the energy density up to certain limit (5 J/mm²-8 J/mm²), the material encounters higher degree of deviation. This is mainly due to the dissipation of higher laser energy into the powder bed and the molten pool becomes less viscous, thus, upon solidification. However, by increasing the energy density beyond this maximum, the strength of the part will be decreased because of a thermal damage (Simchi 2006). Moreover, the dependence on laser power is more pronounced i.e. heat penetration mainly depends only on laser power which directly affects the percentage of deviation in the melted layer. Therefore, it was found out that better densification rate of the powder was achieved at lower energy density. It is to be noted that at high laser energy density, the intensity of the laser is large enough to cause the powder material to vaporise as reported by Gusarov et al. (2009). The laser melting can be considered as “high power density short interaction time” process (Simchi 2006). The delivered energy heats up the exposed powder particles rapidly beyond the melting temperature. The particle bonding is then performed and the kinetics of densification depends on the working temperature. Consequently, the parameters involved in determining the method of energy delivered to the powder medium control the melting rate. Meanwhile, the evaporation of exposed powder in the laser melting process may occur, particularly at an intensive laser energy input. It was found that as the laser energy input increases better densification is achieved. Nevertheless, there is a
saturation level of 10 J/mm$^2$ beyond this level, full density cannot be obtained even thermal distortion may take place at very intensive laser energy (Gusarov et al. 2009).

6.1.2. ABSORBANCE

6.1.2.1. RESULTS

Absorptivity has been found out for powder bed of particle size 20 µm and thickness of 100 µm. The absorptivity of powder porosity ranging from 40-60 % is represented in Figure (6.2-6.6). It has been reported that the porosity of metallic powders used for laser melting processes are in the range of 40-60% (Gusarov et al. 2009). At different percentage of porosity, the total absorptivity of powder as well as substrate has been found out. The graphs of absorptivity Vs optical depth are obtained by formulating the powder characteristics using Eq.s (4.2- 4.6). The results show more or less same deflection ranges in all the range of porosity. In addition, absorptivity of the powder bed is comparatively higher with lower percentage of porosity. In higher percentage of porosity the absorptivity of the powder bed is less. Moreover at higher porosity, the absorptivity of the substrate is more as compared with lower percentage of porosity.
Fig. 6.2. Total absorptivity of the system powder-substrate ($A_{ps}$) and fractions of the incident laser radiation absorbed by the surface of the substrate ($A_s$) and in the powder ($A_p$) versus optical depth of the powder layer ($\gamma$) at the reflectivity of dense material $\rho=0.7$ and porosity 40%.

Fig. 6.3. Total absorptivity of the system powder-substrate ($A_{ps}$) and fractions of the incident laser radiation absorbed by the surface of the substrate ($A_s$) and in the powder ($A_p$) versus optical depth of the powder layer $\gamma$ at the reflectivity of dense material $\rho=0.7$ and porosity 45%.
Fig. 6.4. Total absorptivity of the system powder-substrate (\(A_{ps}\)) and fractions of the incident laser radiation absorbed by the surface of the substrate (\(A_s\)) and in the powder (\(A_p\)) versus optical depth of the powder layer \(\gamma\) at the reflectivity of dense material \(\rho=0.7\) and porosity 50%.

Fig. 6.5. Total absorptivity of the system powder-substrate (\(A_{ps}\)) and fractions of the incident laser radiation absorbed by the surface of the substrate (\(A_s\)) and in the powder (\(A_p\)) versus optical depth of the powder layer \(\gamma\) at the reflectivity of dense material \(\rho=0.7\) and porosity 55%.
Fig. 6.6. Total absorptivity of the system powder-substrate (Aps) and fractions of the incident laser radiation absorbed by the surface of the substrate (As) and in the powder (Ap) versus optical depth of the powder layer $\gamma$ at the reflectivity of dense material $\rho=0.7$ and porosity 60%.
6.1.2.2. DISCUSSION

From the mathematical model described in chapter 4, it is noticed that the low optical depth leads to higher absorptivity of powder, whereas it is decreasing when exposed in higher optical depth for all the percentage levels. At higher optical depth, scattering of laser doesn’t happen so the light escapes without scattering as reported by Gusarov et al. (2009). This scattering of laser in the powder bed mainly leads to absorption. When comparing the percentage of porosity, at lower porosity the results show a higher absorption in powder as well as the substrate. Whereas the porosity is higher, the voids space in the powder bed is higher so the substrate will absorb more laser energy. Furthermore, in all the range of porosity (40-60 %), the maximum absorptivity of powder is less than 0.9 (Fig 6.2-6.6). Absorptivity of the powder-substrate ($A_{ps}$) is calculated from Eq.4.3 (section 4.2). The fraction of incident laser radiation absorbed by the substrate calculated from Eq.4.4 in (section 4.2) and absorptivity of the powder is represented as ($A_p$) in Eq.4.5 (section 4.2).

It is noted that at 40 % porosity the maximum absorptivity of powder is less than 0.825 (Fig.6.2). The fraction of incident laser radiation absorbed by the substrate decreases with the optical thickness of the powder layer (Fig 6.3). Whereas the fraction absorbed in the powder ($A_p$) increases with lower optical depth. Hence the total absorptivity of the powder-substrate ($A_{ps}$) is found to be considerably increased. Moreover, in lower optical depth, the absorptivity of the powder is high as the optical thickness depends on the absorptivity of the dense material ($1−\rho =0.3$). At different percentage of porosity, the total absorptivity as well as powder and substrate absorptivity is found out and represented.

For powder, at low optical depth the absorptivity is high. The optical depth increases as the absorptivity is decreasing. For all the percentage levels the phenomena remains the same. When comparing the percentage of porosity, at lower porosity the result shows a higher absorption in powder. Whereas, higher percentage of porosity, the substrate absorbs more heat energy.
6.1.3. WETTING

6.1.3.1. RESULTS

Wettability of the all laser melted specimens were found out and the relation of wetting angle with the interfacial energy ratio has also been investigated. The ratio of wetting angle and interfacial energy for nine laser process parameters were obtained from Eq. 4.19 (Section 4.5). Wetting angle is measured for various process parameters is shown in table 6.2. The relation between wetting angle and the energy densities of different process parameters is represented in Figure 6.7. In which at lower energy density (1 J/mm$^2$ to 4 J/mm$^2$) the wetting angle is found to be high and beyond 4 J/mm$^2$ the wetting angle gradually reduces. Figure (6.8) depicts the effect of energy density on the interfacial energy ratio and it is clearly understood that at lower energy density 1 J/mm$^2$ to 4 J/mm$^2$ the interfacial energy ratio is high, whereas from 5 J/mm$^2$ onwards the interfacial energy ratio becomes less. Figure (6.9) shows the effect of process parameters on wetting phenomena. The result shows that at lower scanning speed of 2.4 m/min, the wetting angle is found to be less and as the scanning speed increases the wetting angle also increases. In addition, at higher laser power of 200 W the wetting angle is higher.
Table 6.2 Wetting angle and interfacial energy for different experimental trials (with L9 Taguchi process parameter window)

<table>
<thead>
<tr>
<th>Trial No</th>
<th>Laser Power W</th>
<th>Laser Speed m/min</th>
<th>Spot Diameter µm</th>
<th>Energy Density J/mm²</th>
<th>Interfacial Energy Ratio τ</th>
<th>Wetting Angle θ⁰</th>
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<td>2.4</td>
<td>300</td>
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<td>2</td>
<td>100</td>
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<td>400</td>
<td>1.785</td>
<td>0.61812</td>
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<td>3</td>
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<td>12</td>
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<td>0.52069</td>
<td>32.4130</td>
</tr>
<tr>
<td>4</td>
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<td>137.3940</td>
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</table>
Fig. 6.7. Energy Density Vs Wetting Angle.
Fig. 6.8. Energy Density Vs Interfacial Energy Ratio.

Fig. 6.9 Effect of process parameters on Wetting angle
6.1.3.2. DISCUSSION

The correlation between wetting angle and the energy densities of different process parameters is witnessed in Fig. (6.7). It is clearly understood that wetting angle increases at the lower energy density level. However it is noted that at lower energy density level, the melting of the powder won’t happen properly which lead to distortion and further cause’s poor wettability. In the case of higher energy density, the amount of energy absorbed by the powders which inducing a larger degree of melting leads to good wettability. Moreover the wetting of the grain boundaries by a continuous liquid film occurs for \( \tau \) (Fig.6.8) less than 0.5(\( \theta < 60^\circ \)) and for values above 0.5, the resistance to cracking increases. Figure (6.8) shows that interfacial energy ratio has an influence on the energy density of the laser. From the Fig (6.8) the interfacial energy ratio remains lower at both higher and lower energy density, this effect is mainly due to the wettability of the powder bed. Figure (6.9) reveals the effect of different process parameters on wetting; it is evident from the results that as the laser power increases wetting angle also increases same as in the case of laser speed. If the laser speed is high due to the pulse separation, the contact on all sides of the droplet becomes solid-liquid in nature. So the wettability is altered primarily because of the speed and pulsing of the laser. However it is noted from the Fig (6.9) higher the beam size the tendency of wettability is very high, this is mainly because of the larger beam which melts the powder particles. For laser melting, a good degree of wetting implies that the molten powder spreads on the substrate or previously melted layer, instead of balling up on its surface. Higher the solid–liquid surface energy, the greater is the tendency to minimize the liquid–solid interface by formation of isolated pockets of liquid instead of continuous melt.

6.1.4. MARANGONI FLOW

6.1.4.1. RESULTS

The two dimensional multi physics simulation of Marangoni flow is carried out using comsol 4.2a software. The parameters used for the simulation is listed in table 6.3. All the nine energy densities have been selected for marangoni convection studies and their multi physics simulation of temperature distribution as well as the isothermal contours is represented in Fig 6.10 (a-p). Two types of Marangoni flow identified during simulation: source flow and solutal flow. The thermal component of
Marangoni flow will lead to a clockwise flow pattern also defined as source flow. Whereas the solutal one does the opposite as defined as converging flow. It is observed that the clockwise thermal component is weaker than the counter clockwise solutal flow.

Table 6.3 Physical properties of SS316L (Ruidi et al. 2010)

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
<th>Region</th>
</tr>
</thead>
<tbody>
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<td>Density (kg/m$^3$)</td>
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<td>Solid</td>
</tr>
<tr>
<td></td>
<td>$7433 + 0.0393T - 1.801 \times 10^{-4}T^2$</td>
<td>Liquid</td>
</tr>
<tr>
<td>Thermal conductivity (W/m-K)</td>
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<td>Solid</td>
</tr>
<tr>
<td>Specific Heat (J/kg-K)</td>
<td>$462 + 0.134T$</td>
<td>Solid</td>
</tr>
<tr>
<td></td>
<td>775</td>
<td>Liquid</td>
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<tr>
<td>Effective Thermal Conductivity (W/m.K)</td>
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<td>Viscosity (kg/m-s)</td>
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<tr>
<td>Thermal expansion co-efficient (1/K)</td>
<td>$17.3 \times 10^{-6}$</td>
<td></td>
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</table>
Fig. 6.10 (a) Temperature distribution during Marangoni convection at 2.5 J/mm²

Fig. 6.10 (b) Marangoni effect at 2.5 J/mm²
Fig. 6.10 (c) Temperature distribution during Marangoni convection at 4.761 J/ mm$^2$

Fig. 6.10 (d) Marangoni effect at 4.761 J/ mm$^2$
Fig. 6.10 (e) Temperature distribution during Marangoni convection at 9.375 J/ mm$^2$

Fig. 6.10 (f) Marangoni effect at 9.375 J/ mm$^2$
Fig. 6.10 (g) Temperature distribution during Marangoni convection at 1 J/ mm$^2$

Fig. 6.10 (h) Marangoni effect at 1 J/ mm$^2$
Fig. 6.10 (i) Temperature distribution during Marangoni convection at 1.785 J/ mm²

Fig. 6.10 (j) Marangoni effect at 1.785 J/ mm²
Fig. 6.10 (k) Temperature distribution during Marangoni convection at 2.142 J/ mm²

Fig. 6.10 (l) Marangoni effect at 2.142 J/ mm²
Fig. 6.10 (m) Temperature distribution during Marangoni convection at 10 J/ mm$^2$

Fig. 6.10 (n) Marangoni effect at 10 J/ mm$^2$
Fig. 6.10 (o) Temperature distribution during Marangoni convection at 8.33 J/ mm$^2$

Fig. 6.10 (p) Marangoni effect at 8.33 J/ mm$^2$
6.1.4.2. DISCUSSION

Temperature distribution during Marangoni convection clearly shows that the melt pool is wider and deeper in nature as represented in Fig 6.10 (a-p). The convection directions are seen that are represented by the arrows taking place in the clockwise direction on the molten metal pool. The convection here is essentially a free convection. The result shows that at higher energy, the melt pool is comparatively bigger and this could be due to higher convection effect (Fig 6.10 f). The isotherms are closely spaced at the heat source as compared to the melt/solid interface. Further, the thermal and solutal gradients could affect the Marangoni flow on the free surface. Here, the thermal component of the Marangoni flow will lead to a clockwise flow pattern (Fig 6.10 (a-p)). This indicates that the sum of the clockwise components is weaker than the counter clockwise solutal Marangoni flow. Over all flow found in this studies are of clockwise flow. However, the flow in such a molten stainless steel pool is very difficult to be determined quantitatively under the present experimental conditions. As the value of surface tension is negative, the higher surface tension of the cooler liquid pool tends to pull the liquid metal away from the centre of the liquid pool, where the liquid metal is hotter and surface tension is lower. Fluid flow on the surface is radially outward. It is also clear that the Marangoni flow influences the flow of the fluid in the specimen and the distribution of temperature. The study shows that the magnitude of the flow mainly depends on the viscosity, surface tension gradient, temperature gradient and thermal diffusion. In addition, the heat flux increases the convection is predominant in the distribution of temperature.
6.1.5. TEMPERATURE DISTRIBUTION

6.1.5.1. RESULTS

In this study, the three dimensional FEA model is developed using ansys 12.0 software to calculate the temperature distribution in the powder bed thickness of 100 μm. Eventually, laser beam moves over a distance of 40 mm along the x axis and irradiates the powder particles. An analytical model is developed for this set of parameters by selecting the specific point at laser scan path on the laser-travelling path to study the history of the temperature with respect to time. The geometry of the FEA model represents a single powder layer (thickness of 100 μm). It is noticed clearly that the temperature distribution occurring in the powder bed after a single pass of laser beam.

The hexahedral mesh structure of powder of dimension is represented in Fig (6.11). The size of the mesh elements is optimized, balancing the demand for simulating precision and computational efficiency. A moving Gaussian heat flux is applied to the ‘x’ direction of the powder bed (Fig.6.12). Given the physical parameters of SS316L and the suitable boundary conditions, the nodal temperature and the time can be calculated in this study. The physical parameters of SS316L has been used to developed a model is shown in Table 6.2. Figure (6.12) shows the distribution of the temperature when the laser beam is travelling along the x-axis on the top surface.
Fig. 6.11. The hexahedral mesh structure
Fig. (6.12) Temperature distribution at power 100 W; laser speed 2.4 m/min; spot diameter 300 µm
Fig. (6.13). Temperature distribution at power 100 W; laser speed 8.4 m/min; spot diameter 400 µm
Fig.(6.14) Temperature distribution at power 100 W; laser speed 12 m/min; spot diameter 500 µm.
Fig. (6.15) Temperature distribution at power 150 W; laser speed 2.4 m/min; spot diameter 400 µm
Fig. (6.16). Temperature distribution at power 150 W; laser speed 8.4 m/min; spot diameter 500 µm.
Fig. (6.17). Temperature distribution at power 150 W; laser speed 12 m/min; spot diameter 300 µm
Fig. (6.18). Temperature distribution at power 200 W; laser speed 2.4 m/min; spot diameter 500 µm
Fig. (6.19). Temperature distribution at power 200 W; Laser speed 8.4 m/min; spot diameter 300 µm
Fig. (6.20). Temperature distribution at power 200 W; laser speed 12 m/min; spot diameter 400 µm
6.1.5.2. DISCUSSION

The numerical simulation was carried out for all the nine parameters as in table 6.3. A moving Gaussian heat flux is applied to the x direction of the powder bed. The temperature distribution at power 100 W; laser speed 2.4 m/min; spot diameter 300 µm represented in Fig (6.12). Current simulation results show the temperature distribution at different time steps. In addition, the range of heat transfer happens after laser irradiation indicates in Fig (6.12). The maximum average temperature attained by the powder bed is 3654 K in the x direction. Time versus temperature graph also noted that the average peak temperature attained by the laser beam is around 3654 K (Fig 6.12).

The highest predicted temperature corresponding to the molten zone of the powder material is 1926 K for power 100 W; laser speed 8.4 m/min and spot diameter 400 µm is represented in Fig (6.13). The drop of maximum temperature can be attributed to the increased conductivity of the previously solidified regions of the track compared to the low thermal conductivity of the powder bed. The thermal field in the powder bed changes as the laser source travels along the track and the melt pool moves along with the laser source. It is further observed from the simulation that the temperature gradient in the front side of the moving laser beam is much steeper than that in the rear side. In Figure (6.13) the melt pool shape resembles as in comet tail profile. This trend of skewed temperature distribution towards the rear of the laser was also observed by many researchers (Patil et al. 2007, Hussein et al. 2013, Islam et al. 2013). This can be attributed to the fact that the rapidly cooling molten material has greater conductive properties than the untreated powder in front of the laser.

At laser power 100 W; Laser speed 12 m/min and spot diameter 500 µm, the maximum average temperature obtained by the powder bed is 1240 K (Fig 6.14) which is insufficient to melt SS316L. Hence a insignificant melt occurs over the melted track. Furthermore, the time versus temperature profile which indicates the temperature attains at the maximum at a sudden which can be the cause of insignificant melt. This is mainly because of the higher laser speed which reduce the melting solidification time, thus the proper melting won’t happen.

Temperature distribution at Power 150 W, Laser speed 2.4 m/min and Spot diameter 400 µm obtained a maximum average temperature of 3692 K (Fig 6.15). It is noted
that, this set of parameters the track is found to be continuous and smooth. From the result it is observed that the laser beam moves at particular point at particular time, the temperature rises rapidly (3692 K) due to a high density of the laser power. Furthermore, after the laser beam moves away from this point, the temperature descends slowly 2063 K. This temperature changes could be due to the result of heat loss by conduction, irradiation, and convection.

At power 150 W, laser speed 8.4 m/min and spot diameter 500 μm, the numerical simulation shows a maximum average temperature of 2000 K and a minimum average temperature of 688 K (Fig 6.16). The temperature distribution throughout the melted track produces insignificant melt due to the over melting of the powder particles. Time versus temperature graph (Fig 6.16) shows the temperature distribution at different time steps.

Whereas at laser power 150 W, laser speed 12 m/min and spot diameter 300 μm the numerical result shows a maximum average temperature of 3537 K and minimum average temperature of 662 K (Fig 6.17). At these process parameters the track is found to be continuous with irregularities.

Temperature distribution at power 200 W, laser speed 2.4 m/min and spot diameter 500 μm, the simulation result shows that the maximum temperature attains 3500 K (Fig 6.18). Thus a melted layer with distortion happened in these process parameters. Figure (6.19) represents the temperature distribution of laser heat flux when keeping the laser power 200 W, laser speed 8.4 m/min, and spot diameter 300 μm. The track found to be more distortion and this could be due to rapid changes of temperature with respect to time is also represented.

The graph indicates the temperature versus time graph during laser melting process of distance 40 mm in x axis direction (Fig 6.19). It is observed that the maximum peak temperature is 5057 K at particular point at particular time. Whereas the laser beam moves away from this point, the temperature reduced rapidly to 1888 K. From the results it is clear that the energy becomes insufficient to melt the substrate, and the stabilizing effect of the contact zone (penetration into substrate) disappears. If energy is enough to maintain the boiling and evaporation of the molten powder, the vapour recoil pressure causes distortion of the melted tracks as suggested by Yadroitsev et al. (2010).
Finally temperature distribution at power 200 W, laser speed 12 m/min and spot diameter 400 µm indicates the temperature distribution of the powder bed after laser heat flux irradiation (Fig 6.20). The maximum peak temperature attained by the powder bed is 3044 K which is far more than the melting temperature of stainless steel powder.

6.2. RESULTS AND DISCUSSION: EXPERIMENTATION

Results and discussions are presented together for all the set of experiments performed according to Taguchi L9 orthogonal array. This thesis includes a series of scan tracks which were made by scanning the first layer of SS 316L powder on a stainless steel AISI 316L substrate.

6.2.1. PARTICLE SIZE DISTRIBUTION

6.2.1.1. RESULTS

Initially the particle size distribution analysis has been performed on SS 316L powder with laser particle size analyzer. The results represented in Fig (6.21) shows that particle size of the given powder is in the range of 15-20 µm. The SEM morphology of the SS316L powder particle and it is regular spherical shapes is shown in Fig (6.22).

6.2.1.2. DISCUSSION

Initially the particle size distribution analysis has been performed on SS 316L with laser particle size analyzer and the particle size is in the range of 15-20µm is represented in Fig (6.21). Finer powder particle have higher absorptivity than coarser particle. The observation of the powders in SEM shows that the particles had a spherical morphology with dendritic structure (Fig 6.22). The 10 to 20 µm 316L powder had the highest surface area to volume ratio, so inter-particle friction would be the highest and the density was the lowest.
Fig 6.21. Particle size distribution for SS 316L powder

Fig 6.22. Scanning electron microscopic image of SS316L
6.2.2. LASER MELTING PROCESS

6.2.2.1. RESULTS

Investigation of formation of the single tracks is a focus of this current research. Different tracks of SS 316 L powder on an AISI 316L substrates were produced successfully by designing the process parameters with Taguchi L9 orthogonal array system (Table 6.4). According to the L9 orthogonal array process parameters were optimized and the laser melting process was carried out for all the nine process parameters. The repeatability has been confirmed by tracking three trials for each set of parameters. Nine single layer track were made and the all the tracks were having its own geometric characteristics.

6.2.2.2. DISCUSSION

Initially, the stainless steel powder was spread over the substrate and maintaining the thickness of 100µm using scraper blade. Stainless 316L steel powders were preheated at 800 °C for 60 s and Nd: YAG pulsed laser JK 300P (UK) of pulse duration 0.6 ms was used for single track formation by varying the laser power, scanning speed and spot diameter. Laser melting was carried out with nine different process parameters and the single track was made and the geometric characteristics of the track gave an insight how the process parameters directly affects the laser melting process.

Table 6.4. The selected process parameters for laser melting for making single layer track.

<table>
<thead>
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</tr>
<tr>
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<td>200</td>
<td>12</td>
<td>400</td>
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</tbody>
</table>
6.2.3. XRD ANALYSIS

6.2.3.1. RESULTS
In order to investigate the phase evolution of 316L stainless steel powders as the part of the work were analyzed by XRD patterns is represented in Fig (6.23). The peaks in the graph represent the major constituent in the sample. Mainly three major peaks are visible from the Fig (6.23).

6.2.3.2. DISCUSSION
Figure (6.23) shows the XRD patterns obtained at the surface of the samples, three major peaks are clearly visible from the graph, the major peaks indicates the Fe, Cr, and Ni which also supported by Montasser (2012). The phase evolution of 316L stainless steel powder was obtained by XRD analysis at the surface of the samples. The major peaks indicate the dominance of Fe, Cr and Ni.

Fig.6.23. XRD pattern of SS316L powder
6.2.4. FTIR ANALYSIS

6.2.4.1. RESULTS

Fourier transform infrared spectrum analysis for un-melted stainless steel 316L powder is shown in Fig (6.24). The spectrum band ranges shows the range of materials present in the samples.

6.2.4.2. DISCUSSION

From the results it is observed that the band ranges from 3250 cm\(^{-1}\) to 3750 cm\(^{-1}\) resembles the Fe content in the un-melted powder which is the main composition in the SS316L. In addition, it is also noticed from the FTIR analysis, the absence of O\(_2\) further confirmed that there is no oxidation on the un-melted powder. This result is further supported by the researchers (Bavya et al. 2011 and Wiria et al. 2007).

![FTIR analysis](image)

Fig. 6.24. FTIR analysis in pre-melted SS 316L powder on AISI 316L substrate
6.2.5. MACRO STRUCTURAL ANALYSIS

6.2.5.1. RESULTS

The macrograph of single track formation of SS 316L powder on SS 316L substrate is represented for all the nine process parameters (Fig 6.25). Macrostructure shows that each track produced by the laser process parameters having unique geometrical characteristics. The geometric characteristics of the laser melted track like smoothness, irregularities, distortion and balling effect were visible from Figure (6.25).

6.2.5.2. DISCUSSION

The balling effect was identified while keeping low laser power, scanning speed and spot diameter which is evident from Fig (6.25 a, b). The same effect was also observed when using the higher laser power, scanning speed and spot diameter (Fig 6.25 i). It could be due to the indirect interaction by heat conductivity of the substrate and the decreases in convection phenomena. Furthermore the amount of powder involved in the process of track formation diminishes and the penetration into the substrate is almost absent (Fig 6.25 e). This induced balling effect extensively influences the kinetic and thermodynamic characteristics during melting may result in the formation of discontinuous scan tracks as suggested by many researchers ( Gu et al. 2007, Yadroitsev et al. 2009, 2010, Maeda and Childs 2004, Rehme and Emmelmann 2006).

Das et al. (2003) reported that the balling problem is more likely to occur during laser melting of SS powder due to a contamination layer of oxide being present on the surfaces of SS melt. It is also observed that there is insignificant melt in the track when keeping low laser power at high scanning speed is represented in Fig (6.25 c). This may be due to the laser power which is insufficient to melt the powder and to create a molten pool of the powder particle on the substrate.

In addition there is some distortion was noticed when keeping the high laser power and scanning speed (Fig 6.25 g, h). This is could be due to the heat sink into the substrate diminishes which leads the molten pool of particle become overheating and the tracks turn into unstable and irregular shape. The continuous smooth layer was observed when keeping the medium laser power, scanning speed and spot diameter is indicated in Fig (6.25 f, d).
Figure 6.25. The macrograph of single track formation of SS 316L powder on SS 316L substrate

- (a) P 100 W; V 2.4 m/min; d 300 µm
- (b) P 100 W; V 8.4 m/min; d 400 µm
- (c) P 100 W; V 12 m/min; d 500 µm
- (d) P 150 W; V 2.4 m/min; d 400 µm
- (e) P 150 W; V 8.4 m/min; d 500 µm
- (f) P 150 W; V 12 m/min; d 300 µm
- (g) P 200 W; V 2.4 m/min; d 500 µm
- (h) P 200 W; V 8.4 m/min; d 300 µm
- (i) P 200 W; V 12 m/min; d 400 µm
6.2.6. MICRO STRUCTURAL ANALYSIS

6.2.6.1. RESULTS
The transverse section of laser melted track has been analysed using optical microscope as ascribed the laser parameters influencing the re melted zone (Fig 6.26 a-f). From the results it was observed that the laser power and the scanning speed strongly influence the re-melted depth.

6.2.6.2. DISCUSSION
It can be seen that, with the increase of laser speed, the re melted depth is gradually reduced and found to be the balling effect, the balling problem is more likely to occur during laser melting of stainless steel powder due to a contamination layer of oxide being present on the surfaces of stainless steel melt. Furthermore, the wetting angle between substrate and molten pool is increased, showing deteriorative wetting condition leads to balling effect (Fig 6.26 d-f). Moreover, the re-melted depth is increased and found to be continuous regular track when keeping the optimum process parameters (Fig 6.26 a-c). Furthermore this result also supported by the other researchers (Ruidi et al. (2010,2011), Jinhui et al. 2010, Dongdong et al. 2009, Das et al. 2003).
Fig 6.26. The micrograph of single track formation of SS 316L powder on SS 316L substrate
(a) P 150 W; V 12 m/min; d 300 µm; (b) P 200 W; V 2.4 m/min; d 500 µm; (c) P 200 W; V 8.4 m/min; d 300 µm
(d) P 100 W; V 2.4 m/min; d 300 µm; (e) P 100 W; V 8.4 m/min; d 500 µm; (f) P 150 W; V 8.4 m/min; d 500 µm
6.2.7. SEM MORPHOLOGY

6.2.7.1. RESULTS

The SEM morphology of laser melted track is shown in Fig (6.27 a-g) which indicates the effect of laser process parameters on the laser track. Figure (6.28 a-c) shows the cross section of the single track having continuous and smooth surface. The re-melted zone was found out from the cross sectional SEM analysis. SEM morphology revealed that the effect of laser power, scanning speed and spot diameter which has major effect on the morphology of the laser melted track.

6.2.7.2. DISCUSSION

The SEM surface morphology was inferred that the decrease of the scanning speeds, the heat affected zone becomes larger involving more powder from the vector boundaries and the single layer track causes distortion and irregularities (Figure 6.28 a-c). From the results, it is observed that at a laser power of 150 W and scanning speed 2.4 m/min the scan track section showed a hump shape combined with a powder particle cohered and found to be well defined zone of consolidation (Fig 6.28 a, b). It was caused by the sufficient liquid spreading ability of molten powder on metal substrate.

1. TRACK WIDTH

RESULTS

Track width of the laser melted specimens depends on the laser process parameters. From the SEM the track width is found to be very clear. The SEM surface morphology of the single track indicates the width varied from 193.569 µm to 504.143 µm with respect to different process parameters. Maximum track width of 500 µm obtained at laser power 150 W; laser speed 2.4 m/min and spot size of 400 µm. Minimum track width of 193.569 µm got at laser power 150 W; laser speed 12 m/min and spot diameter of 300 µm. Table 6.5 represents the track width of all laser melted specimens.

DISCUSSION

The SEM results showed that the track width mainly depends on spot diameter of the beam and laser power is represented in Fig 6.28. It is evident from the graphical representation (Fig 6.29) that the track width increased at higher laser power and laser speed. This could be the reason that for the given laser powers the volume of the
molten powder is higher at lower scanning speeds due to higher temperature as reported by Grigoriev et al. (1991). The SEM results of laser power 150 W and scanning speed 2.4 m/min the scan track section showed a hump shape combined with a powder particle cohered and found to be well defined zone of consolidation (Fig 6.28 a, b). It was caused by the sufficient liquid spreading ability of molten powder on metal substrate. Whereas at 200 W with medium scan speed of 8.4 m/min, the size of scan track section was noticeably increased is represented in Fig (6.28 c). In addition, wide track width was observed at an enhanced laser power.

2. TRACK HEIGHT

RESULTS
The experimental measurement of the track height mentioned in Table (6.5). The results indicate the influences of the process parameters on the track height. The track height of the laser melted specimens is revealed in Fig (6.27). The maximum track height attained was 96.121 µm and the minimum track height attained was 42.833 µm.

DISCUSSION
In laser melting process, with increase of scan speed, the molten pool of powder become spread on the substrate, coupled with an increased track height. This could be due to the different melting conditions of molten pools under varied scan speeds and laser power were also attributed to the different energy input. The measured track height including all experimental data is mentioned in table 6.4.
Table 6.5. Experimental description on laser melted track

<table>
<thead>
<tr>
<th>Sl No</th>
<th>Laser Power W</th>
<th>Scan Speed m/min</th>
<th>Spot Dia µm</th>
<th>Energy Density J/mm²</th>
<th>Track Height µm</th>
<th>Deviation %</th>
<th>Track Width µm</th>
<th>Wetting Angle ϴ°</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>100</td>
<td>2.4</td>
<td>300</td>
<td>8.33</td>
<td>59.027</td>
<td>40.973</td>
<td>403.179</td>
<td>35.804</td>
<td>Non continuous track causes large semi circle droplets</td>
</tr>
<tr>
<td>2</td>
<td>100</td>
<td>8.4</td>
<td>400</td>
<td>1.785</td>
<td>72</td>
<td>28</td>
<td>376.261</td>
<td>72.023</td>
<td>Non continuous track causes small semi circle droplets</td>
</tr>
<tr>
<td>3</td>
<td>100</td>
<td>12</td>
<td>500</td>
<td>1</td>
<td>42.833</td>
<td>57.167</td>
<td>252.335</td>
<td>32.413</td>
<td>Non continuous track with non significant melt</td>
</tr>
<tr>
<td>4</td>
<td>150</td>
<td>2.4</td>
<td>400</td>
<td>9.375</td>
<td>77.288</td>
<td>22.712</td>
<td>504.143</td>
<td>24.936</td>
<td>Continuous and smooth track</td>
</tr>
<tr>
<td>5</td>
<td>150</td>
<td>8.4</td>
<td>500</td>
<td>2.142</td>
<td>72.764</td>
<td>27.236</td>
<td>333.353</td>
<td>34.653</td>
<td>Non continuous track with improper melt condition</td>
</tr>
<tr>
<td>6</td>
<td>150</td>
<td>12</td>
<td>300</td>
<td>2.5</td>
<td>96.121</td>
<td>3.879</td>
<td>193.569</td>
<td>35.268</td>
<td>Continuous track with minor irregularity</td>
</tr>
<tr>
<td>7</td>
<td>200</td>
<td>2.4</td>
<td>500</td>
<td>10</td>
<td>79.434</td>
<td>20.566</td>
<td>342.053</td>
<td>28.918</td>
<td>Continuous track with minor distortion</td>
</tr>
<tr>
<td>8</td>
<td>200</td>
<td>8.4</td>
<td>300</td>
<td>4.761</td>
<td>73.845</td>
<td>26.155</td>
<td>357.006</td>
<td>58.325</td>
<td>Continuous track with distortion</td>
</tr>
<tr>
<td>9</td>
<td>200</td>
<td>12</td>
<td>400</td>
<td>2.5</td>
<td>80.081</td>
<td>19.919</td>
<td>318.057</td>
<td>137.394</td>
<td>Non Continuous track with large droplets</td>
</tr>
</tbody>
</table>
Fig 6.27 (a) Laser power: 100 W; Laser speed: 2.4 m/min; Spot diameter: 300 µm

Fig 6.27 (b) Laser power: 100 W; Laser speed: 8.4 m/min; Spot diameter: 400 µm
Fig 6.27 (c) Laser power: 150 W; Laser speed: 2.4 m/min; Spot diameter: 400 µm

Fig 6.27 (d) Laser power: 150 W; Laser speed: 8.4 m/min; Spot diameter: 500 µm
Fig 6.27 (e) Laser power: 200 W; Laser speed: 2.4 m/min; Spot diameter: 500 µm

Fig 6.27 (f) Laser power: 200 W; Laser speed: 8.4 m/min; Spot diameter: 300 µm
Fig 6.27 (g) Laser power: 200 W; Laser speed: 12 m/min; Spot diameter: 400 µm
Fig 6.28 (a) Laser power: 150 W; Laser Speed: 2.4 m/min; Spot diameter: 400 µm

Fig 6.28 (b) Laser power: 150 W; Laser Speed: 12 m/min; Spot diameter: 300 µm
Fig 6.28 (c) Laser power: 200 W; Laser Speed: 8.4 m/min; Spot diameter: 300 µm

![Track Width Image](image)

Fig 6.29. Track width Vs Process parameters
3. WETTING ANGLE

RESULTS

Wetting angle for the all laser melted samples were observed and the results gave an in depth idea on how the laser process parameters affect the wettability of the track. Minimum wetting angle of 24.936° found out for laser power 150 W; laser speed 2.4 m/min and spot diameter of 400 µm. Maximum wetting angle of 137.394° obtained for laser power 200 W; laser speed 12 m/min and laser spot diameter of 400 µm.

DISCUSSION

The results show that the wetting angles are mainly depends on the scanning speed of the laser. From the results it is noticed that the wetting angle is lower when scanning speed is minimum. Whereas it increases at higher scanning speed (Figure 6.22 g). It is also noted that this molten track with high wetting angle indicates the poor wetting ability. In addition, the flow ability became better and the corresponding wetting angle was reduced when keeping high laser power. Many researchers reported that the different wetting features of molten pools under varied laser powers. This could be understood by considering the correction between laser power and laser-induced liquid viscosity (Agarwala et al. 1995, Kruth et al. 2004, Apinyaet al. 2012). The laser power input is the deciding parameters with respect to liquid viscosity. The higher laser power could facilitate an enhanced laser energy input which leads to superior melting temperature. This leads to favourable wetting, spreading which results a formation of big-sized molten pool (Figure 6.23 b).

6.2.8. EDX ANALYSIS

6.2.8.1. RESULTS

The EDX analysis for all the samples was performed at the cross section of the samples and the results are shown in Figures (6.30 a-e). Figure (6.30 a) shows the EDX results for the track employed using laser power: 100 W; laser speed: 2.4 m/min; spot diameter: 400 µm. this shows that all the major composition of SS316L Fe, Ni and Cr and Mn are present with acceptable weight percentage. In addition, the percentage of chemical composition is more or less the same as the SS316L (Fig 6.30 a-c). However at laser power of 200 W the percentage of chromium is comparatively lower than of laser powers 100 W and 150 W (Figures 6.30 d, e).
Fig 6.30 (a) Laser power: 100 W; Laser Speed: 2.4 m/min; Spot Diameter: 400 µm

Fig 6.30 (b): Laser power: 100 W; Laser Speed: 12 m/min; Spot Diameter: 500 µm
Fig 6.30 (c): Laser power: 150 W; Laser Speed: 2.4 m/min; Spot Diameter: 400 µm

Fig 6.30 (d): Laser power: 200 W; Laser Speed: 2.4 m/min; Spot Diameter: 500 µm
Fig 6.30 (e): Laser power: 200 W; Laser Speed: 8.4 m/min; Spot Diameter: 300 µm
6.2.8.2. DISCUSSION

The EDX analysis of the samples in the melted zone is represented in Fig 6.30 (a-e). The results clearly indicates that there is no major changes in the chemical composition after melting and very less percentage of oxidation witnessed during laser melting. Whereas at higher laser power the percentage of major constituents is lower and this can be due to the evaporation phenomenon during laser melting process. The higher laser power will evaporate the elements in the melt pool. The increase in chromium and nickel maintains the austenitic structure of the melted layer and it will improve the mechanical properties of the melted layer.

6.2.9. SURFACE ROUGHNESS ANALYSIS

6.2.9.1. RESULTS

Continuous tracks were selected for finding out the surface roughness of the laser melted process and the results are shown in Fig 6.31 (a-c). It is noted that the track employed by laser power 150 W; laser speed 2.4 m/min and spot diameter 400 µm, the surface roughness attained is 1.056 µm. Whereas at laser power 150 W; laser speed 12 m/min; spot diameter 300 µm, it is recorded that value of Rₐ is 1.6901 µm. Also by keeping laser power of 200 W; laser speed 2.4 m/min and spot diameter 500 µm, surface roughness was 1.927 µm.

6.2.9.2. DISCUSSION

During laser melting process the surface roughness in the horizontal surface is generated by the rippling effect. When the laser travels from one point to another there is a temperature gradient between the laser beam and the solidifying zone, a shear force is generated on the liquid surface that is contrasted by surface tension forces. However, due to quick melt pool solidification time, the relaxation process is often not fully achieved; instead a residual rippling on the surface is formed. However, it is possible to reduce the roughness generated by rippling effect, by surface re-melting. The final surface roughness depends on the initial surface roughness, thus, the single track surface roughness studies help us to get the better understanding Figure.(6.36 a) at laser power 150 W; laser speed 2.4 m/min and spot diameter 400 µm shows very minimum surface roughness.
Fig. 6.31 (a) P 150 W; V 2.4 m/min; d 400 µm

Fig. 6.31 (b) P 150 W; V 12 m/min; d 300 µm

Fig. 6.31 (c) P 200 W; V 2.4 m/min; d 500 µm
6.3. COMPARISON WITH EXPERIMENTAL

From the numerical results it is observed that temperature distribution at power 100 W; laser speed 2.4 m/min; spot diameter 300 µm, the temperature involved in the powder is 3654 K. The experimental results revealed that large semicircle droplets formed over the melted track is witnessed in Fig (6.25 a). Temperature distribution at power 100 W; laser speed 8.4 m/min spot diameter 400 µm, the maximum average temperature obtained is 1926 K (Fig 6.13) which produces small semicircle droplets in the single track (Fig 6.25 b). At laser power 100 W, laser speed 12 m/min and spot diameter 500 µm the maximum average temperature obtained by the powder bed is 1240 K (Fig 6.14) which is insufficient to melt SS316L, balling phenomena is clearly visible thus an insignificant melt occurs over the melted track as shown in Fig (6.25 c). Temperature distribution at power 150 W, laser speed 2.4 m/min and spot diameter 400 µm (Fig 6.15) obtained a maximum average temperature of 3692 K. These process parameters gave a continuous and a smooth track as is evident from Figure 6.25 (d). From the experimental results the tracks which produce discontinuous as well as large droplets have τ more than 0.5 and θ more than 60° (Table 6.1). During wetting process the adhesion between the solid and liquid is greater than the cohesive force of the liquid. The comparison of results obtained from experimental and simulated geometry characteristics of the single track is represented in Fig (6.32 a-b). The simulated track width having good agreement with the experimental track width is witnessed in Figure (6.32a). However, it is noted that experimentally measured track height (Fig 6.32.b) was found to undergo thermal shrinkage and densification compared to simulated values as evident from Figures. (6.33 a-f).
Fig. 6.32.(a) Comparison of experimental and simulated Track width.

Fig. 6.32.(b) Comparison of experimental and simulated Track height.
Fig. 6.33. Numerical versus Experimental comparison of the cross section of single track formation of SS 316L powder on SS 316L substrate. (a) P 150 W; V 12 m/min; d 300 µm; (b) P 200 W; V 2.4 m/min; d 500 µm; (c) P 200 W; V 8.4 m/min; d 300 µm; (d) P 100 W; V 2.4 m/min; d 300 µm; (e) P 100 W; V 8.4 m/min; d 500 µm; (f) P 150 W; V 8.4 m/min; d 500 µm.