<table>
<thead>
<tr>
<th><strong>Title</strong></th>
<th>Thermal fluid modelling of selective laser melting</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Author(s)</strong></td>
<td>Tan, Jie Lun; Tang, Chao; Wong, Chee How</td>
</tr>
<tr>
<td><strong>Date</strong></td>
<td>2018</td>
</tr>
<tr>
<td><strong>URL</strong></td>
<td><a href="http://hdl.handle.net/10220/45918">http://hdl.handle.net/10220/45918</a></td>
</tr>
<tr>
<td><strong>Rights</strong></td>
<td>© 2018 Nanyang Technological University. Published by Nanyang Technological University, Singapore.</td>
</tr>
</tbody>
</table>
ABSTRACT: Selective Laser Melting (SLM) has been increasingly popular in producing metal parts in the manufacturing industry. Its flexibility in printing complex shapes has given it an advantage over conventional manufacturing methods. There are many experimental studies conducted to obtain the optimized parameters for different materials. By varying parameters such as laser power and scanning speed, it will affect the energy density on the powder bed, hence affecting the quality of the part. Since there are many parameters in the SLM process, it will take numerous experiments to determine the optimized parameters. Numerical modelling can be introduced to study the melting of the powders during SLM. The Marangoni force and recoil pressure play important roles in replicating the laser melting process. This paper will discuss on the effects on these two factors and the importance of their inclusion in the model.

KEYWORDS: Selective laser melting, modelling, recoil pressure, Marangoni force

INTRODUCTION
Additive Manufacturing (AM) is the process of fabricating a 3D part from a Computer Aided Design (CAD) file by building layer upon layer (ASTM, 2015). It has seen applications in the automotive, aerospace as well as medical industries (Chua, Yeong, & Wong, 2017; Lim, Le, Lu, & Wong, 2016). Selective Laser Melting (SLM) is one of the methods of AM which uses a powder bed fusion technology. A layer of powder with predefined thickness will be recoated on the substrate, and the laser will proceed to melt the powders at the selected regions according to the sliced CAD files. Once the laser completes the scanning of the top layer, the platform will be lowered according to the layer thickness and a fresh layer of powder is deposited. This process will continue until the 3D part is completed (Tang, Li, & Wong, 2014; Gan & Wong, 2016a; Tan & Wong, 2016).

In SLM, there are numerous parameters which can affect the quality of the printed part (Yadroitsev, Bertrand, & Smurov, 2007; Gan & Wong, 2016b; Gan & Wong, 2017). There are many methods to determine the quality of the printed part (Lu & Wong, 2017; Lu & Wong, 2018). However, they could be time consuming and costly and modelling can help tackle these issues. Since SLM is a multi-physics process, there are many factors to consider when building the model. Two important...
factors in the model are the recoil pressure and Marangoni force. In laser processes, the temperature of the metal can reach well over its boiling point. This will cause the metal to vaporize, and exert a pressure on the surface of the molten metal known as the recoil pressure (Semak & Matsumawa, 1997), leading to the formation of a keyhole as reported in experiments (Fabbro, 2010). In SLM, the rapid cooling of the melt track will cause a large temperature gradient between the trailing and leading ends of the track. In turn, this will produce a large surface tension gradient and affect the flow of the molten metal (Lu, Fujii, & Nogi, 2004). This is known as the Marangoni effect. This paper aims to study the effects of recoil pressure and Marangoni force on the characteristics of the melt track.

**METHODOLOGY**

To model the deposition of the powders, a Discrete Element Method (DEM) software, LIGGGHTS®, was used. The powders follow a Gaussian distribution with mean diameter of 27 μm, and were deposited on a surface of 200 × 1000 μm. The coordinates and radius of the powders were exported into a Computational Fluid Dynamics (CFD) software. The software, OpenFOAM®, was used to simulate the laser melting process of SLM. In the model, the Volume Of Fluid (VOF) method approach was used to determine the composition of metal and gas. \( \alpha_1 \) represents the metallic phase and \( \alpha_2 \) represents the gas phase. When the mesh has a value of \( \alpha_1 = 1 \), it means that the mesh consists solely of the metallic phase. Similarly, when the mesh gives \( \alpha_2 = 1 \), it means that there is only gas phase in that mesh. The mesh size used in the simulations is 2.5 μm. The relationship between \( \alpha_1 \) and \( \alpha_2 \) is given in Equation 1 (Qiu, et al., 2015)

\[
\alpha_1 + \alpha_2 = 1
\]

In the metallic phase, the liquid fraction method was applied to distinguish if the metal is in solid phase or liquid phase (Rösler & Brüggemann, 2011). This is represented by \( \gamma \) which ranges from 0 to 1. When the metal is in solid state, \( \gamma \) will give a value of 0. When the metal is in liquid state, \( \gamma \) will give a value of 1. Values of \( \gamma \) between 0 and 1 will mean the metal is in a molten state.

**Governing Equations**

The metal was assumed to be an incompressible fluid in its molten state, therefore its continuity equation representing the conservation of mass is given as

\[
\nabla \cdot \bar{u} = 0
\]

where \( \bar{u} \) represents the velocity vector of the flow. Next, the Navier-stokes equation includes the forces present in the SLM process such as surface tension, Marangoni force and recoil pressure. This gives the conservation of momentum equation (Panwisawas, et al., 2017)

\[
\frac{\partial \rho \bar{u}}{\partial t} + \nabla \cdot (\rho \bar{u} \otimes \bar{u}) = -\nabla p + \nabla \cdot (\rho \bar{u} \otimes \bar{u}) + \rho g \hat{z} \beta (T - T_{ref}) - K_c \left[ \frac{(1 - f_i)^2}{f_i^3 + C_i} \right] \bar{u} + \left( \sigma \bar{u} + \frac{d \sigma}{dt} \right) (\nabla - \bar{u} \cdot \nabla T) + p_v \left[ \alpha_i \left( \frac{2 \rho}{\rho_{metal} + \rho_{air}} \right) \right]
\]

where \( \rho \) is the density, \( \mu \) is the viscosity, \( t \) is the time, \( T \) is the temperature, \( T_{ref} \) is the reference temperature, \( p \) is pressure, \( g \) is gravitational acceleration, \( p_v \) is the recoil pressure, \( \hat{z} \) is the unit normal to the gravitational force, \( \beta \) is the thermal expansion coefficient, \( K_c \) is the permeability
coefficient, \( f_i \) is the fraction of liquid metal, \( C_k \) is a constant to avoid division by zero, \( \sigma \) is the surface tension, \( \kappa \) is the surface curve normal to \( \hat{n} \). In equation 3, the three surface force terms are surface tension, The Marangoni force is defined by \( \sigma k \hat{n} \cdot \frac{d\sigma}{dt} [VT - \hat{n}(\hat{n} \cdot VT)] \), while the recoil pressure, \( p_v \), is defined as

\[
p_v = 0.54 p_0 \exp \left( \frac{\Delta H_{LV} \left( T - T_{LV} \right)}{RTT_{LV}} \right)
\]  

(4)

where \( p_0 \) is the atmospheric pressure, \( \Delta H_{LV} \) is the latent heat of vaporization, \( R \) is the universal gas constant, and \( T_{LV} \) is the boiling temperature at atmospheric pressure.

The energy conservation equation is given in Equation 5. It takes into account the heat loss from conduction, convection, evaporation and radiation as well as heat input from the laser beam.

\[
\frac{\partial \tilde{\rho} \tilde{C}_p T}{\partial t} + \nabla \cdot (\tilde{\rho} \tilde{u} \tilde{C}_p T) = -\frac{\partial \tilde{\rho} \Delta H_f}{\partial t} - \nabla \cdot (\tilde{\rho} \tilde{u} \Delta H_f) + \nabla \cdot (\tilde{k} \nabla T) \nonumber \\
- \left[ k \left( T - T_{ref} \right) + \sigma_\varepsilon \left( T^4 - T_{ref}^4 \right) + Q_v \right] \left[ \frac{2 \tilde{C}_p \tilde{\rho}}{C_{p,metal} \rho_{metal} + C_{p,w} \rho_{w}} \right] + Q_T
\]  

(5)

where \( \tilde{C}_p \) is the specific heat, \( \Delta H_f \) is the enthalpy change due to fusion, \( \tilde{k} \) is the thermal conductivity, \( h_c \) is the heat transfer coefficient, \( \sigma_\varepsilon \) is the Stefan-Boltzmann constant, \( \varepsilon \) is the emissivity, \( Q_v \) is the heat loss from evaporation and \( Q_T \) is the heat source from laser beam. The laser beam follows a Gaussian distribution (Teng, et al., 2016). The laser beam power used was 200 W with a scanning speed of 2 m/s for all simulations.

RESULTS AND DISCUSSIONS

In the first simulation, the effects of recoil pressure and Marangoni force were neglected. Fig. 1 shows the top view and cross-section of the track. In Fig. 1 (a), the track was observed to be relatively flat throughout. Further observation of the cross-section of the track in Fig. 1 (b) shows that the melt pool at the center of the laser beam did not have a keyhole. Instead, it has a melt height of 10 \( \mu \)m. Fig. 1 (b) and (c) shows the melt pool geometry did not change as the scanning progressed with the melt pool having a plateau cross-section. (c). From this simulation, it can be observed that the powders are melted with the laser beam and the molten metal solidified at the spot they were melted.

![Fig. 1 Melt track without recoil pressure and Marangoni force (a) top view, (b) cross-section of melt track at center of laser beam at y = 870 \( \mu \)m, (c) cross-section of solidified melt track at y = 500 \( \mu \)m](image-url)

559
For the second simulation, the recoil pressure was considered while neglecting the effects of Marangoni force. Fig. 2 (a) shows a keyhole formed at the position of laser beam which was absent in the first simulation. Fig. 2 (b) shows the cross-section of the keyhole. The melt pool’s depth was observed to be deeper than that in Fig. 1 (b). When there is recoil pressure, the molten metal will be pushed away from the center of the laser beam and will allow for more melting of the metal, generating a deeper melt pool. The cross-section of the melt track observed in Fig. 2 (c) was smaller when compared to Fig. 1 (c). As the laser moves away from the keyhole, molten metal from the sides of the keyhole will fill up the keyhole. The absence of Marangoni force means there is no molten metal flowing from the leading edge of the track to the trailing edge of the track, resulting in a smaller cross-section of the track.

![Fig. 2 Melt track with recoil pressure but without Marangoni force](image)

In the third simulation, the Marangoni force was included while neglecting the effects of recoil pressure. In Fig. 3 (a), the top surface of the melt tracks was observed to have more ripples when compared to Fig. 1 (a). This is due to the flow of the molten metal towards the trailing edge of the melt pool due to Marangoni force. Fig. 3 (b) shows a shallow keyhole. This is a result of the flow of the molten metal away from the region where the laser beam was due to Marangoni force. This shows that the recoil pressure plays a more significant role than Marangoni force in determining the characteristics of the keyhole. The height of the melt track in Fig. 3 (c) was greater than that in Fig. 2 (c). The flow of material towards the rear of the melt track will affect the melt pool’s characteristics such as its height and width. This will improve the accuracy of the model when comparing the melt tracks’ dimensions of the model and experiments.
Fig. 3 Melt track without recoil pressure but with Marangoni force (a) top view, (b) cross-section of melt track at center of laser beam at $y = 870 \, \mu m$, (c) cross-section of solidified melt track at $y = 500 \, \mu m$

In the fourth simulation, recoil pressure and Marangoni force were included in the model. From Fig. 4 (a), there is a keyhole at the leading edge of the track and ripples caused by the recoil pressure and Marangoni force respectively. In Fig. 4 (b), the cross-section of the keyhole shows a thinner film of molten metal when comparing with Fig. 2 (b). It is due to the Marangoni force which aids the flow of molten metal away from the keyhole due to the surface tension gradient. In Fig. 4 (c), the cross-section of the track shows similar shape as compared to that in experiments by Yadroitsev et al. (Yadroitsev, Gusarov, Yadroitsava, & Smurov, 2010). Comparing the cross-sections of all four simulations, the cross-section of the model which includes recoil pressure and Marangoni force prove to closely resemble that in experiments. This shows the important of these two forces when modelling SLM process.

Fig. 4 Melt track with recoil pressure and Marangoni force (a) top view, (b) cross-section of melt track at center of laser beam at $y = 870 \, \mu m$, (c) cross-section of solidified melt track at $y = 500 \, \mu m$

CONCLUSIONS
This paper shows recoil pressure is responsible for the keyhole formation in SLM process and Marangoni force plays a role in the flow of the molten metal. When these two factors are applied to the model, the characteristics of the track are similar to those in experiments. In the absence of these two forces, the powders are noted to have melted and solidified at the same spot.

ACKNOWLEDGMENTS
This work is supported by Singapore Economic Development Board (EDB) – Industrial Postgraduate Programme (IPP) and a joint lab between Singapore Center for 3D Printing and SLM Solutions Group AG.

REFERENCES


