

Dross Formation Mechanisms and Impact for Selective Laser Melting

Hong Yao ¹, Lucy Guo ¹, Guoqiang Li ^{1,2}, S.M. Guo ¹

¹Dept. Mechanical and Industrial Engineering, Louisiana State University

²Dept. Mechanical Engineering, Southern University

Abstract: In this paper, the composition of dross formed on SLM specimens as well as the effects of supporting structures on dross formation is studied. Although high oxygen level is found on the dross surface, the actual oxide layer is thin. The major impact of dross formations in SLM is the development of poor geometrical replications.

Keywords: (Selective Laser Melting (SLM), Support Structures, overhang, defects)

1. Introduction

Selective Laser Melting (SLM) is a key Additive Manufacturing (AM) technology capable of producing complex 3D metallic parts with a wide range of applicability ^[1]. By employing a high power laser source and fine metallic powders, SLM creates 3D metal/alloy parts using CAD-directed, selective melting of thin powder-bed layer-by-layer. In the layer-by-layer fabrication process, each new layer would either bond to a previously solidified layer, or rest on the powder bed, the so-called overhang regions. An overhang is defined as a region that is not fully supported by a solidified substrate on the bottom side during the layer-by-layer building process. In real applications, overhanging structures cannot always be avoided, Fig 1^[2].

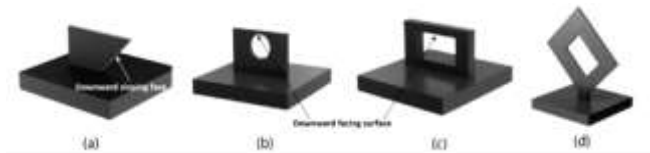


Fig.1 Example of overhanging structures: (a) downward sloping face, (b) & (c) downward facing surfaces and (d) downward sloping faces obtained by orientation in the building platform.

A major challenge in SLM is dross formation in overhang regions which causes reduced dimensional accuracy and introduces defects. For a solidified substrate, Fig. 2 region a, after laser irradiation, the heat conduction rate is high; the reflection of laser energy from the substrate is high; and there is no chance for the molten metal to penetrate deep into the substrate. Supported only by loosely packed powders, the SLM melt pool in the overhang region, Fig.2 region b, behaves differently. For the overhang region, the heat conduction rate is much lower; the laser beam can penetrate deep into the porous powders ^[3]; and the porous substrate provides a capillary suction to the molten pool. The effective thermal conductivity of the loose metallic powder layer, which is controlled by gas within the pores, may be more than 100 times smaller than the bulk conductivity of metal. For a 10–50 μm SLM powder layer, the effective thermal conductivity was reported as low as 0.1 to 0.2 W/(mK) ^[4]. Therefore, the absorbed laser energy

for the powder bed is much higher and the penetration depth is much thicker in the powder-supported overhang zones. This will result in the melt pool spreading and permeating deep into the powder bed due to the combined gravity and capillary wetting forces. The goals of this study are to examine the dross formation mechanisms and to identify the related impact to SLM printed parts.

2. The support structures for SLM process

A Conceptlaser *Mlab-cusing-R* SLM system is used. To illustrate the importance of support structures to dross formation, a 19x19x4 mm specimen is selected. The necessary support structures for this specimen, Fig.3, were

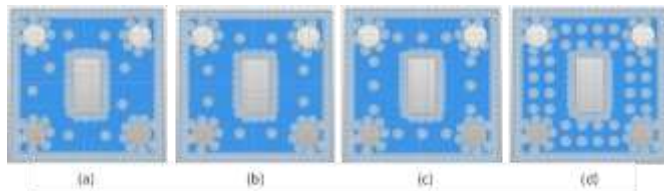


Fig.3 Automatically generated support structures using different semi-default parameters: (a) Inside, (b) XY Grid 4x4mm (c) XY Grid 3x3mm and (d) XY Grid 2x2mm.

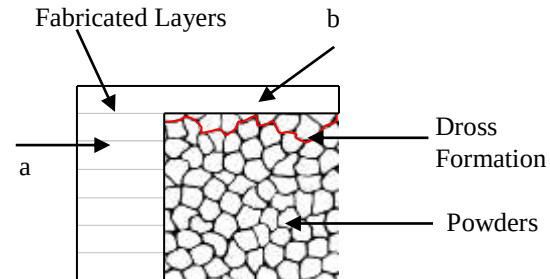


Fig.2 Dross formation in SLM overhanging regions

generated using the Autofab Mlab package. This software allowed users to either automatically generate support structures based on certain parameters given, or manually insert modified supports. An initial examination of automatically generated supports was conducted with varying parameters. Figure 3 shows four type of supports generated using automatic area coverage option with different semi-default parameters.

3. Dross formation mechanism and impact

SLM parts were printed using stainless steel 316 powders on different support structures 4 mm in height. The cone shaped support has a diameter of 0.7 mm at the plane in contact with the part and a diameter of 0.8mm in contact with the building platform. The unsupported areas in Fig.3 are the overhang regions and clearly show a yellowish color in Fig.4, indicating dross formation. Dross formation is directly related to the size of the unsupported areas, where a large gap leads to a more pronounced discoloration and a poorer definition of the targeted geometry. To show the impact of dross formation to the quality of the 3D printed parts, the microstructure and the chemical compositions of the printed parts were examined using a field-emission scanning electron microscope FE-SEM (FEI, Quanta 3DFEG) equipped with BSE and EDS detectors. Figure 5, right side, partially shows a cone shaped support structure. Most of the areas shown in Fig.5 can be classified as overhang regions. It's apparent that the porous powder bed provides a capillary suction to the molten pool. The melt pool spreads and permeates unevenly into the powder bed and many powders stick to the surface due to partial melting. The elemental compositions on the surface of the dross region were determined by EDS scans, Fig.6. Although the Conceptlaser Mlab-cusing-R SLM system maintains an oxygen level of only around 0.3% in the processing chamber, the dross region has a very high oxygen level. Based on the measurements, Fig. 6, the oxygen level on the surface of dross is as high as 19%. Many nano-sized particles on the dross surface indicate a vapor condensation process, Fig.6 (c). The cross-section

SEM image, Fig.6 (d), reveals the major impact of dross formation is poor geometrical replication. Although the oxidation layer is rough, the thickness is actually quite small.



Fig.4 Dross formation in the overhang regions (the yellowish color regions)

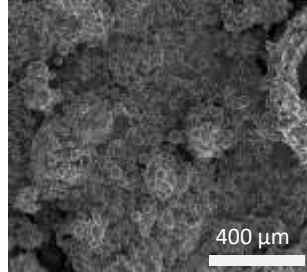
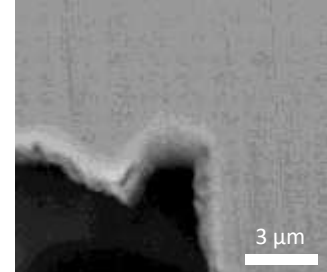
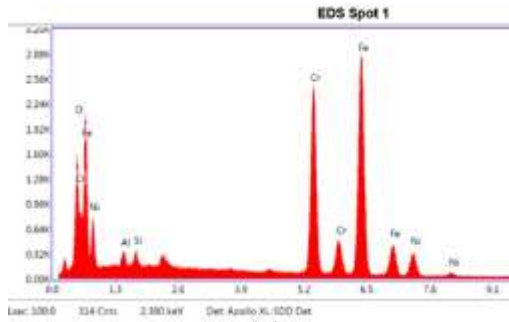


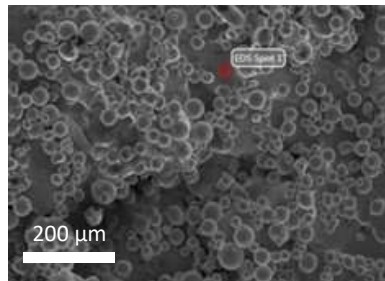
Fig.5 SEM image showing dross formation



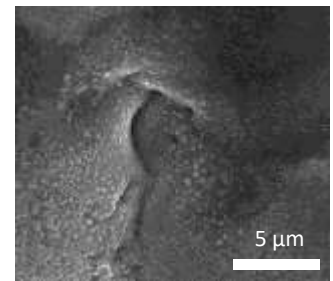
(d)



(a)



(b)



(c)

2

Fig.6 (a), (b): EDS showing high oxygen level, around atomic 19%, on the dross surface; (c): formation of nano-sized particles; (d) the cross-section showing a thin oxide layer.

4. Discussions

Prior to this study, very few investigations were conducted on the chemical compositions of the SLM dross regions. In the first instance, the drastic increase in oxygen content on the surfaces of the overhang regions may appear puzzling for a well-engineered SLM system, which limits the oxygen level inside the build chamber to 0.3% through a closed-loop control. While oxidation of stainless steel is usually a slow process, it is known that oxidation can occur at a very rapid rate under extremely high temperatures. During the laser melting process, such temperatures can and are achieved. For the fully supported regions, solidified structures underneath the powder layer conduct and absorb a significant amount of heat emitted from the laser. The vaporization of the thin particle layer can be easily carried away by circulating vent gas; however, for overhang regions, the low heat conduction rate and the deep penetration of the laser provide the necessary environment for vaporization within the powder bed. During the printing process, dark colored fumes were observed originating from the powder bed, specifically during the printing of overhang regions of the specimen. These fumes, composed of minute metal particles, have a tendency

of reacting with residual oxygen to form metal oxides. Because of the deep penetration of the laser in overhang regions, some of these oxides are trapped in the dross. It is also important to note that the distance between the supporting structures can greatly influence dross formation. Compared to a 10mm diameter, 3mm height circular disk, Fig.7, printed in a previous experiment, the dross formation of the square specimen, Fig.8, is much less intense. The support structures used for both specimens were 4mm in length and of identical dimensions. The only difference was the increased distance between support structures for the circular disk as well as a lack of supports around the outer edge of the specimen. The support structure for Fig.8 was manually enhanced from Fig.3, to limit the gap to be around 1 mm. Vaporization of metal powders during the SLM process was also identified by Lawrence Livermore National Laboratory (LLNL) researchers recently. After conducting an experimental study on SLM process, LLNL group found that vaporization during laser heating caused released vapor to push neighboring small particles away, significantly affecting the quality of SLM parts [5]. However, there have been no reports on the oxidation associated with the vaporization of metal powders.



Fig.7 Less optimized support



Fig.8 Better supports

5. Conclusion

In a SLM process, it is challenging to handle the overhang areas where dross may easily form due to the lack of support structure. Under EDS scans, the surfaces of dross areas are found to be high in concentrations of oxygen. This oxidation is due to the reaction between the residual oxygen and the vaporized metal powders under laser heating. Black fumes observed during the SLM process confirm that vaporization was occurring. Due to the lack of solidified structures underneath to absorb and reflect that heat in the overhang regions, vaporization of metal powders occurs deep inside the powder bed and a portion of oxidation products is trapped within the dross surface. The major impact this has on dross formation is poor geometrical replication. Finally, it was noted that the distance of the supporting structures, especially around the edge of the specimens, can greatly influence the dross formation. The gap between the support structures should be limited to around 1 mm.

6. Acknowledgments

The current work is funded by the NSF EPSCoR CIMM project under award #OIA-15410795 and Louisiana Board of Regents under award LEQSF-EPS(2015)-OPT-IN-42.

7. References

- ¹ E.C. Santos, M. Shiomi, K. Osakada, and T. Laoui, *Int. J. Mach. Tools Manuf.*; 46:1459. (2006).
- ² F. Calignano, *Materials and Design* 64, 203–213. (2014)
- ³ J. P. Kruth, P. Mercelis, J. Van Vaerenbergh, and T. Craeghs, *Proceedings of the 3rd International Conference on Advanced Research in Virtual and Rapid Prototyping*, Leiria, Portugal, 521-527 (2008)
- ⁴ M. Rombouts, L. Froyen, A. Gusarov, E.H. Bentefour, C. Glorieux, *In J.Appl. Phys.* 97, pp. 024905 1-8. (2005)
- ⁵ <https://www.llnl.gov/news/lawrence-livermore-discovery-%E2%80%98big-step-forward%E2%80%99-metal-3-d-printing-process>