14 Aug 2019

Simulated Effect of Laser Beam Quality on the Robustness of Laser-Based AM System

Aaron Flood

Frank W. Liou
Missouri University of Science and Technology, liou@mst.edu

Recommended Citation

A. Flood and F. W. Liou, "Simulated Effect of Laser Beam Quality on the Robustness of Laser-Based AM System," *Proceedings of the 30th Annual International Solid Freeform Fabrication Symposium (2019, Austin, TX)*, pp. 1340-1349, University of Texas at Austin, Aug 2019.

Solid Freeform Fabrication 2019: Proceedings of the 30th Annual International
Solid Freeform Fabrication Symposium – An Additive Manufacturing Conference

SIMULATED EFFECT OF LASER BEAM QUALITY ON THE ROBUSTNESS OF LASER-BASED AM SYSTEM

Aaron Flood* and Frank Liou*

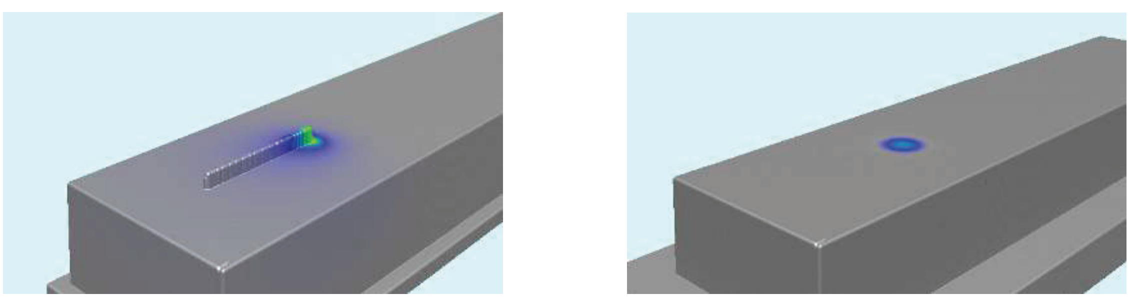
*Department of Mechanical and Aerospace Engineering, Missouri University of Science and Technology, Rolla, MO 65409

Abstract

In many metal AM techniques, a laser is used as the heat source and in some applications, it can be advantageous to work off of the focal plane. When operating outside of focus, the beam quality of the laser can have drastic impacts on the ability to manufacture quality parts. This study investigates the effect of the beam quality and distance from the focal plan on the ability to deposit Ti-64, aluminum, and steel through the simulation of the blown powder process.

1 Introduction

In metal additive manufacturing (AM) there is a very high cost associated with each build. This has led to the development of many simulations suites [1, 2, 3, 4] which attempt to minimize the number of trial and error runs which need to be performed in order to produce an acceptable part. One aspect of these simulations which is typically not taken into account is the effect of laser quality on the processability of a given material. The laser beam quality can have a drastic effect on its ability to generate and sustain a melt pool. These differences are illustrated in Figure 1. These simulations are identical except for the laser quality and waist offset are different. This

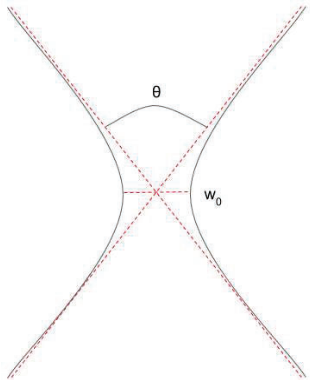


(a) BPP 0.5 Working Dist. 0.0mm (b) BPP 1.5 Working Dist. 10.0mm

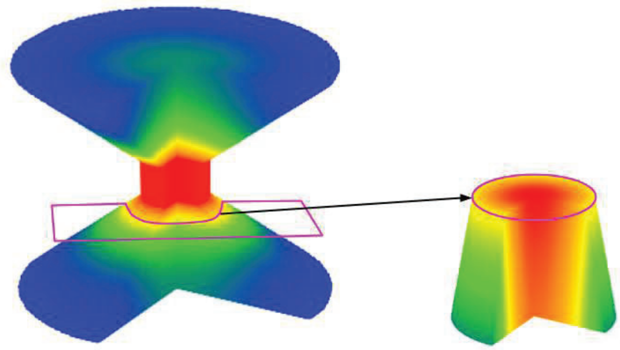
Figure 1: Comparison of aluminum simulations where a one built successfully and one failed to build

shows that if a laser is of lower quality or poor care is taken during setup then the results could differ drastically.

This effect can not be seen in many AM simulations due to the techniques used for laser simulations. In many simulations, the laser is applied as a perfect circle with a diameter the same size as the beam waist. In reality, the laser has a shape which can be seen in 2 dimensions in Figure 2a. The light of the laser is focused at the beam waist and then begins to diverge again after the beam waist. In 3 dimensions it looks like Figure 2b. The quality of the laser can be defined using



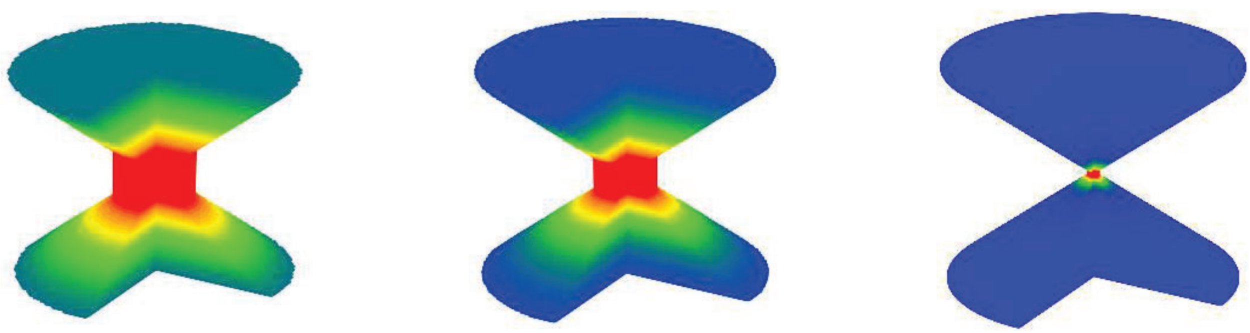
(a) 2 dimensional laser profile



(b) 3 dimensional laser profile

Figure 2: Illustration of laser beam shape

beam parameter product (BPP) which is defined as $BPP = \frac{\theta W_0}{2}$ where θ is the divergence angle of the laser and W_0 is the beam waist. Figure 3 demonstrates the effect that the BPP has on the laser distribution. The smaller the BPP the taller the beam waits and the higher the energy density



(a) BPP = 0.1

(b) BPP = 3.0

(c) BPP = 10.0

Figure 3: Comparison of effect of BPP on laser distribution

is at any given slice off the of the beam waist when compared to higher BPP profiles.

This effect can be compounded by human error and inability to align equipment perfectly. If the work piece is set up in such a way that it does not intersect the laser beam at the beam waist the laser size and profile can be altered. As the work piece gets farther out of the beam waist the energy density becomes drastically lower. This, compounded with a laser with a poor BPP, can result in a small distance in the z direction where deposition can take place.

2 Experimental Setup

In order to explore the effect that the BPP and working distance on the ability to deposit, a full factorial design of experiment (DOE) was used. The parameters used can be seen in Table 1. It

Table 1: Factors and levels used in design of experiment

Material	Laser Standoff	Laser BPP
Ti-64	0.0 mm	0.5
Al	5.0 mm	1.0
SS304	10.0 mm	1.5

resulted in 9 unique simulations needing to be preformed for each material. In order to ensure that other parameters did not effect the results the standard set of setup parameters were used and can be seen in Table 2. The process simulated was blown powder directed energy deposition.

Table 2: Setup parameters used across all materials

Resolution	100 μm
Material Insertion Rate	2.75 g/min
Ambient Temperature	298 K
Substrate Size	12.7 mm x 55 mm x 6.35 mm

3 Simulation Results

3.1 Aluminum

In order to simulate aluminum depositions the laser setup parameters needed to be gathered. These can be seen in Table 3.

Table 3: Laser parameters for Aluminum simulations

Laser Waist	1.0 mm
Laser Power	1500 W
Laser Distribution	Gaussian
Laser Scan Speed	1150 mm/sec

Throughout the 9 experimental runs, 6 of the runs generated acceptable deposits where as 3 did not. A scatter plot of the results can be seen in Figure 4. As can be seen from the graph there is a distinct segregation of the builds that were a success and those that failed. Once the energy density was low enough, either due to a high BPP or working distance, a melt pool was unable to form. This results in the inability of the build to successfully complete. A comparison of the successful build can be seen in Figures 5, 6, and 7.

From these images only small differences in the results can be seen. These results are most likely from small variations in the simulation time being displayed. This is hypothesized due to

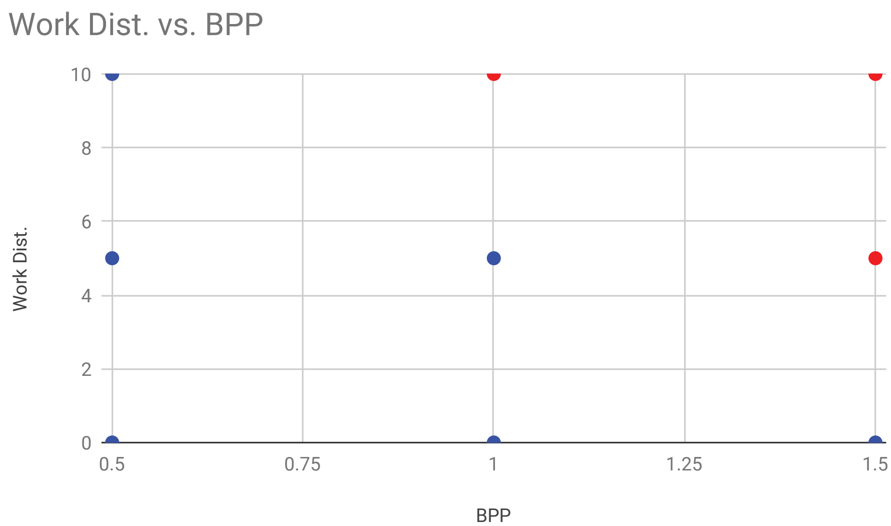
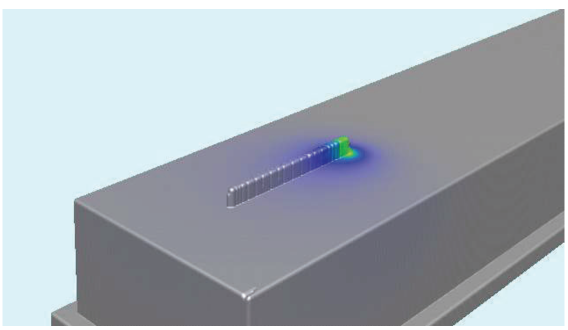
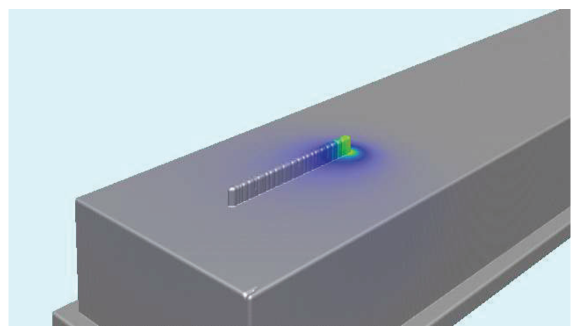


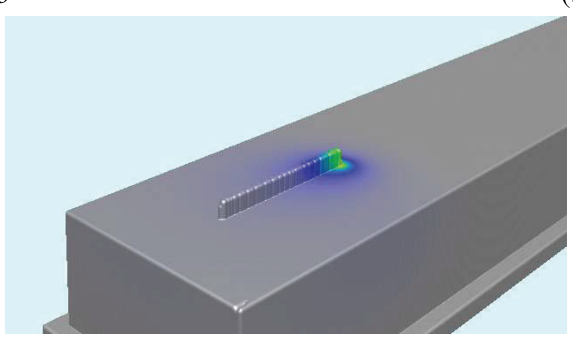
Figure 4: Scatter plot showing which aluminum simulations which completed (blue is completed red is failed)



(a) BPP 0.5



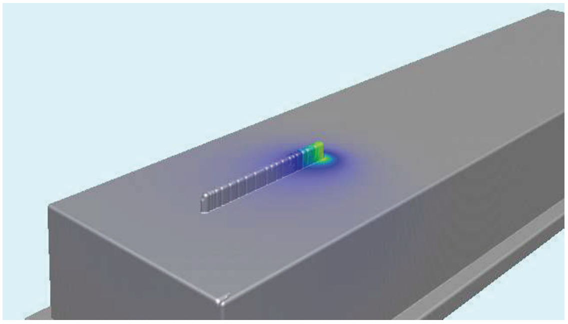
(b) BPP 1.0



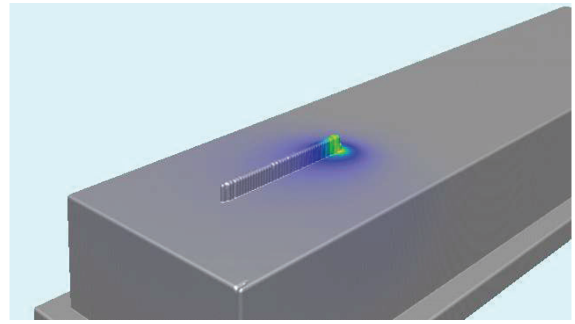
(c) BPP 1.5

Figure 5: Aluminum depositions with a working distance of 0.0 mm

the fact that the simulation with a BPP of 0.5 and working distance of 5.0 mm (Figure 6a) appears hotter than the simulation with a BPP of 0.5 and working distance of 0.0 mm (Figure 5a). This result is the opposite of the expected increase of temperature with increased energy density. When comparing across a standard BPP (for example Figures 5a, 6a and 7), no forseeable differences



(a) BPP 0.5



(b) BPP 1.0

Figure 6: Aluminum depositions with a working distance of 5.0 mm

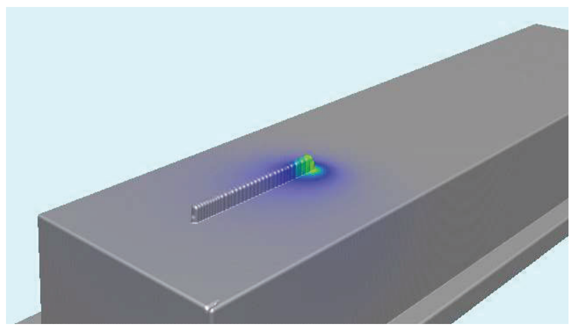


Figure 7: Aluminum depositions with a BPP 0.5 and working distance of 10.0mm

can be observed. Likewise, when comparing across a standard working distance (Figures 5a, 5b and 5c) no differences can be seen. From this it can be concluded that aluminums response to the energy density of the laser is binary, either the material will deposit if above a threshold or won't if it's below the threshold. This means that so long as the material will deposit, only minor adjustments can be made by getting a better laser quality or tweaking the working distance.

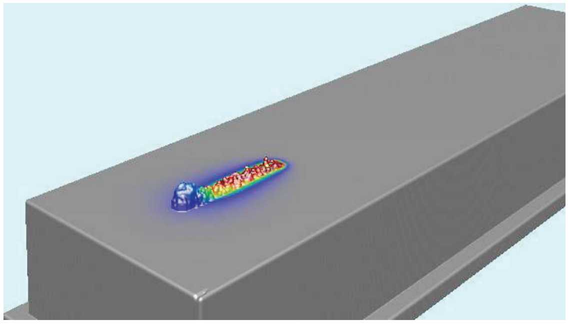
3.2 Ti-64

In order to simulate Ti-64 depositions the laser setup parameters needed to be gathered. These can be seen in Figure 4.

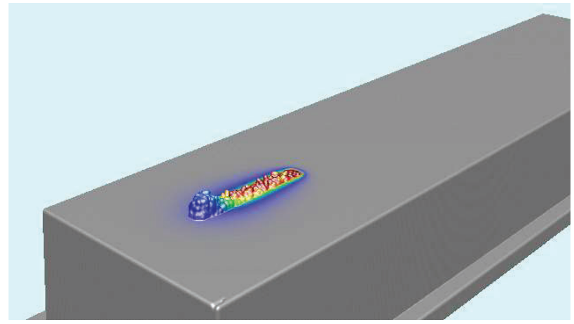
Table 4: Laser parameters for Ti-64 simulations

Laser Waist	1.0 mm
Laser Power	1360 W
Laser Distribution	Gaussian
Laser Scan Speed	900 mm/sec

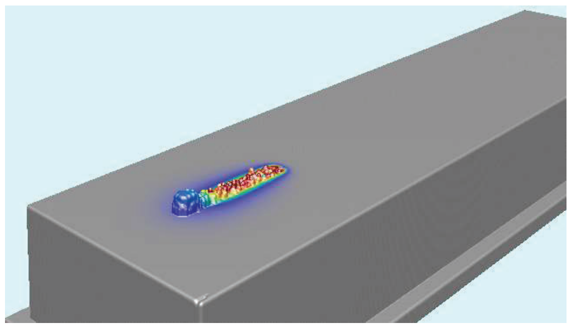
In the simulation of Ti-64, all of the experiments resulted in deposits, these can be seen in Figures 8, 9, and 10. These deposits were not as consistent as the aluminum deposits. As can be expected, as the working distance and the BPP are increased the laser spot will increase. This increase in spot size also leads to an increase in the melt pool size. Some errors can be seen



(a) BPP 0.5



(b) BPP 1.0



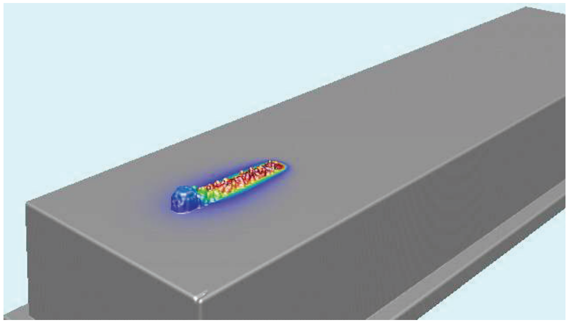
(c) BPP 1.5

Figure 8: Ti-64 depositions with a working distance of 0.0 mm

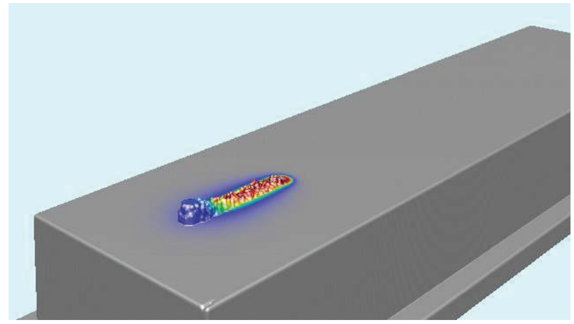
with respect to the simulated control system for the powder flow. It appears that the simulation adds extra powder at the start of the track and then slows down to an appropriate level of material addition. More investigation needs to be done to determine the source of this error.

The variation in the Ti-64 simulations can be looked at from both the perspective of BPP and working distance. When comparing the effect of the working distance, Figure 10 shows the largest differences in the spot size. As can be seen, the simulation farthest off the focal plane, Figure 10c, has a very large spot size and appears to be a much shorter deposit when compared to being directly in the depth of focus, Figure 10a. The shorter deposit is an artifact of the fact that the additional material added is being spread over a much larger area. As the spot size shrinks the profile increases due to the smaller area to catch powder. This effect needs to be correlated to experiments and may be an artifact of the techniques used to simulate the addition of powder into the simulation.

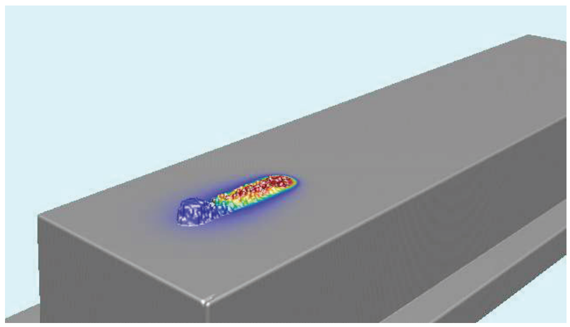
Another source of variation in the builds is due to the changes in the working distance, this can be seen by comparing Figures 8c, 9c, 10c. The trend with the working distance is similar to that of the BPP, as the substrate is farther out of the depth of focus the spot size becomes larger. Both of these results lead to the conclusion that Ti-64 is a more robust material for deposition in terms of its reaction to changes in energy density from laser quality and working distance. However, the quality of the deposit can be increased by increasing the laser quality or setting the working distance more precisely.



(a) BPP 0.5

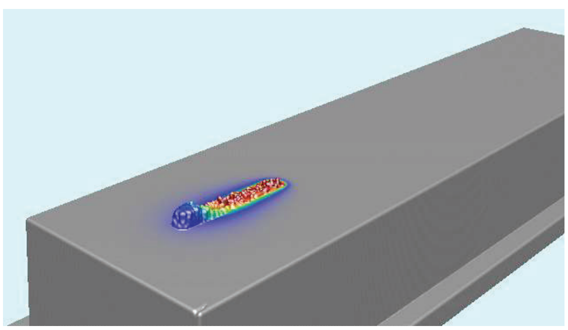


(b) BPP 1.0

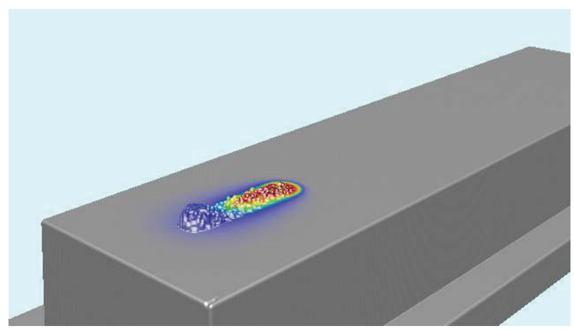


(c) BPP 1.5

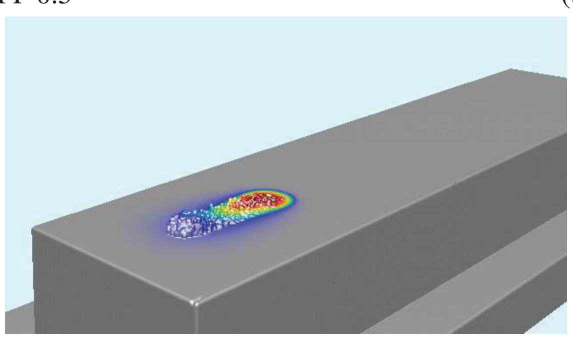
Figure 9: Ti-64 depositions with a working distance of 5.0 mm



(a) BPP 0.5



(b) BPP 1.0



(c) BPP 1.5

Figure 10: Ti-64 depositions with a working distance of 10.0 mm

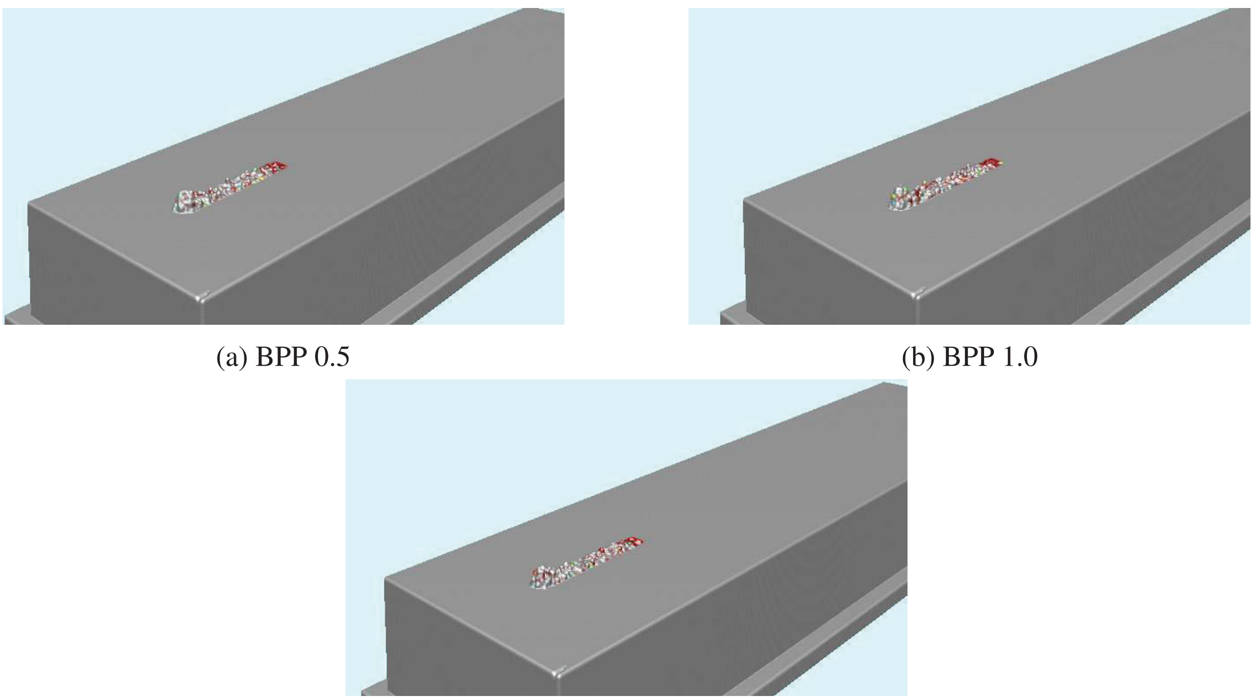
3.3 SS 304

The laser parameters which were specific to the simulation of SS 304 can be seen in Table 5.

Table 5: Laser parameters for SS-304 simulations

Laser Diameter	1.0 mm
Laser Power	1360 W
Laser Distribution	Gaussian
Laser Scan Speed	900 mm/sec

All of the simulations of SS-304 resulted in melt pools and a small deposit, these results can be seen in Figures 11, 12, and 13. As can be expected, as the BPP and working distances were



(a) BPP 0.5

(b) BPP 1.0

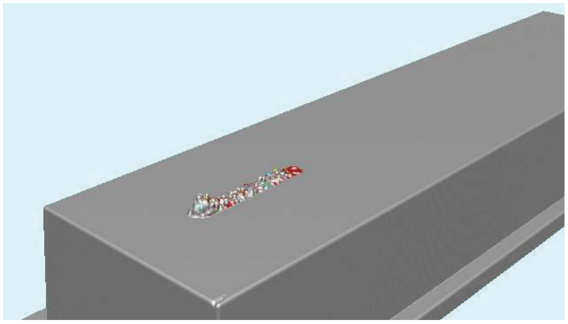
(c) BPP 1.5

Figure 11: SS-304 depositions with a working distance of 0.0 mm

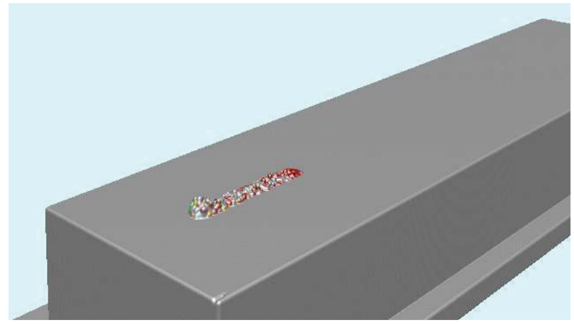
increased the spot size increased resulting in a larger melt pool. This is most clearly illustrated by the extremes of the design space Figures 11a and 13c.

When looking at the effect that the BPP has on the resulting melt pool, Figure 13 shows the most stark contrast. A trend can be seen from these images that shows that as the BPP increases so does the melt pool. And when looking at the effect of the working distance, the expected trend is observed. This trend, illustrated by Figure 11c, 12c, and 13c, shows that as the working distance is increase the resulting melt pool is increased as well.

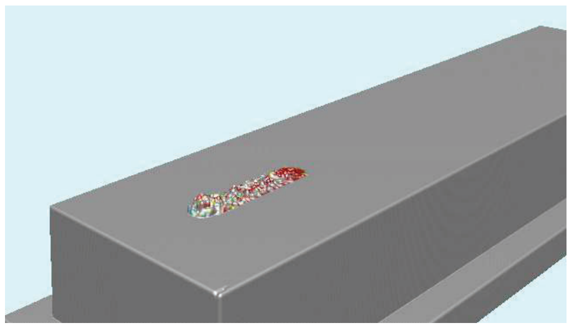
From this study, it shows that SS-304 is not extremely sensitive to the effect that a low quality laser and working distance have on the ability to develop a melt pool and deposit material. These parameters however have a drastic impact on the quality of the build and should be tuned to ensure optimal deposition results.



(a) BPP 0.5

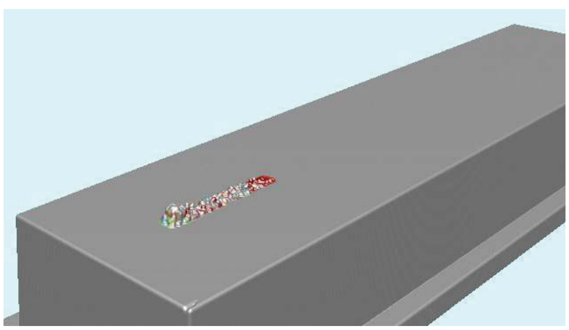


(b) BPP 1.0

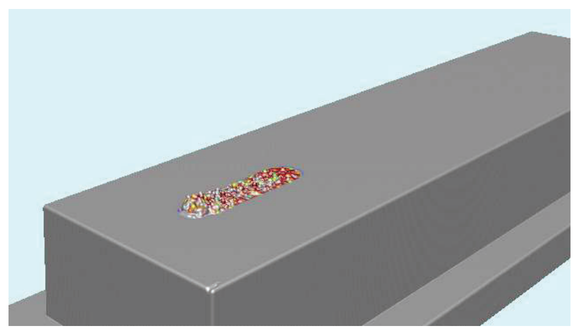


(c) BPP 1.5

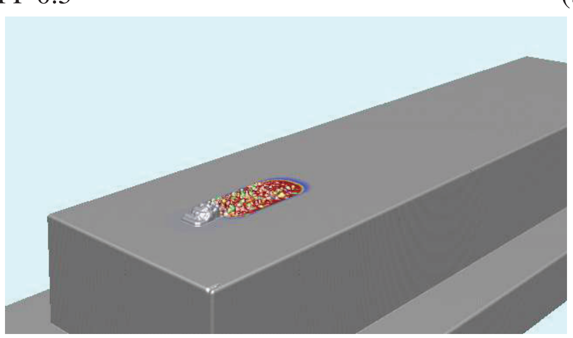
Figure 12: SS-304 depositions with a working distance of 5.0 mm



(a) BPP 0.5



(b) BPP 1.0



(c) BPP 1.5

Figure 13: SS-304 depositions with a working distance of 10.0 mm

4 Conclusions

Throughout these simulations it was shown that changing the BPP of the laser and the working distance have a noticeable and sometimes drastic effect on the final depositions. It was seen that, for the design space selected, the deposits of aluminum were either identical results or did not print depending on the resulting energy density. The quality of the build did not appear to change noticeably with the changing of process parameters. For both the Ti-64 and SS-304, an unprintable solution was not be found. This led to the conclusion that these materials are more robust in their print-ability. In these materials however, a drastic difference was observed in the melt pool size and shape. The lower the laser quality or the farther off the depth of focus the melt pool became much larger. This shows that the quality of the deposit with these materials is susceptibility to the quality of the laser and the distance off the beam waist.

Acknowledgments

The support from Department of Energy Grant DE-SC0015207 and NSF grants CMMI 1625736 and EEC 1004839 are appreciated. We also appreciate the financial support provided by the Center for Aerospace Manufacturing Technology (CAMT) at the Missouri University of Science and Technology.

References

[1] M. F. Zäh and S. Lutzmann. "Modelling and simulation of electron beam melting". In: *Production Engineering* 4.1 (2010), pp. 15–23. ISSN: 09446524. DOI: 10.1007/s11740-009-0197-6.

[2] Zhiqiang Fan and Frank Liou. "Numerical Modeling of the Additive Manufacturing (AM) Processes of Titanium Alloy". In: *Titanium Alloys - Towards Achieving Enhanced Properties for Diversified Applications* (2012), pp. 3–28. DOI: 10.5772/34848. URL: http://www.intechopen.com/books/titanium-alloys-towards-achieving-enhanced-properties-for-diversified-applications/numerical-modeling-of-the-additive-manufacturing-am-processes-of-titanium-alloys.

[3] Erik R. Denlinger, Jeff Irwin, and Pan Michaleris. "Thermomechanical Modeling of Additive Manufacturing Large Parts". In: *Journal of Manufacturing Science and Engineering* 136.6 (2014), p. 061007. ISSN: 1087-1357. DOI: 10.1115/1.4028669. URL: http://manufacturingscience.asmedigitalcollection.asme.org/article.aspx?doi=10.1115/1.4028669.

[4] Saad A. Khairallah et al. "Laser powder-bed fusion additive manufacturing: Physics of complex melt flow and formation mechanisms of pores, spatter, and denudation zones". In: *Acta Materialia* 108 (2016), pp. 36–45. ISSN: 13596454. DOI: 10.1016/j.actamat.2016.02.014. arXiv: arXiv:1011.1669v3. URL: http://dx.doi.org/10.1016/j.actamat.2016.02.014.