

Effect of Shield Gas on Surface Finish of Laser Powder Bed Produced Parts

Colt Montgomery*, Christopher Farnin**, Greg Mellos*, Michael Brand*, Robin Pacheco*, and
John Carpenter*

*Los Alamos National Laboratory, Los Alamos, NM 87545

**Department of Materials Science and Engineering, Lehigh University, Bethlehem, PA 18015

Abstract

Additive manufacturing (AM) of metals is a novel manufacturing technique that allows for net-shape or near net-shape parts to be produced quickly. Within additive manufacturing a large concern is the produced surface finish, especially for upward and downward facing surfaces on complex geometries. Surface finish is of utmost importance for many engineering applications. In melting of powders, the gas used dominates the thermal conductivity of the metal powder. Manipulation of the type of shield gas may provide a means to modify the surface finish without adjustment of established lasing parameters and thereby produce a higher quality part with minimal post processing. These results have potential applications in aerospace, automotive, and biomedical sectors where surface finish requirements coupled with complex geometries are extremely common.

Introduction

Surface finish is an important consideration of any part that can be subjected to fatigue loading as it can dramatically affect part life. With traditional manufacturing surface finish control is critical to reduce friction and noise. Additively Manufactured (AM) produced parts are no different with the ability to control surface finish being critical. AM parts, particularly those of Laser Powder Bed Fusion (L-PBF) are commonly rougher than machined counterparts and this is inherent to the process.

The downward facing surfaces are often rough in L-PBF produced parts due to overmelting and a limited heat conduction path provided by the metal powder that the surface is being deposited upon [1] [2]. It has been found that the thermal conductivity of metallic powder is dominated by the thermal conductivity of the gas that fills the pores between the powder particles [3] [4]. This has particular implication to powder-bed based additive manufacturing where overhanging and edge features are built on top of or bordering powder.

Strano et al investigated the effect of powder particles on the surface finish of L-PBF produced parts [5]. Little research has been done, however, in how the inert gas selection affects the resulting surface finish. Shield gas research is traditionally constrained to traditional welding technologies. It has long been known that the shield gas can affect melt pool morphology as well as stability in the traditional welding process [7] [8] [9]. The effect on morphology should be further enhanced within the powder bed process when the results are coupled with the effect of the metal powder. The hypothesis is that by adjusting the shield gas used surface finish can be improved in the laser powder bed fusion process.

Methods

The artifact chosen represents a variety of surface geometric features found within actual parts. The samples resemble those produced in literature but with added downward facing features such as the arch and horizontal flat [10]. An illustration of the part can be seen in Figure 1. The sample has angles ranging from 45 degrees up to 90 degrees in 15 degree increments that represent both upward and downward facing surfaces. The angles were chosen to represent the limits of unsupported surfaces in the laser powder bed fusion process. Each side is 5 mm or longer and is 3 mm wide to allow for multiple passes by the chisel probe tip specified by the ASTM B946-11 standard for surface finish on powder metallurgy produced products. This standard corresponds to the same standard used by the machine manufacturers and other researchers in the field [6] [11] . A DektakXT (Bruker, Billerica, Massachusetts) was used to take these measurements using a 12.5 μm ball tip with 3 measurements of 2.5 mm each performed on each surface. It should be noted that since this is contact profilometry it is possible that the tip filtered the data by not being able to fit into extremely narrow valleys. This could be rectified by using a non-contact method in the future. No additional filtering was done on the data.

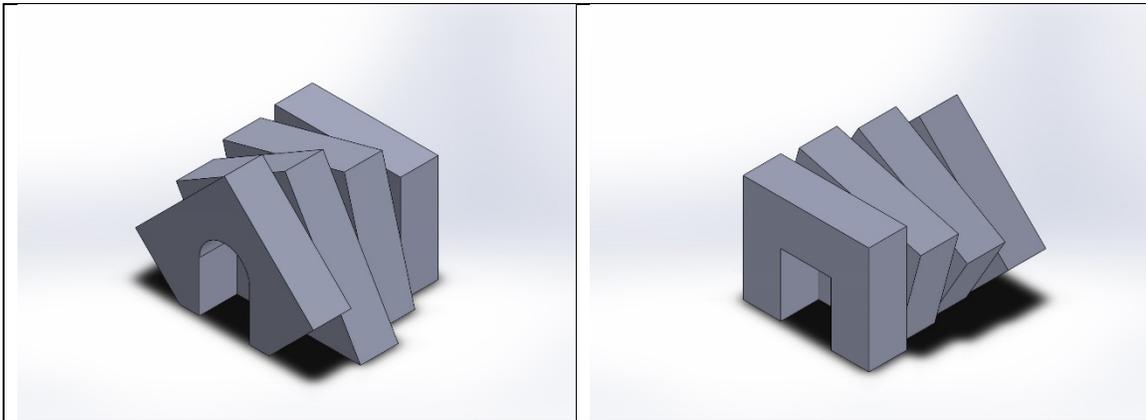


Figure 1: Surface finish sample

The gases chosen to be tested are argon (standard), nitrogen (standard), and a 75% Argon 25% CO₂ weld gas mix (non-standard). These three gases are chosen due to their different thermal conductivities and use in traditional welding. Table 1 shows the degree of variation of thermal conductivity for each of the proposed gases as well as the effective thermal conductivity of the powder based on the Yagi-Kunni model for powders [4]. Nitrogen has the greatest thermal conductivity of the three gases tested by a factor of 1.4. An asterisk designates that the conductivity was calculated as a volumetric ratio of the individual gases thermal conductivities.

Table 1: Shield gas thermal conductivities and effective thermal conductivities of metallic powder.

| Shield Gas | Thermal Conductivity @ 300 K (W/mK) | Effective Thermal Conductivity of Powder Bed @ 300 K (W/mK) |
|-------------------------------|-------------------------------------|-------------------------------------------------------------|
| Argon | 0.018 | 0.17527 |
| 75% Argon 25% CO ₂ | 0.0177* | 0.17241* |
| 90% Argon 10% Helium | 0.03187* | 0.30524* |
| Helium | 0.151 | 1.26766 |
| Nitrogen | 0.026 | 0.25076 |

The use of helium gas was attempted but due to the low molecular weight and high intrinsic speeds, the gas was difficult to pump and establish a differential pressure within the equipment. No build was successfully completed with the helium gas, a mixture is currently being tested of 90% Argon and 10% Helium to take advantage of the high thermal conductivity of helium but maintain nearly the density of argon. In traditional welding a 75% Argon and 25% CO₂ gas mixture is commonly used to improve surface finish of stainless steel welds resulting in a wider but shallower melt pool. This tests compositional differences in gas since the mixture has an almost identical thermal conductivity to that of pure argon.

The material chosen for these experiments was 304 Stainless Steel (composition is listed in Table 2) because of its widespread use within industry as well as its stability. 304 Stainless steel has applications in the medical, culinary, and general machinery industries. Stainless steel should not have any issues with measurement probe stylus (usually made of diamond) potentially scratching the surface. This can be an issue with softer materials because of the force applied to the tip during measurement [12]. Powder for these experiments is 304L Stainless Steel produced via gas atomization and provided by LPW falling within a size range of 15-45 μm and composition listed in Table 2.

Table 2: Composition of 304 Stainless Steel Powder

| Fe | Cr | Ni | Mn | Si | C | S | P | N | O |
|------|-------|------|------|------|-------|-------|------|-------|-------|
| 69.8 | 18.41 | 9.56 | 1.52 | 0.58 | 0.011 | 0.002 | 0.01 | 0.055 | 0.038 |

15 samples scattered throughout the build area were measured to alleviate location dependence on the surface finish results. 36 total samples were produced in order to allow for future testing and to further define any location dependence. These samples are distributed

evenly about the build plate so as to allow for any discrepancies due to build plate location or orientation as a result of lasing or gas flow. The gas flow will change with the density of the gas used, however, for this study the gas flow is not modified from test to test. Location and orientation dependence work is not discussed in this paper but is ongoing.

Results

The measured values along with box and whisker plots of the data for each gas can be seen in Figure 2 with the argon appearing in green, nitrogen in blue, and the 75/25 mix in yellow. Each dataset consists of 45 measurements of the surface in question. The Average roughness values are reported to the nearest micron in Table 3 for all three angles and gases.

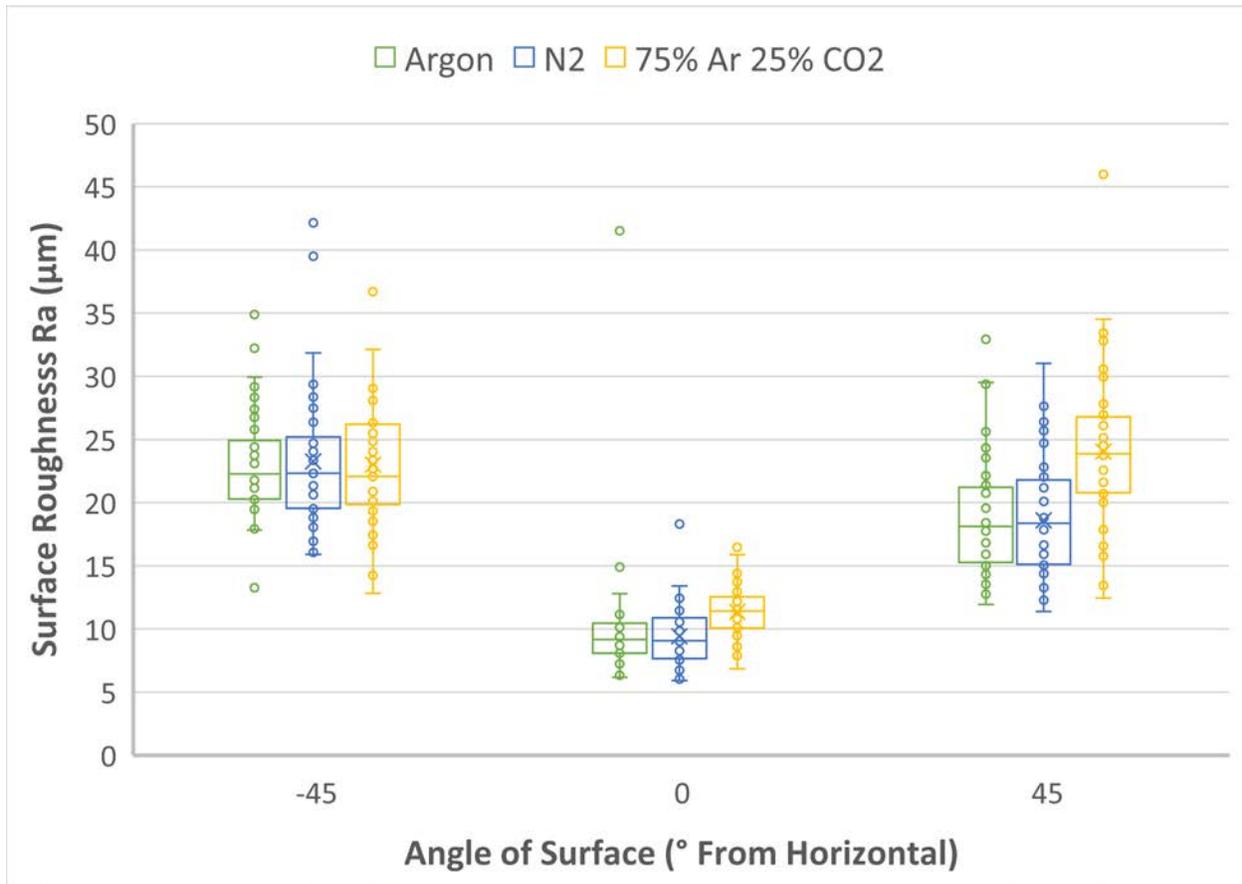


Figure 2: Box and whisker plots along with data for the surface roughness of various surface angles and various shield gases

Table 3: Reported average surface roughness measurements as a function of gas and angle of surface.

| | Surface Roughness (μm) | | |
|-------------------|-------------------------------------|----|----|
| | -45 | 0 | 45 |
| Argon | 23 | 10 | 20 |
| Nitrogen | 23 | 9 | 19 |
| 75% Ar 25% CO2 | 23 | 11 | 24 |

The 75% Argon 25% CO2 mix had issues with oxygen due to the plasma dissociating the carbon and oxygen. This resulted in an increase in measured oxygen levels in the build chamber. Ongoing work is being done to determine if the resulting carbon affected the material composition.

Discussion

The shield gas conductivity seems to have a negligible effect for gases with only a small difference in conductivity. A larger thermal conductivity difference may produce different results.

Nitrogen and Argon have similar Ra values, even though the thermal conductivities are different by a factor of 1.4. This would indicate that a relatively small change in thermal conductivity (on the same order of magnitude) does not greatly change the surface finish. If the downward facing surfaces had been significantly better for nitrogen, as hypothesized, the conductivity would likely be the cause, since all other parameters were held constant.

The Argon/CO2 mix had the worst surface finish of the gases tested. This is in contrast to what was predicted of a better upward facing surface finish because of the carbon addition. This could be due to carbon absorption during deposition leading to an increase in martensite phase fraction and a rougher surface morphology. This result would indicate that gas composition is of a greater importance than the actual thermal conductivity of the gas itself. To test this the sample will be cross-sectioned and examined for compositional and microstructural changes. The distribution is similar in range for the first and third quartiles for all three gases tested, albeit with different values. This shows that the surface finish distributions for a given angle are independent of shield gas but that the mean of the distribution is gas dependent.

Conclusions

Based on current testing there appears to be little difference in the mean surface roughness of the downward facing surfaces with changing of the inert gas used. This agrees with the current hypothesis in literature that downward surface finish is dominated mostly by powder morphology. There could still be a location dependence that is not being seen in the average results. Ongoing work is being done to determine any such dependence.

Upward facing surface finish is affected by the gas composition more than the gas conductivity. This intuitively makes sense since the bulk metal conductivity is orders of

magnitude greater than that of the gas conductivity and for this part orientation the powder will be unable to insulate the weld to as great a degree. This result is likely material dependent and would be different for an alloy more sensitive to composition.

Future Work

Future work is to investigate location and orientation dependence of the samples within all of the builds. This will better inform users where to place parts for optimal surface finish given the gas flow regimes throughout the equipment. The remaining surfaces will also be measured and compared to the current results. Higher conductivity gases will be tested to determine conclusively their effect on surface finish. Finally the samples will be sectioned and mounted to determine any changes in the microstructure due to the shielding gas for identical process parameters. If successful a valve system could be implemented into the gas line to allow for purging of different shield gases in-situ to selectively change the part material properties throughout the build without modifying lasing parameters.

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References

- [1] W. E. King, A. T. Anderson, R. M. Ferencz, N. E. Hodge, C. Kamath, S. A. Khairallah and A. M. Rubenchik, "Laser powder bed fusion additive manufacturing of metals; physics, computational, and materials challenges," *Applied Physics Reviews*, vol. 2, no. 4, 2015.
- [2] I. Yadroitsev, A. Gusarov, I. Yadroitsava and I. Smurov, "Single track formation in selective laser melting of metal powders," *Journal of Materials Processing Technology*, vol. 210, pp. 1624-1631, 2010.
- [3] L. C. Wei, L. E. Ehrlich, M. J. Powell-Palm, C. Montgomery, J. Beuth and J. A. Malen, "Thermal conductivity of metal powders for powder bed additive manufacturing," *Additive Manufacturing*, vol. 21, pp. 201-208, 2018.
- [4] S. Yagi and D. Kunii, "Studies on effective thermal conductivities in packed beds," *A.I.Ch.E. Journal*, vol. 3, no. 3, pp. 373-381, 1957.
- [5] G. Strano, L. Hao, R. Everson and K. Evans, "Surface roughness analysis, modelling and prediction in selective laser melting," *Journal of Material Processing Technology*, vol. 213, pp. 589-597, 2013.
- [6] P. Kah and J. Martikainen, "Influence of shielding gases in the welding of metals," *Int J Adv Manuf Technol*, vol. 64, p. 1411:1421, 2013.

- [7] N. Moyer, "The Evolution of Shielding Gas," American Welding Society, 09 2002. [Online]. Available: <https://app.aws.org/wj/2002/09/feature1/index.html>. [Accessed 8 5 2018].
- [8] Advanced Welding Supply Company Inc., "Gas Guide," Advanced Welding Supply Company Inc., 2017. [Online]. Available: <http://www.advancedweldingsupply.com/gas%20guide.html>. [Accessed 8 5 2018].
- [9] A. Diatlov, D. Buchbinder, W. Meiners, K. Wissenbach and J. Bultmann, "Towards surface topography: Quantification of Selective Laser Melting (SLM) built parts," in *Proceedings of the 5th International Conference on Advanced Research in Virtual and Rapid Prototyping*, Leiria, Portugal, 2011.
- [10] T. Grimm, G. Wiora and G. Witt, "Characterization of typical surface effects in additive manufacturing with confocal microscopy," *Surface topography: metrology and properties*, vol. 3, 2015.
- [11] A. Triantaphyllou, C. L. Giusca, G. D. Macaulay, F. Roerig, M. Hoebel, R. K. Leach, B. Tomita and K. A. Milne, "Surface texture measurement for additive manufacturing," *Surface topography: metrology and properties*, vol. 3, 2015.
- [12] G. T. Smith, *Industrial metrology: surfaces and roundness*, London: Springer, 2002.