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Investigation of Crucial Properties for Polymeric Recoater Materials in Metal Additive Manufacturing

by Alex Butler and Brandon McWilliams

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Investigation of Crucial Properties for Polymeric Recoater Materials in Metal Additive Manufacturing

Brandon McWilliams
DEVCOM Army Research Laboratory

Alex Butler
Oak Ridge Associated Universities

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<p>Laser powder bed fusion metal additive manufacturing creates parts using layers of powder dispersed across a build area that are then selectively melted by a laser. In this iterative process the dispersion of the powder layers is done by a recoater. The uniformity and consistency of the powder dispersion is critical to part performance, properties, and geometric accuracy. The recoater is responsible for distributing powder across the build area. The recoater assembly typically consists of a rigid arm with a replaceable insert. The insert can come in many forms, some examples being metal blades, elastomeric rods or wipers, or hard ceramics. As the recoater arm moves across the build area the gap between the recoater and the build material needs to be uniform to prevent inconsistencies in powder dispersion. If the recoater is damaged or wears away due to interactions with the print, this gap thickness can change heterogeneously across the width of the recoater and result in premature build failures and/or defects in the printed parts. This study investigated the influence of the hardness and size of polymeric recoater materials on the height deviations in the recoater at varying build heights. It was found that the maximum height change of the recoater increases with decreasing hardness. No consistent trend between recoater size and maximum height change or the rate of height change was found. After testing, our team has decided to begin using a harder recoater, as it showed the least amount of height deviation and showed consistent trends regarding height change and build height. This will allow for more confidence in our process and reduced build failures, especially with very long build times.</p>									
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Brandon McWilliams				(410) 306-2237					

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1. Introduction

Laser powder bed fusion (LPBF) is a type of metal additive manufacturing (AM). This process entails spreading a layer of powder over the build area and selectively melting the powder using a laser. The build elevator is then moved down and another layer of powder is dispersed and melted. This iterative process yields an additively manufactured part surrounded by a bed of unmelted powder.

The mechanism that spreads the powder across the build area, called a recoater, is shown in Figs. 1 and 2.



Fig. 1 Aluminum recoater arms with grooves

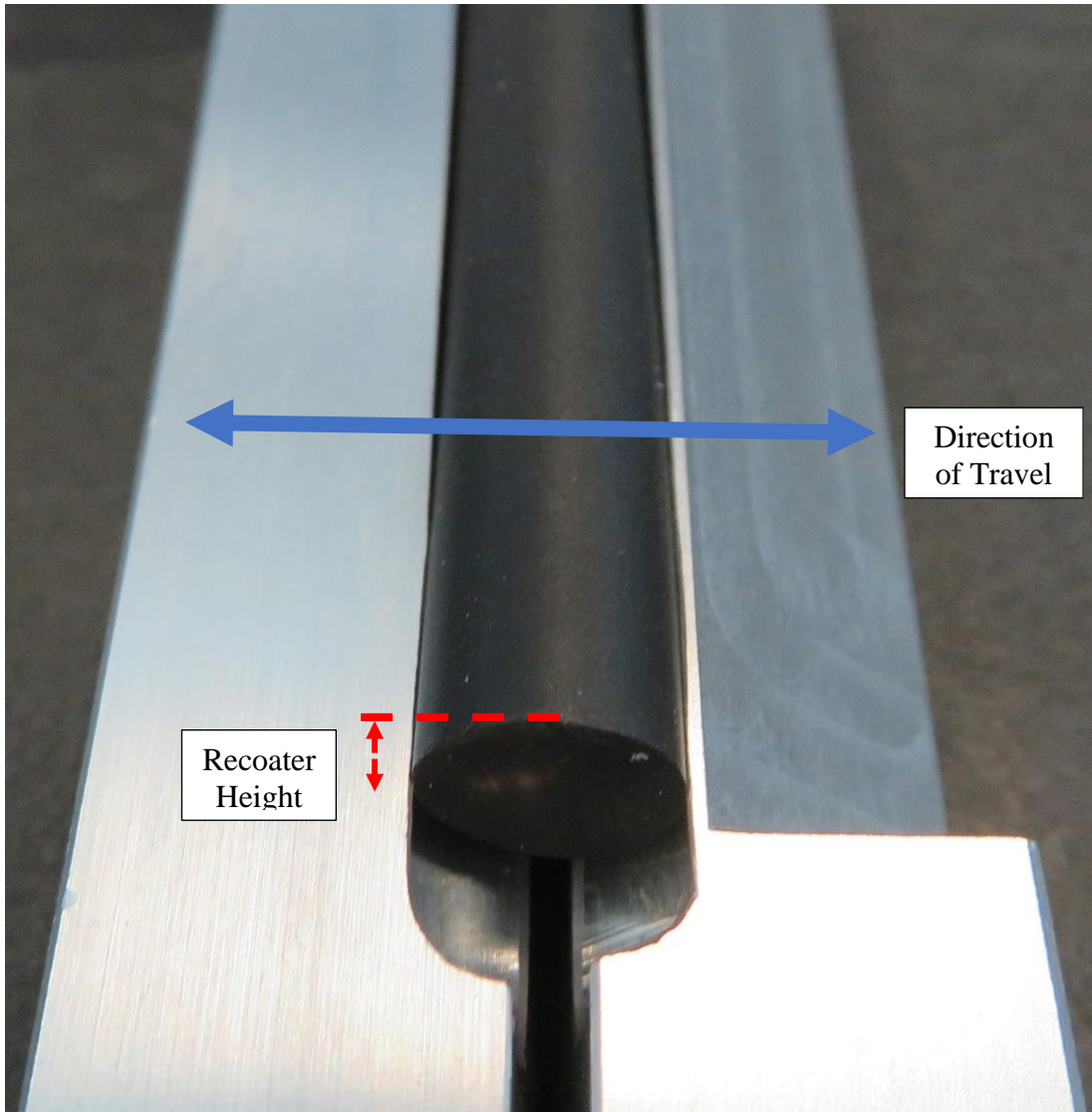


Fig. 2 Aluminum recoater arms with recoater insert placed in the grooves and the direction of travel, reference features, and measured height annotated

A consistent powder bed is critical for ensuring high mechanical properties and nonporous parts.¹ Additionally, build failures due to interactions between the recoater and the build, called recoater crashes, can occur. Some crashes are not catastrophic, and the build can be stopped and adjusted. However, this influences the thermal history of the part, which can create more part distortion and lead to more crashes.² These crashes are especially bad in machines that do not have a method of detecting recoater crashes. In these cases the build will continue, and the print can heavily wear the recoater and possibly damage the part and recoater assembly, Fig. 3 being an example of this. Recoater crashes increase the overall cost of the part as failed builds can be common and, in some cases, constant supervision is required by a trained technician in case intervention is needed.

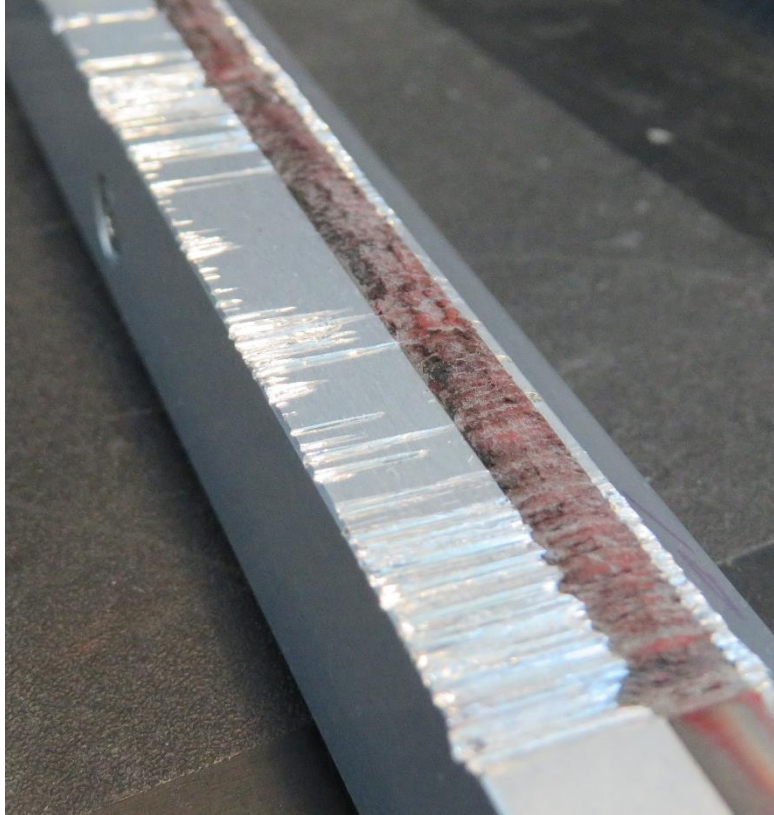


Fig. 3 Example of recoater crash damaging the recoater assembly

The recoater insert can be many different types of materials ranging from soft bristled carbon fiber to hard tungsten carbide blades. Harder recoaters have the ability to remove debris from the print. These recoaters are usually harder than the print material and can scrape debris (e.g., unmelted particles) and contaminants off the part. This, however, comes at a cost. Vibrations from harder recoaters contacting the build can cause inconsistent powder distribution and reduced dimensional accuracy.³ Additionally, higher aspect ratio parts can be bent by harder recoaters as they contact the build, causing recoater crashes. Conversely, softer recoater materials allow for fewer vibrations when in contact with the part but do not remove debris as aggressively as harder recoaters, allowing for higher aspect ratio and more delicate parts.⁴ Additionally, softer recoaters allow for the dispersion of finer particles, yielding a more uniform powder bed.⁵

The Renishaw AM400 LPBF system at the US Army Combat Capabilities Development Command (DEVCOM) Army Research Laboratory (ARL) uses softer polymer recoaters, and on some longer builds we have observed heavy, localized wear on the recoater. These areas of heavy wear inhibit even powder distribution and can lead to build failures as shown in Fig. 4. This wear over time allows for regions of the recoater to wear heterogeneously and disperse powder

unevenly across the build area. This means as the build progresses the uniformity of the powder dispersion decreases along with part quality.⁶ This issue is exacerbated when printing harder materials, such as high-strength steels, of interest for Army applications.



Fig. 4 Premature print failure due to uneven powder dispersion caused by a heavily worn elastomeric recoater

Research has been done on the difference between different recoater types (e.g., metallic, ceramic, and polymeric), but little has been done on what properties are critical to the performance of a polymeric recoater. After difficulties with our system we investigated how the hardness and diameter of a polymeric recoater influences recoater wear and the dimensional accuracy of the print. Understanding this relationship will allow for more confidence in the build quality for longer builds and avoid detrimental recoater crashes.

2. Experimental

Multiple prints using AF9628 steel powder were done on the Renishaw AM400 LPBF system to quantify the wear behavior of four different elastomeric recoater wiper materials. All prints were completed using a layer thickness of 30 μm and a 170 °C baseplate heating temperature. All prints consisted of three 180-mm-long by 7-mm-wide walls, shown in Fig. 5.

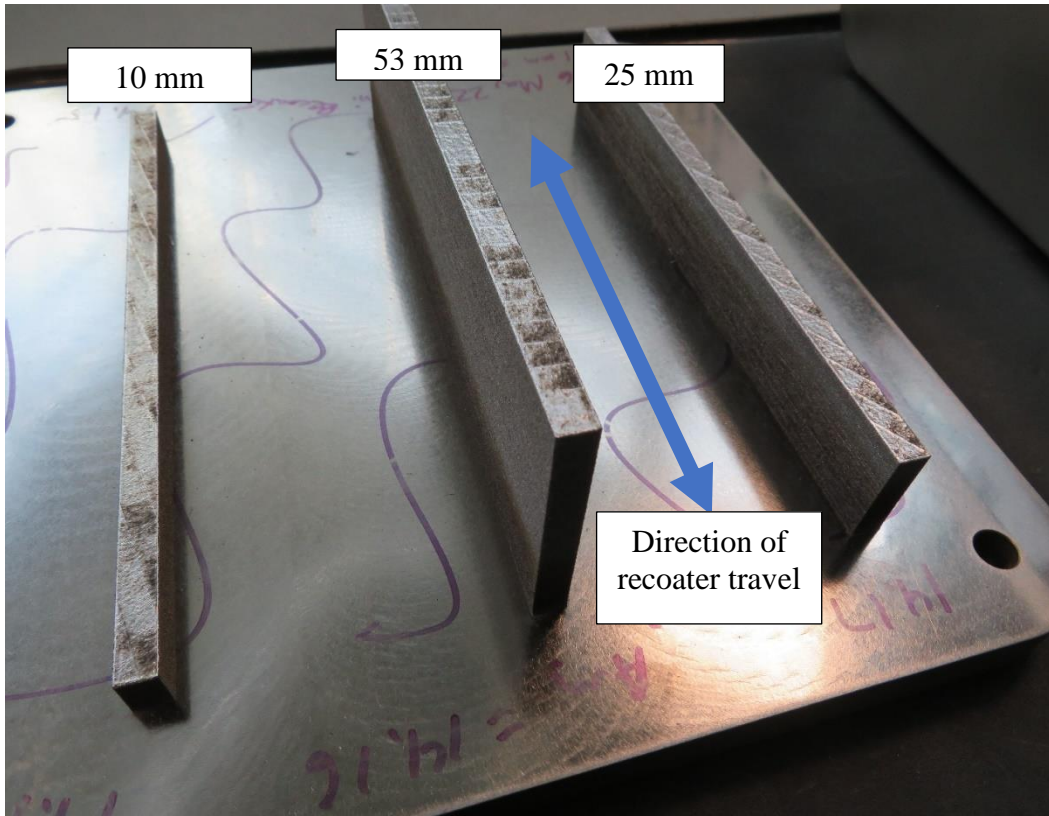


Fig. 5 Printed walls labeled with heights

Each wall had a different height to try to quantify a wear rate as a function of contact distance/time. The walls had heights of 10, 25, and 53 mm, which correspond to contact distances of 60, 150, and 318 m, respectively. By using a stopwatch during the process an estimated recoating time of 2 s was obtained, which yields contact times of 0.2, 0.5, and 1.0 h for the 10-, 25-, and 53-mm walls, respectively. This yields three distinct locations where the built material contacted the recoater material for different amounts of time. A micrometer was used to measure the dimensions of the printed part to evaluate the dimensional accuracy of each. The average of three measurements was taken. To find the amount the printed part deviated from the original dimensions, the following formula was used:

$$\text{Percent Deviation} = \frac{(x_{\text{measured}} - x_{\text{original}})}{x_{\text{original}}} \times 100 \% \quad (1)$$

Four recoaters were selected and tested in this study. All materials were commercially available elastomeric rods; one baseline material being the material supplied by the original equipment manufacturer (OEM) Renishaw for this machine. The other recoater materials were selected based on similar dimensions, material type, and working temperature ranges. A key criterion was the material had to be stable up to a working temperature of 170 °C, which is the baseplate

heating temperature used for printing this steel alloy on the Renishaw system. All recoater materials selected varied in diameter and hardness.

The diameter and hardness of the recoater material was measured to ensure proper comparisons of the materials could be made. The diameter was measured using a micrometer, averaging between three measurements. The hardness was measured using a Shore Type D hardness tester and averaging three measurements. This instrument reports the hardness on the Shore D durometer scale. These recoaters are softer and would be more accurately measured by a Shore A tester but the Shore D tester was what was available at the time of this study. Nevertheless, the Shore D scale is a valid way to at least measure the hardness of the recoater in relation to the other recoaters.

In the Renishaw system the soft recoater is clamped between two aluminum bars with a groove machined into them to accommodate the polymeric rod (Fig. 2). The recoater materials were loaded into four different new recoater arms. Before each print the recoater arms were scanned using the Keyence VHX7000 optical microscope. At least three 2D height profiles were created parallel to the direction of travel for the recoater arm. The height is defined as the distance the polymeric recoater protruded above the aluminum recoater arms (Fig. 2). These profiles were exported and analyzed in Excel.

The top surface plane of the aluminum recoater arms is slightly angled with respect to the plane in which the wiper is mounted. This makes determination of a reference plane to determine the height above which the wiper protrudes nontrivial. This height is the critical metric that determines powder spreading quality and consistency, so it is important that a consistent method was used to compare the wear of the different wiper materials. Therefore, to accurately quantify the height of the wiper protrusion above the aluminum recoater arm it was necessary to normalize the microscope scan data so that each recoater material was referenced to the same zero plane. Two methods of normalization were used for the data.

Method no. 1 was used for the smaller diameter recoaters. In this method a linear line was created from a local minimum on either side of the recoater. These minimums corresponded to a small gap where the recoater contacted the arm, shown in Fig. 2.

However, this did not work for the larger diameter recoaters. These materials bulged out when compressed into the recoater arm and obscured the reference plane, so no minimums could be measured (Fig. 6). Therefore, a different method must be used to standardize the data.

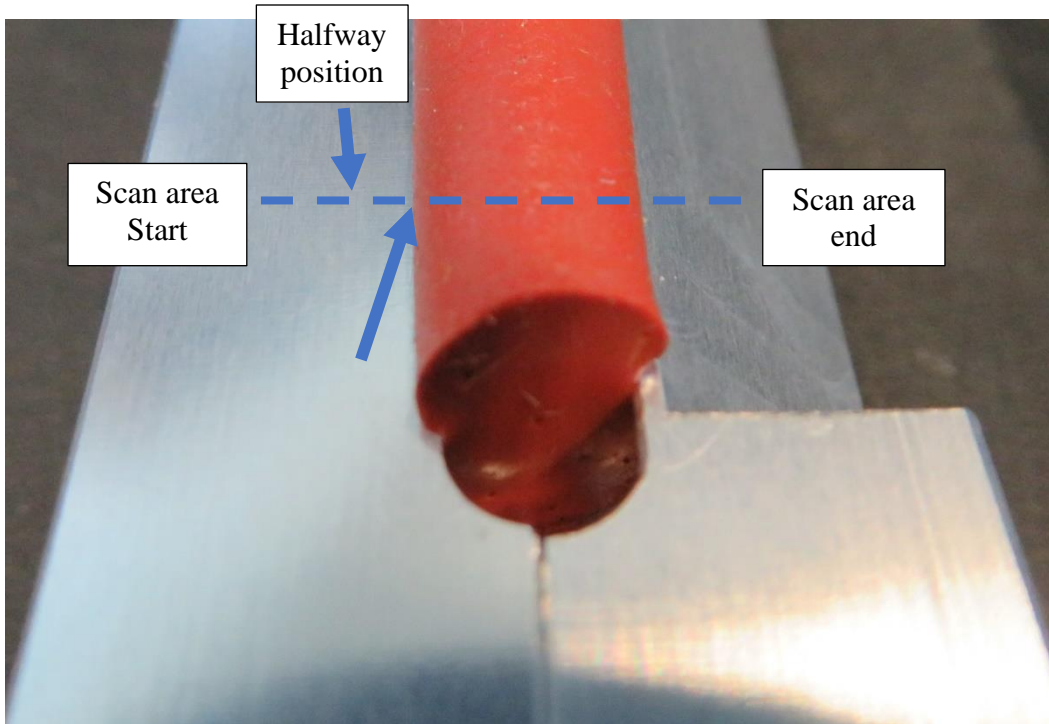


Fig. 6 Larger diameter recoater with Method no. 1 reference features not visible

Method no. 2 was used to normalize the data of the larger diameter recoater materials. This involved roughly identifying the position where recoater material begins, then a linear trendline was fit using the data from the start of the scan area to halfway to the position where the recoater material starts. This ensures a line is fit to a known flat reference surface that does not include any recoater material. Normalized height profiles were created by subtracting the height profiles by the lines created by their respective normalization method. Examples of these methods are shown in Figs. 7 and 8.

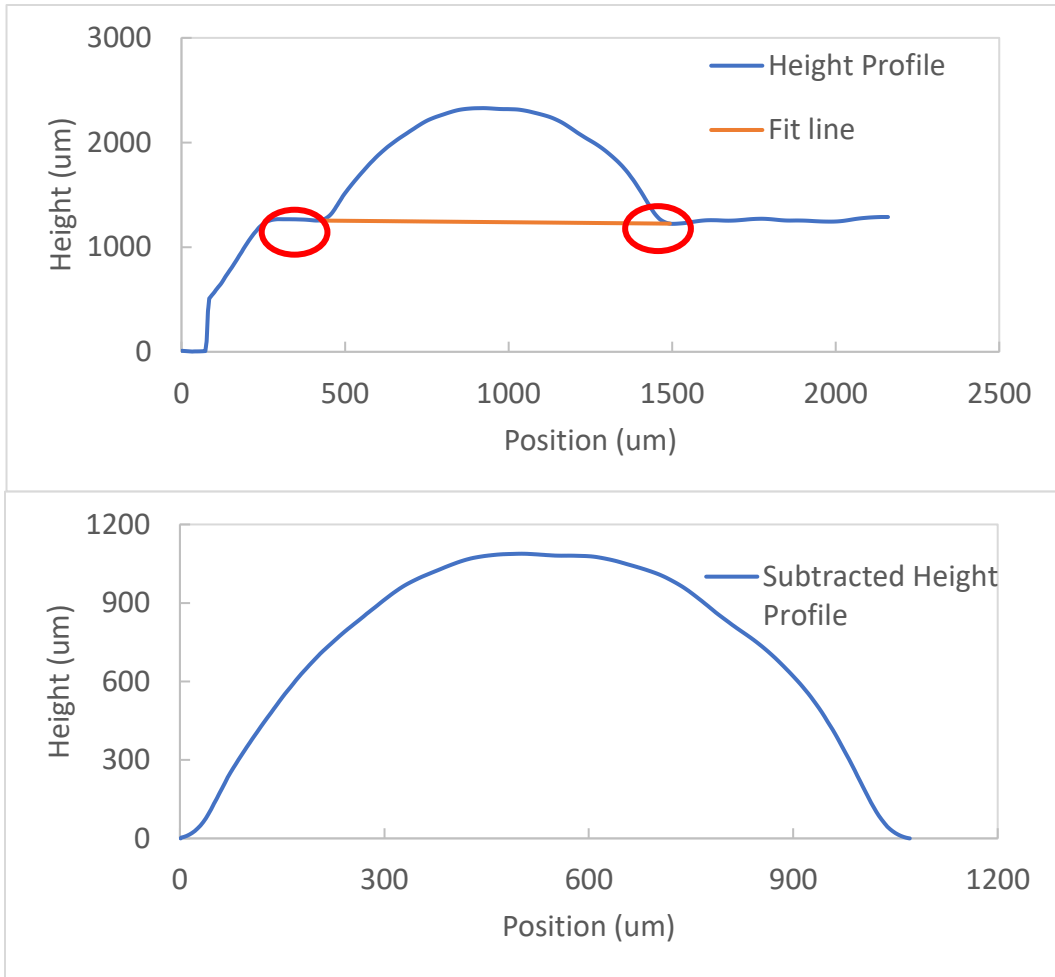


Fig. 7 Example of recoater height normalization using Method no. 1 with local minimums annotated

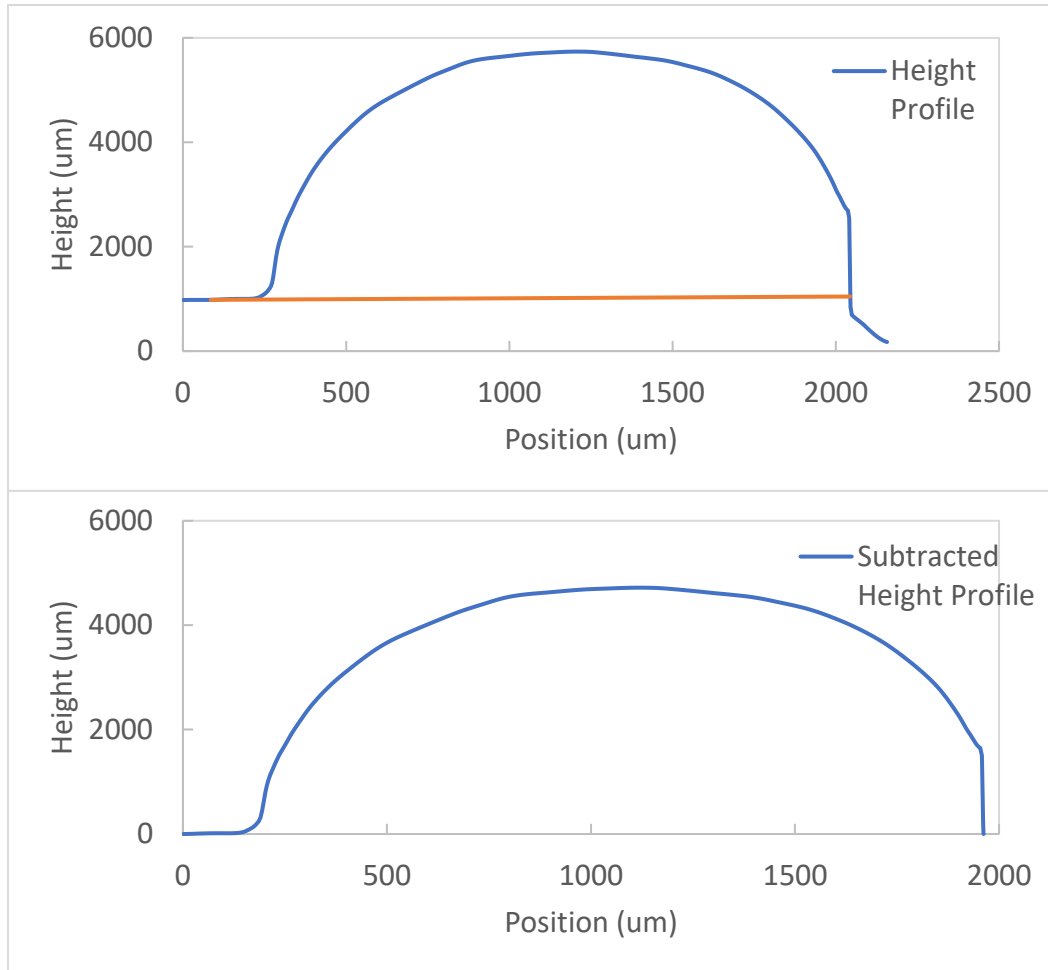


Fig. 8 Example of recoater height profile normalization using Method no. 2

Height profiles were measured using the same microscope and method after the print. At least two profiles were created at each of the three locations of contact between the recoater material and the print (Fig. 9). The wear on the recoater was typically nonuniform in the region that was in contact with the printed parts, so the goal was to quantify the location with the largest height change. The same methods of normalization previously described were used to standardize the data after the build. Note that even though two different methods of normalization were used, the same approach was used for the before-build and after-build for each recoater to determine the change in height caused during the build.

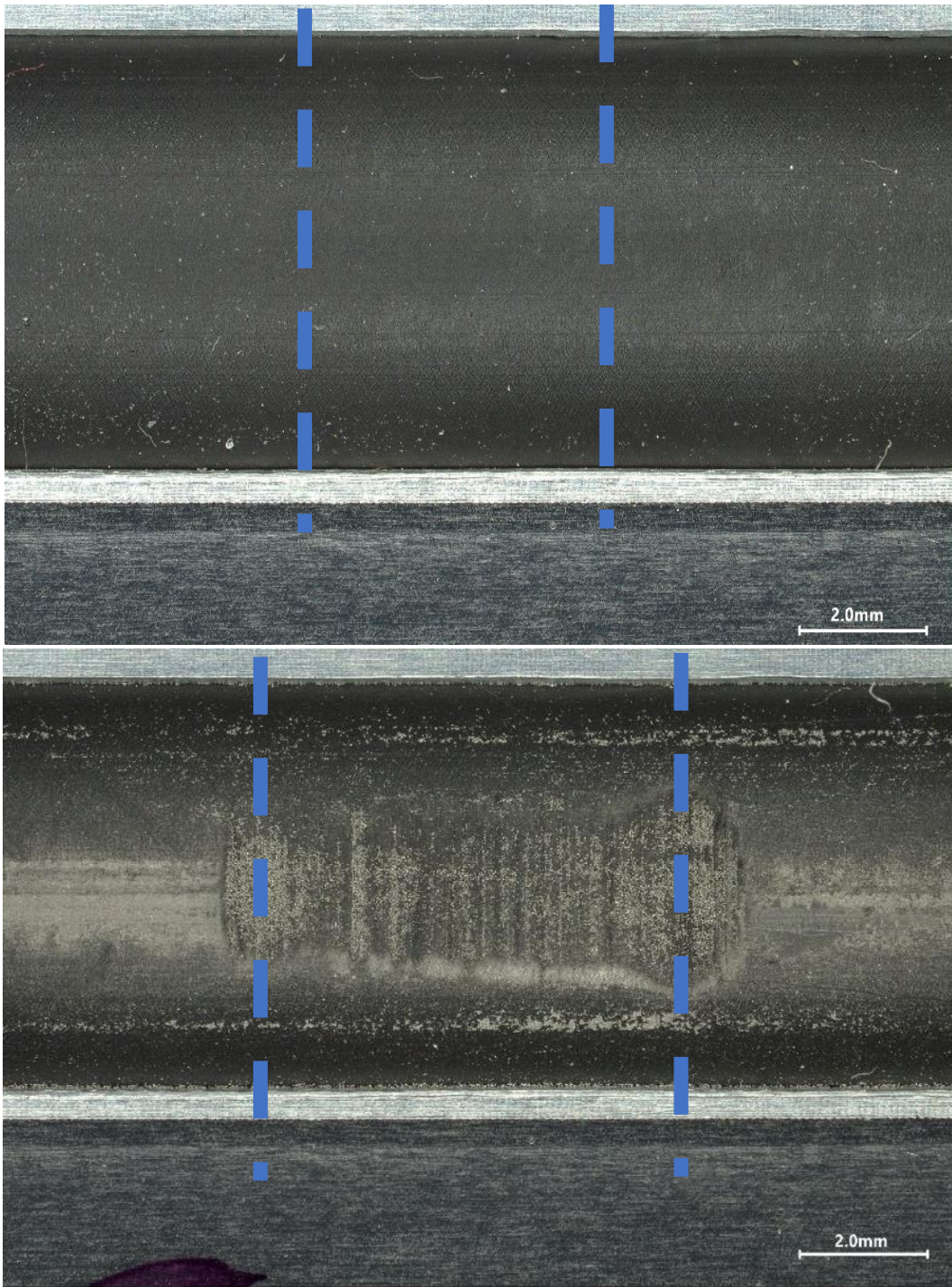


Fig. 9 Example of height profile locations before (top) and after (bottom) the print for Recoater no. 1

Once the normalized height profiles were obtained, the maximum heights for all of the profiles were found. The average of the maximum heights was found for the profiles before the print and used as a baseline. It is assumed that if the recoater

material was loaded into the arm properly, the height would be relatively uniform along the length of the recoater, and an average would be an accurate representation of the height before the build. If the recoater was not loaded correctly, an uneven distribution of powder would have been visible when setting up the build, and this would have been corrected.

The after-build maximum heights were subtracted from the before-build baseline to yield a height change. The maximum height change was then selected for each wear position. The decision to compare the maximum height change was made because this indicates the largest deviation from the rest of the recoater material, and therefore corresponds to the largest inconsistency of powder distribution. These height changes were compared to find any trends relating the diameter or durometer of the recoater materials to the maximum height change or the height change as a function of contact time with the build.

3. Results

The listed and measured properties of the recoaters are shown in Table 1. The Shore D scale does not measure accurately below a value of 6, and Recoater no. 4 measured as a 4.3 ± 0.6 . This means that we do not confidently know the hardness of Recoater no. 4, only that it is less than a 6 on the Shore D scale.

Table 1 Properties of recoater materials with Recoater no. 3 being the baseline recoater supplied by the OEM

Recoater no.	Recoater material	Color	Listed working temperature range (°C)	Measured diameter (mm)	Measured durometer (D)
1	Alfas	Black	-71 to 204	7.85 ± 0.04	30 ± 1.0
2	Silicone	Red	-67 to 204	9.82 ± 0.06	10.3 ± 0.6
3	Silicone	Red	Not listed	7.96 ± 0.01	12.3 ± 0.6
4	Silicone	Black	-73 to 204	9.29 ± 0.19	<6

The notional and actual printed part dimensions are presented in Table 2. The percent deviations are presented in Figs. 10 and 11. All printed parts had less than approximately 2% deviation in dimensions, and no statistically significant trend was seen regarding the effects of hardness or thickness of the recoater on the dimensional accuracy of the printed parts. The dimensional accuracy did vary slightly between recoaters, with Recoater no. 3, the one provided by the OEM, having the least deviation from the original part dimensions. For all walls the thickness deviation was greater than the height deviation. Overbuilding in this dimension is common for AM parts and was expected. Although not particularly

relevant to the goals of the current study regarding recoaters, note that this data will be used to calculate improved geometric compensation values for AF9628 steel alloy printed on the Renishaw AM400 to improve the accuracy of future printed parts.

Table 2 Measured dimensions of printed walls

Wall measured (mm)	Recoater no.	Average height (mm)	Average thickness (mm)
10	1	9.750 ± 0.093	7.433 ± 0.033
	2	10.29 ± 0.09	7.417 ± 0.015
	3	9.885 ± 0.070	7.340 ± 0.027
	4	9.788 ± 0.103	7.385 ± 0.013
25	1	24.68 ± 0.16	7.315 ± 0.045
	2	25.30 ± 0.10	7.368 ± 0.013
	3	24.94 ± 0.27	7.293 ± 0.021
	4	24.88 ± 0.12	7.298 ± 0.005
53	1	52.69 ± 0.134	7.348 ± 0.050
	2	53.24 ± 0.11	7.400 ± 0.041
	3	52.87 ± 0.30	7.308 ± 0.033
	4	52.76 ± 0.13	7.333 ± 0.051

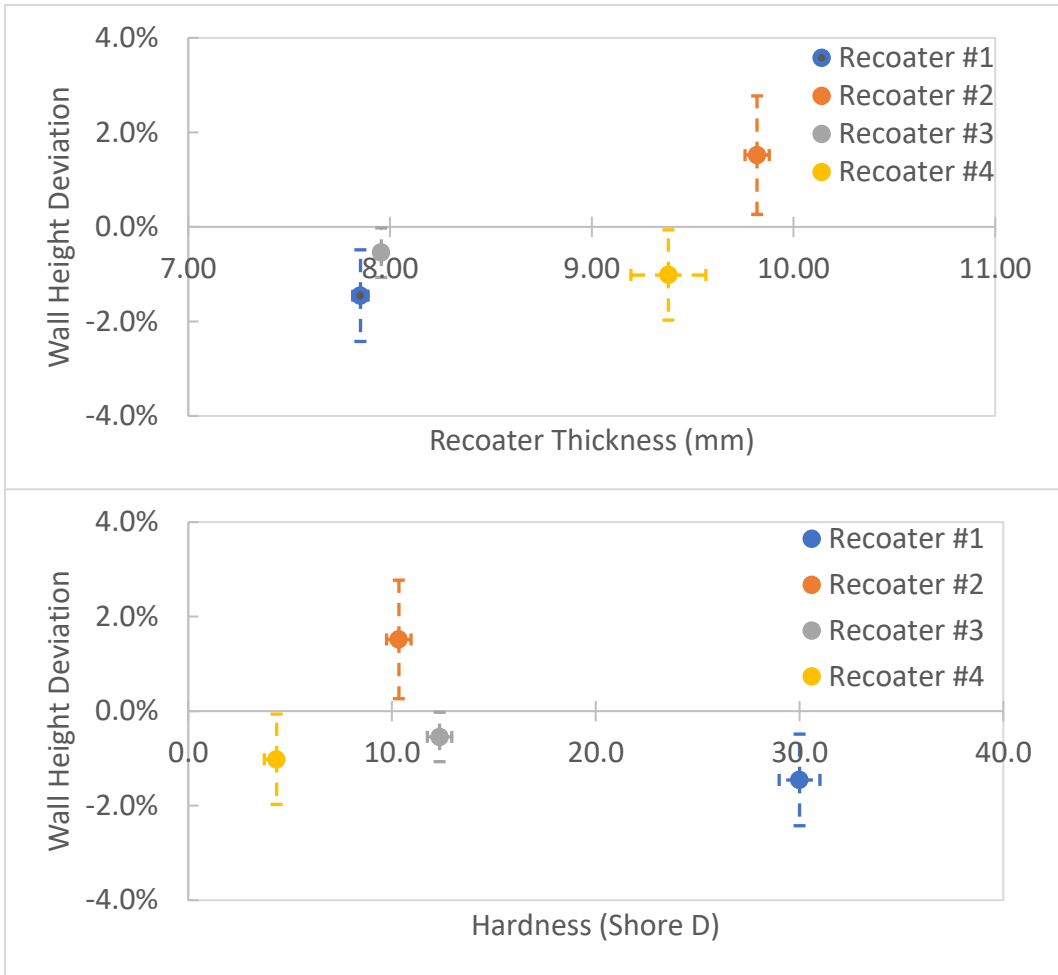


Fig. 10 Wall height deviation as a function of recoater thickness (top) and hardness (bottom)

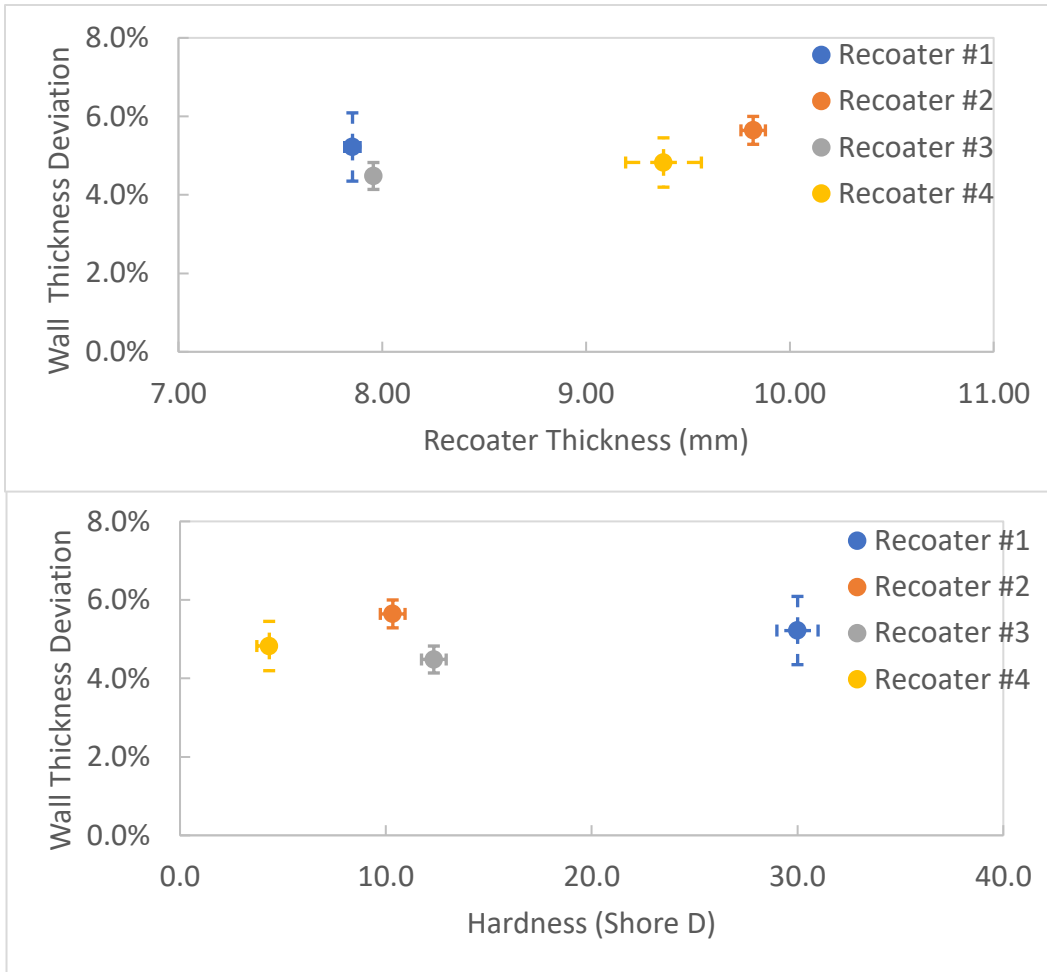


Fig. 11 Wall thickness as a function of recoater thickness (top) and hardness (bottom)

Figures 12–18 show 2D and 3D scans of the recoater arm before the print. All 2D and 3D scans of the recoater arm after the build show the contact location that saw the highest height change after the print. Note that the scales are not consistent across all figures. Wear markings from contact with the printed wall can be seen on the surface of the surface Recoater nos. 1, 3, and 4.

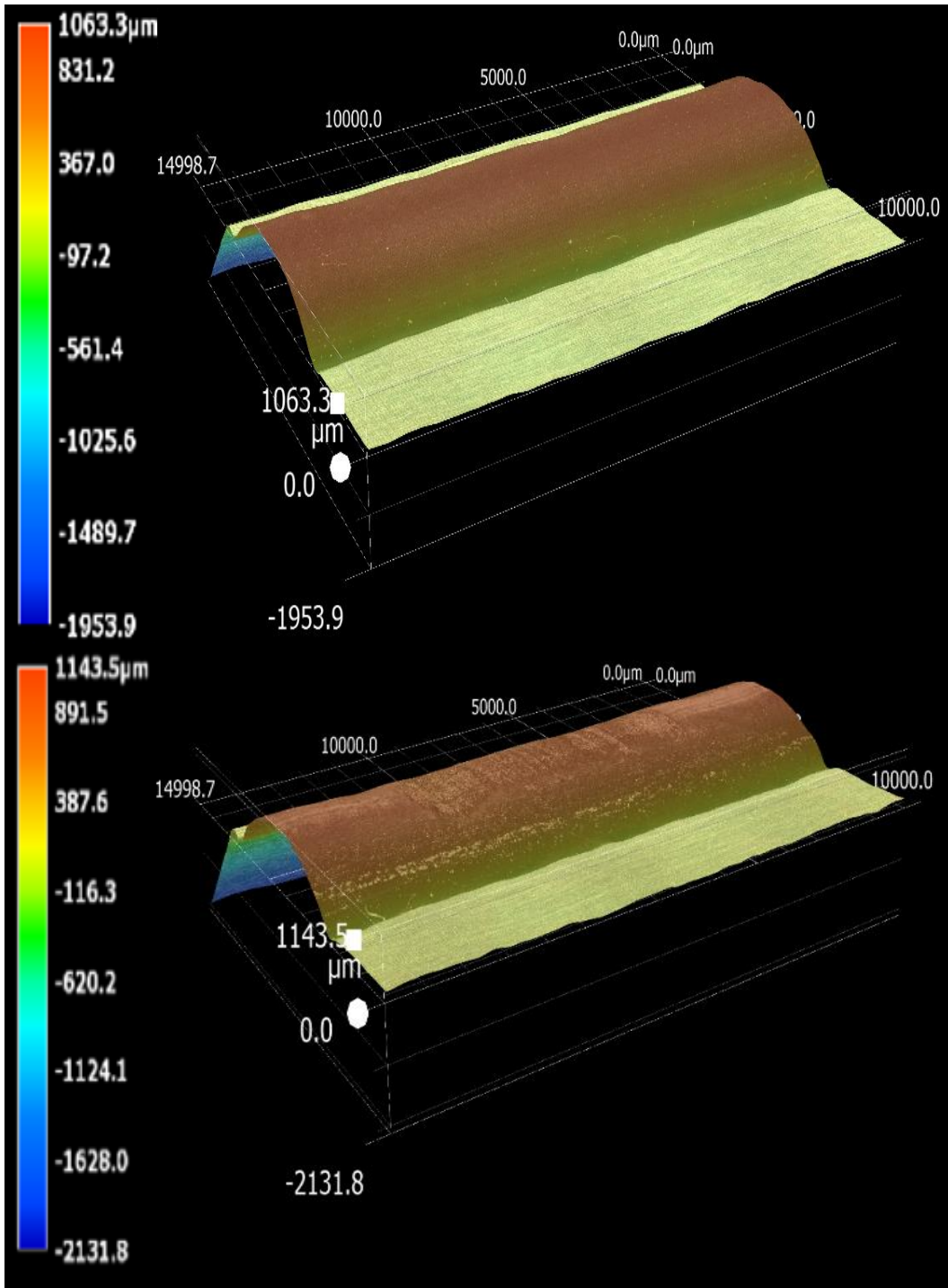


Fig. 12 3D profiles of Recoater arm no. 1 before (top) and after (bottom) the print

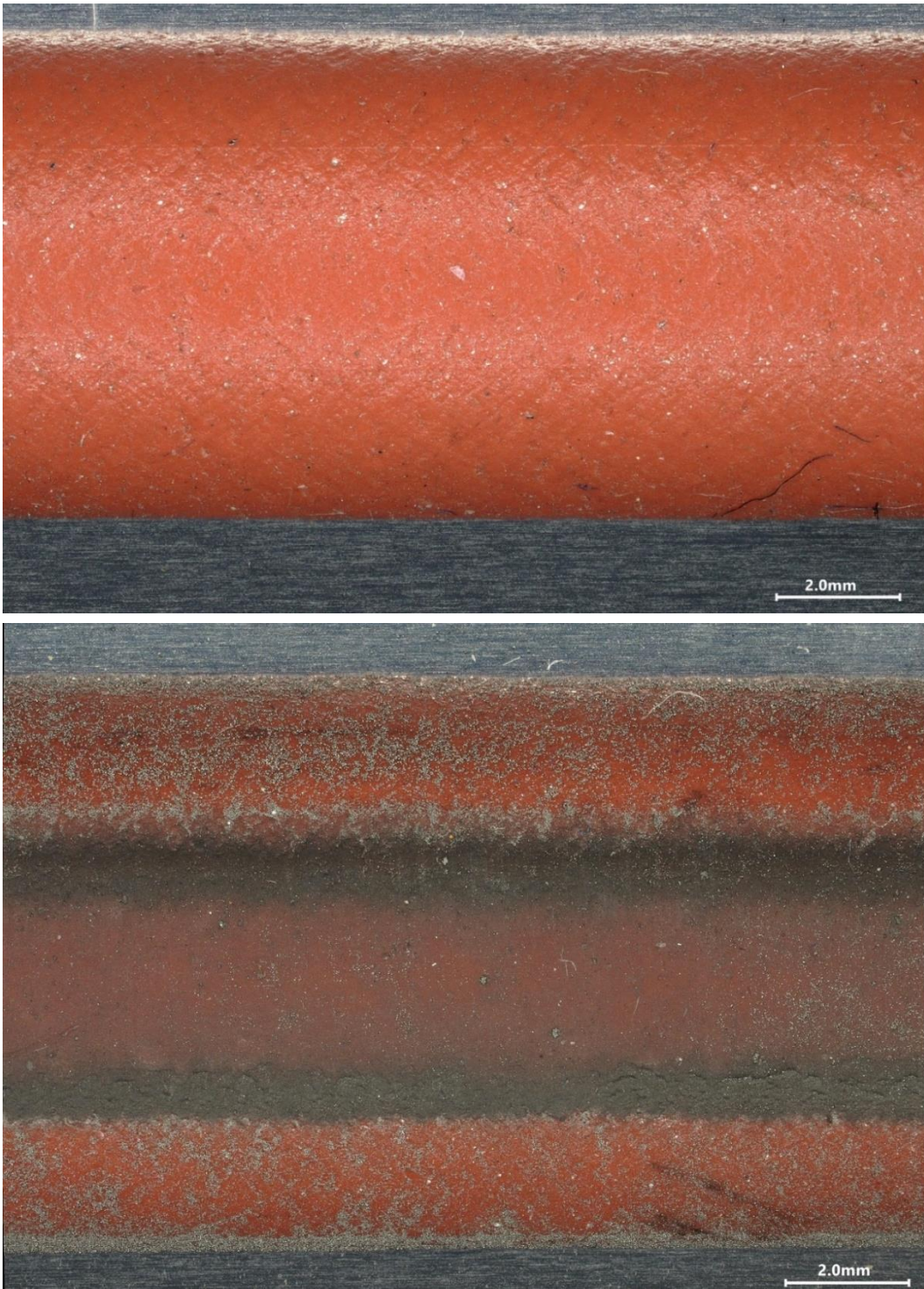


Fig. 13 Recoater arm no. 2 before (top) and after (bottom) the print

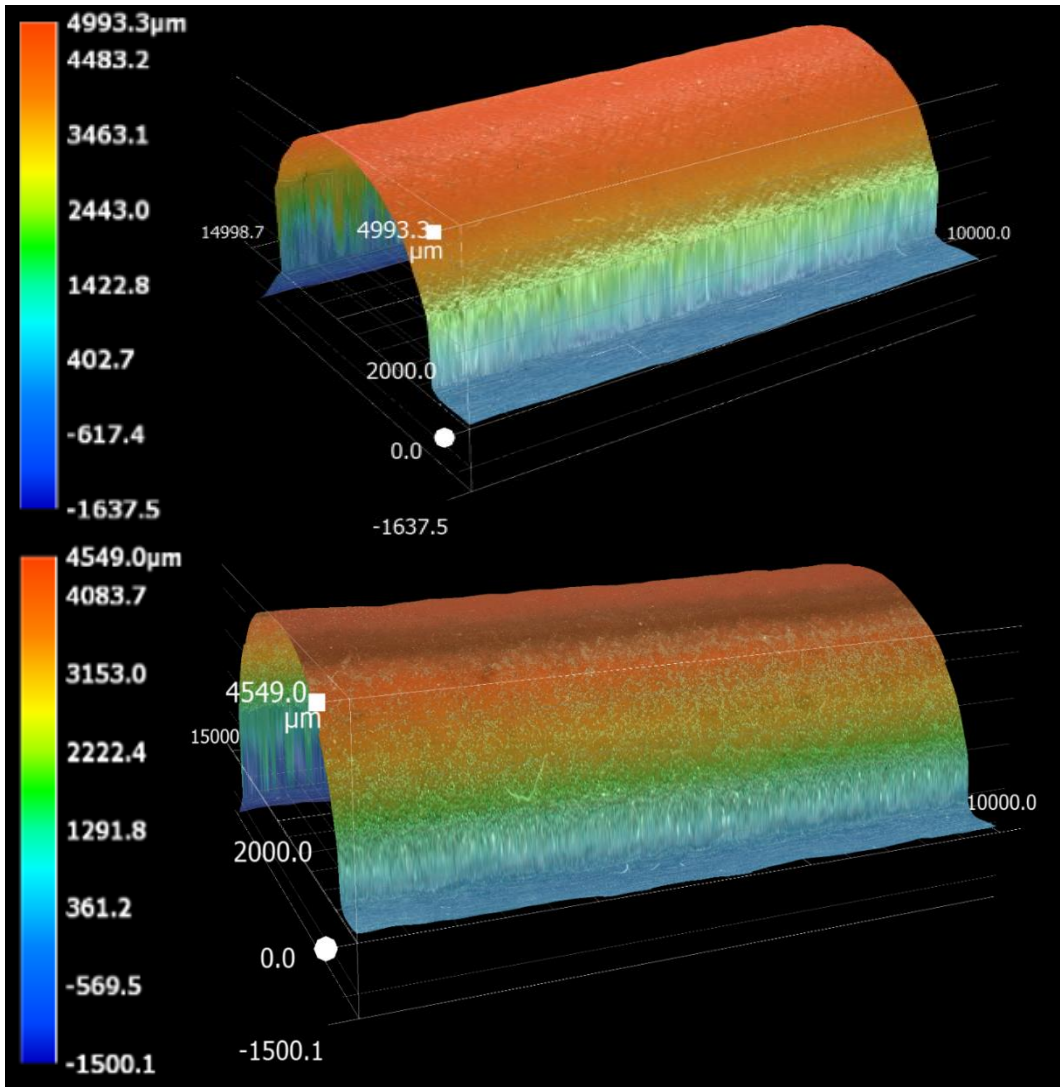


Fig. 14 3D profiles of Recoater arm no. 2 before (top) and after (bottom) the print

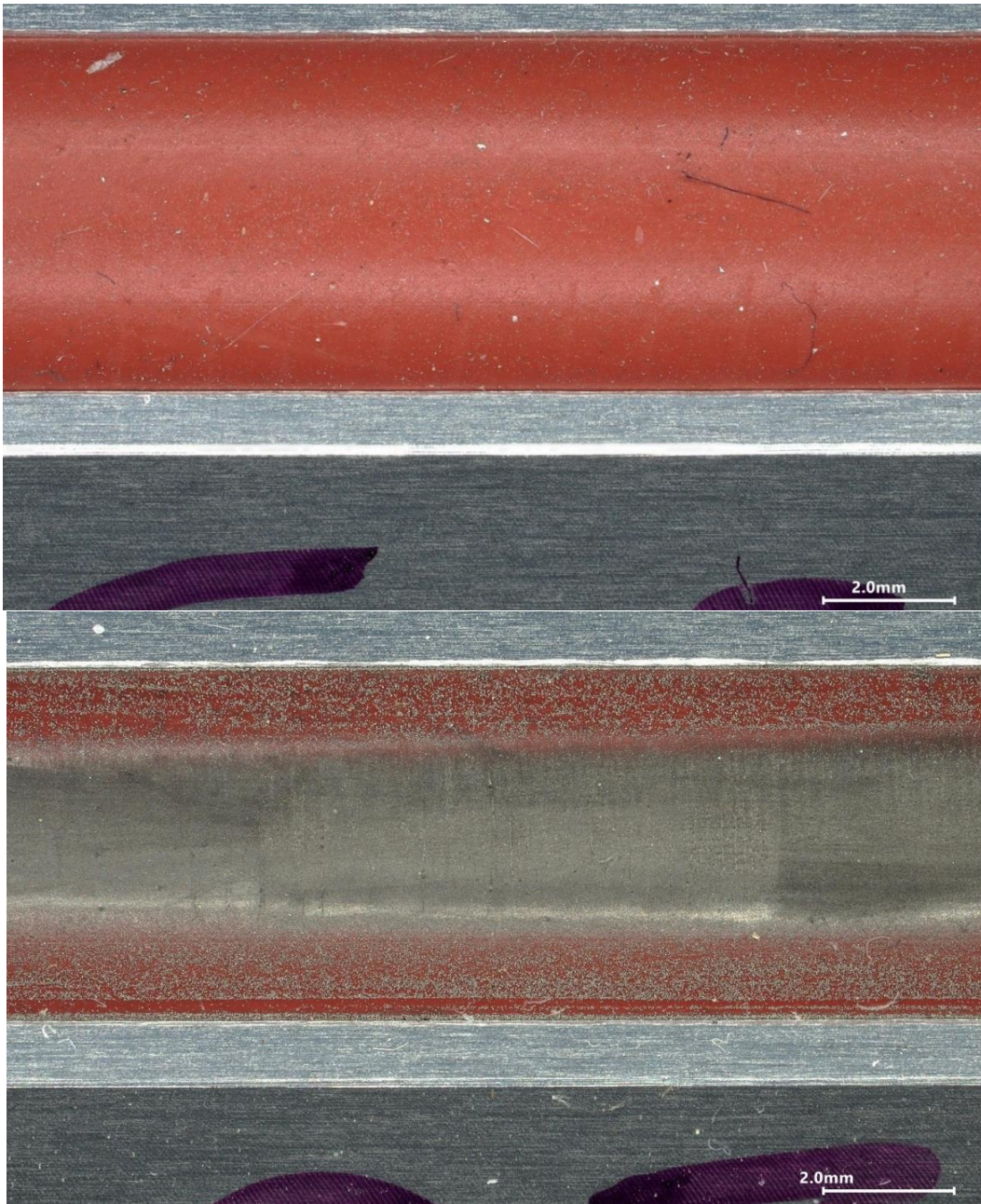


Fig. 15 Recoater arm no. 3 before (top) and after (bottom) the print

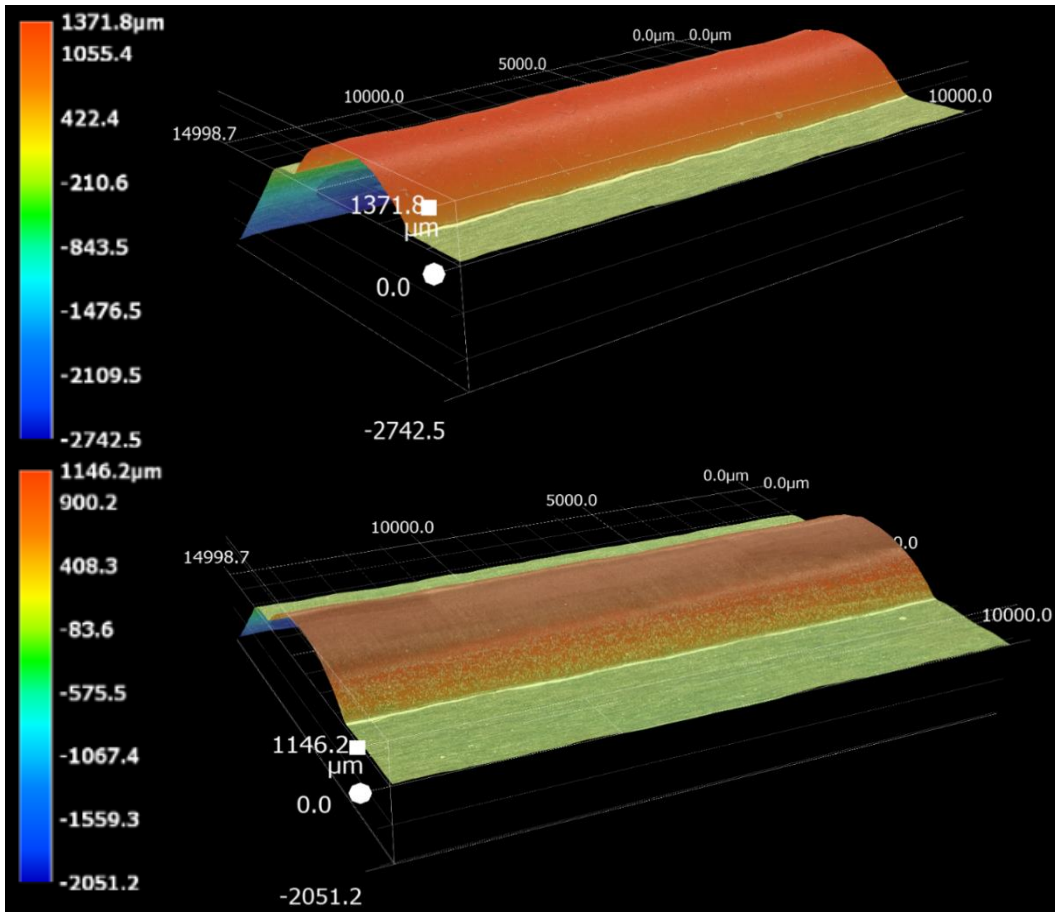


Fig. 16 3D profiles of Recoater arm no. 3 before (top) and after (bottom) the print

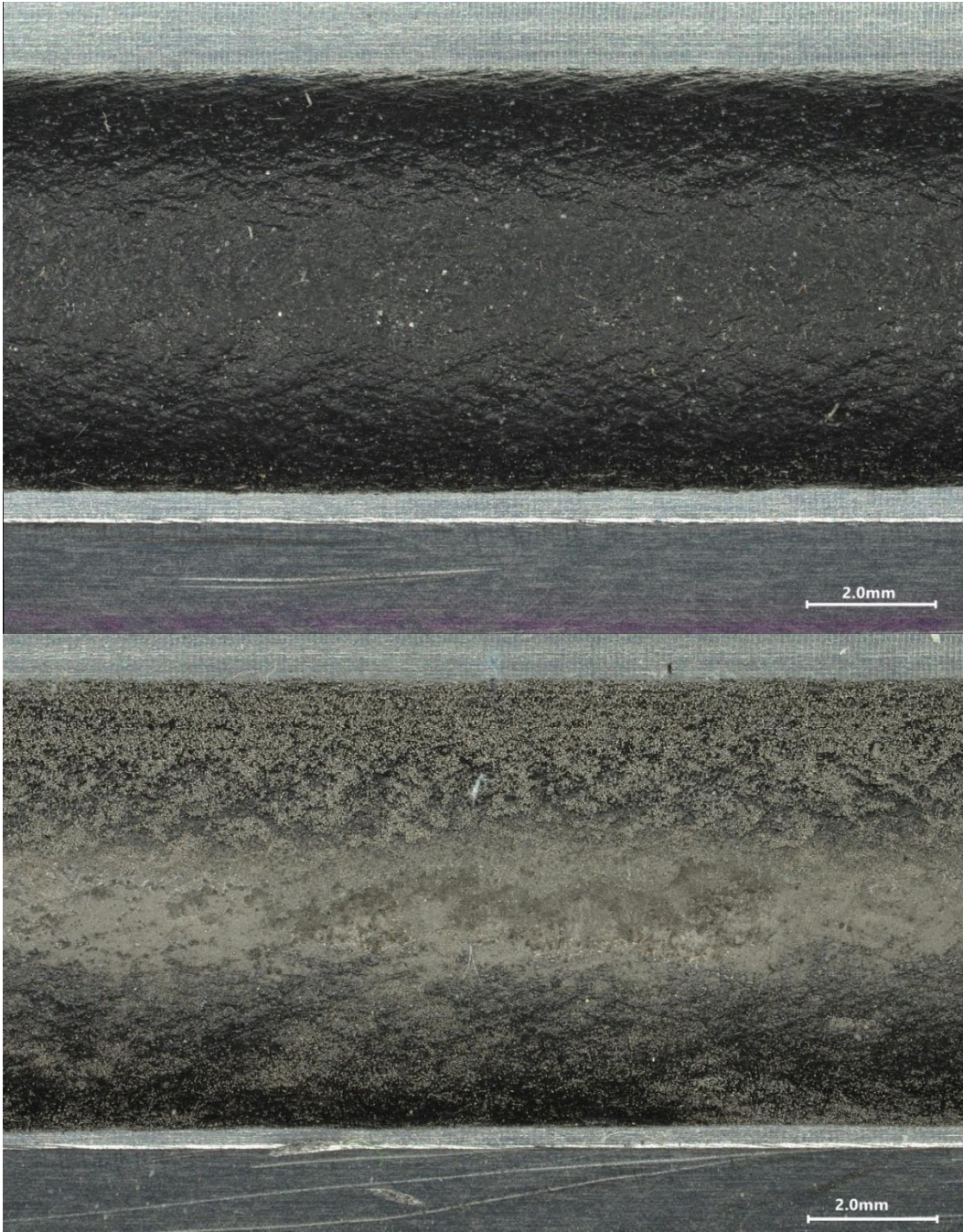


Fig. 17 Recoater arm no. 4 before (top) and after (bottom) the print

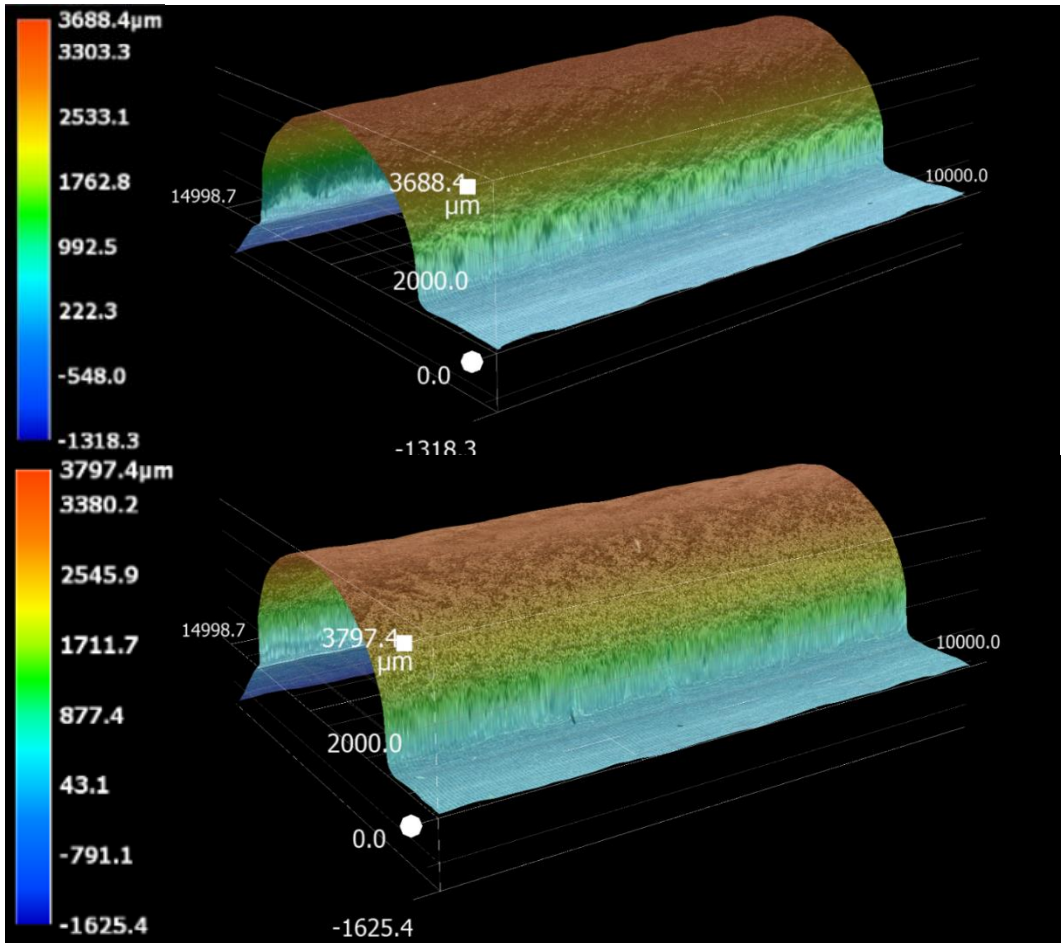


Fig. 18 Recoater arm no. 4 before (top) and after (bottom) the print.

Figures 19–22 show the curves with the largest height change profiles for each wear position compared to their baseline profile. The baseline profile depicted here represents the average normalized maximum height value for that recoater.

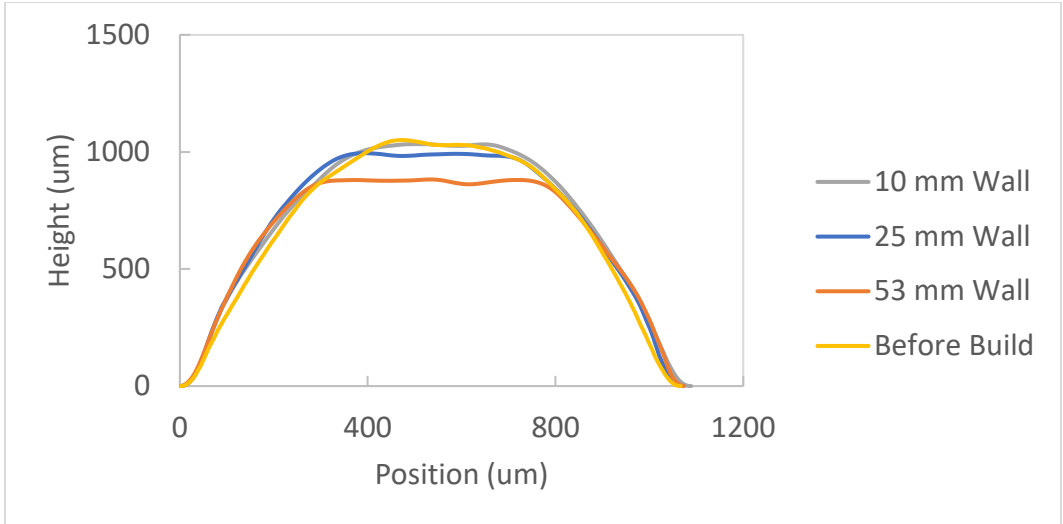


Fig. 19 Maximum height change profiles for Recoater no. 1 compared to baseline profile

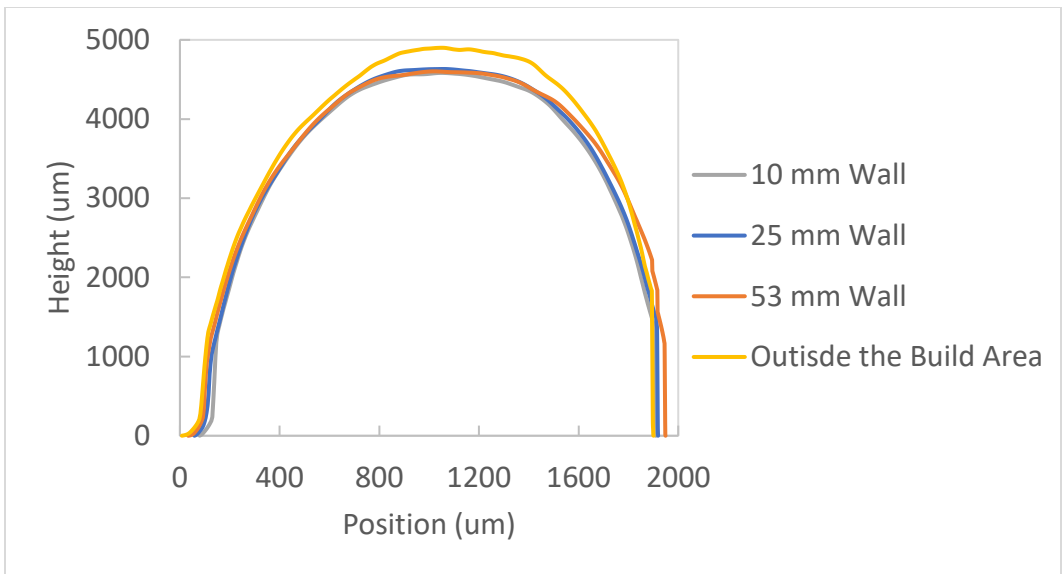


Fig. 20 Maximum height change profiles for Recoater no. 2 compared to baseline profile

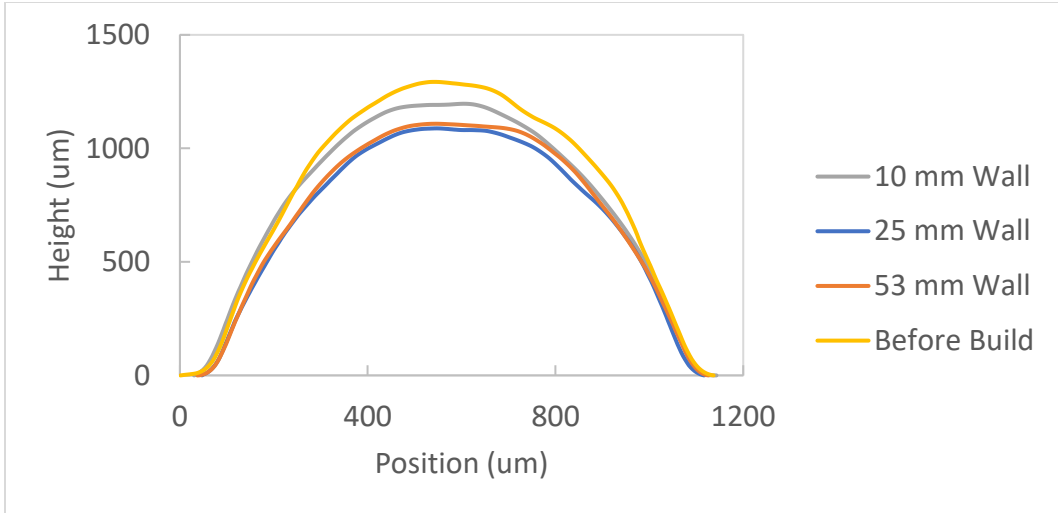


Fig. 21 Maximum height change profiles for Recoater no. 3 compared to baseline profile

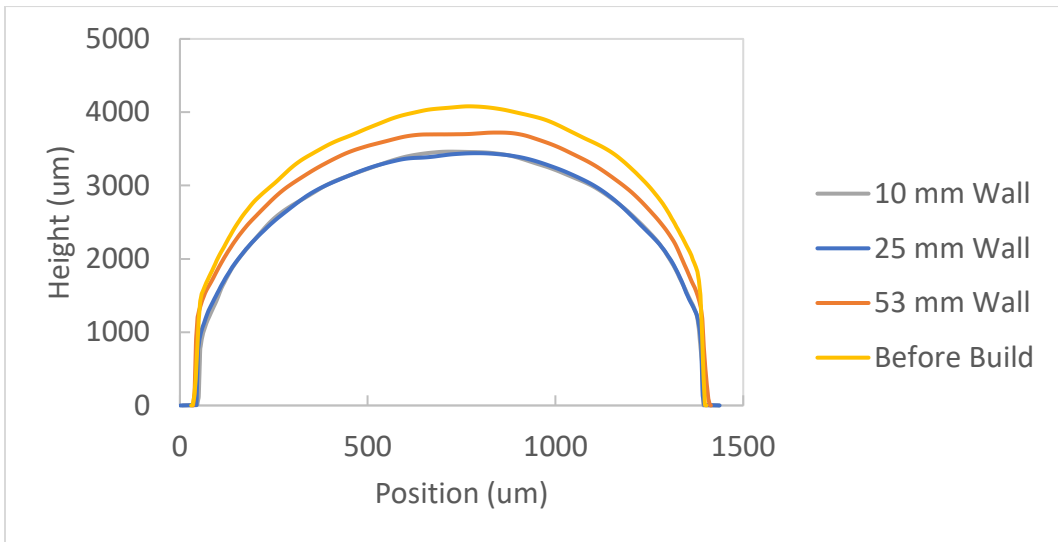


Fig. 22 Maximum height change profiles for Recoater no. 4 compared to baseline profile

When loading Recoater no. 2 into the machine there were some issues securing the arm due to the thickness of the recoater material. Even with the recoater arm mounting set screws moved all the way up, the recoater material was still contacting the build plate and the bottom of the chamber with considerable pressure. With some effort the recoater arm was loaded into the machine with the recoater material compressed. The material remained compressed as the machine heated up to begin the build. We believe that this sustained pressure along with the heating of the chamber allowed the recoater material to permanently deform due to creep, reducing the initial height of the recoater material as compared to the measurements

taken prior to loading into the machine. This change was evident when the recoater was moved back over the build plate after heating, and there was noticeably less resistance and rubbing between the two surfaces. Due to this compression the before-build profiles were no longer accurate baselines for the recoater. To remedy this, additional profiles were taken after the build in locations where no build material was present. This yielded a baseline profile that appeared to bulge outward compared to the original profile. The height changes reported are using these outside the build area curves as a reference. This process was not done for any of the other recoaters. No difficulty was found inserting the other recoater arms and therefore no excessive pressure was placed on the recoater material, which would result in creep and a change in the recoater geometry before the print.

The maximum height change at each wear position on the recoater arm for each recoater material is displayed in Fig. 23. Additionally, the maximum height change across all three walls for each recoater is plotted as a function of hardness and thickness in Figs. 24 and 25, respectively. The standard deviation and error bars come from the standard deviation of the baseline maximum height, as this shows the uncertainty of the height change due to inconsistencies in the baseline height.

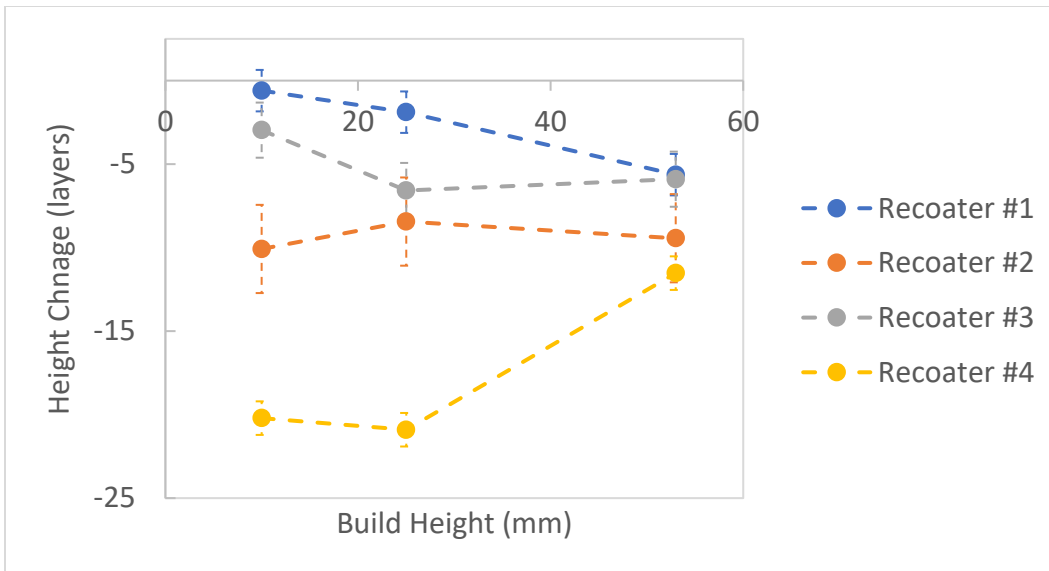


Fig. 23 Height change in the recoater materials represented in build layers (1 layer = 30 μm) as a function of build height

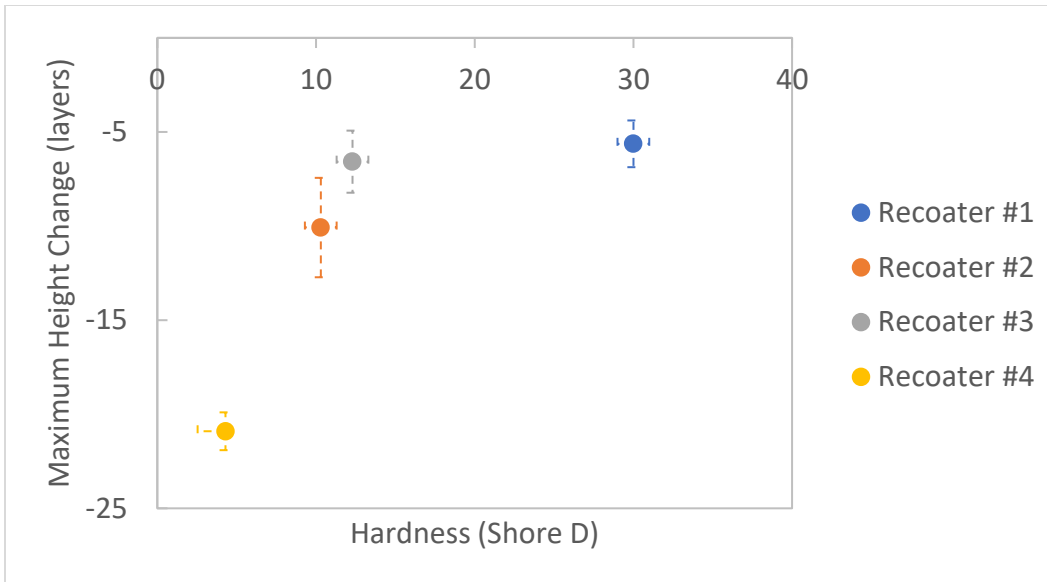


Fig. 24 Maximum height changes in each recoater material as a function of hardness

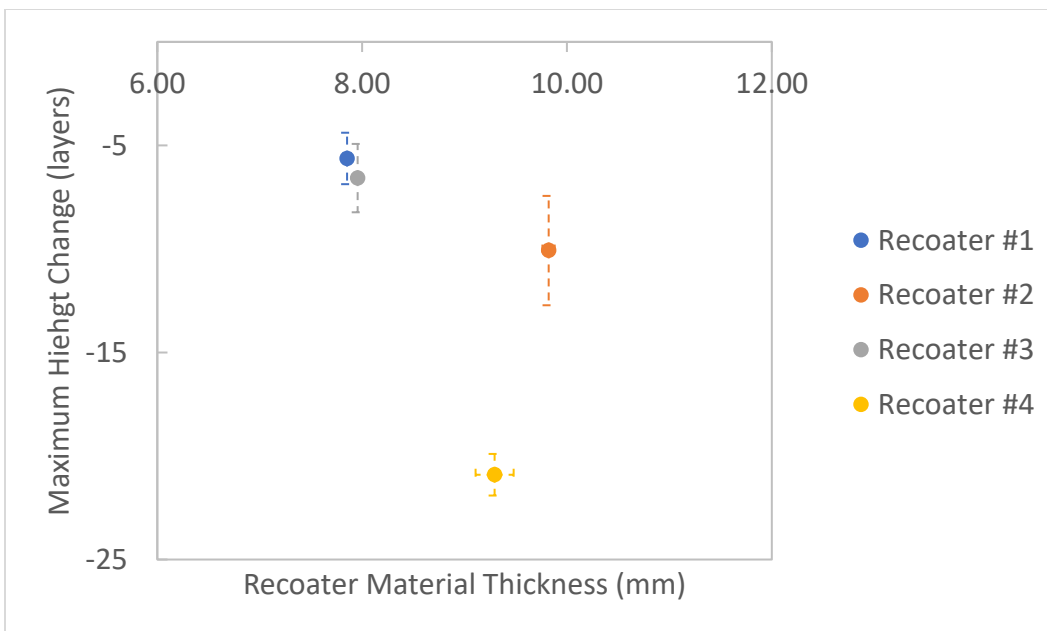


Fig. 25 Maximum height changes in each recoater material as a function of recoater material thickness

4. Discussion

The maximum height change varied between recoaters as did the trends regarding contact time. The data shows height change decreasing with increasing hardness in a somewhat logarithmic relationship. This means the harder the recoater materials, the less of a gap change between the recoater and the build and therefore fewer

inconsistencies in the powder distribution on the build platform. The data shows no consistent trends regarding the height change as a function of material thickness. Additionally, only Recoater no. 1 showed monotonically increasing height change with contact time, and Recoater no. 2 shows relatively consistent height changes independent of contact time.

When analyzing the height profiles of each recoater, we can see some evidence that shed light on the mechanism by which height changes occurs. Recoater nos. 1 and 3, the hardest materials, show a flat spot being worn into the top of the recoater due to material removal during use. This is supported by wear marks seen in the 2D images of the wear areas. Recoater no. 2 shows no clear wear marks as well as no flattening of its height profiles. It is assumed that the material is soft enough to deform out of the way of the build, compressing and undergoing creep, similar to how it deformed when inserted into the machine. Recoater no. 4, however, shows clear signs of material wear on its surface with little flattening of its curve. It is theorized that this material was so soft that it made material removal extremely easy but was able to maintain a constant thickness due to recovery of the elastic strain, and/or creep deformation, imparted during compressing the recoater into the arms.

5. Conclusions

The following insights provided by the current study offer critical quantitative insights on the selection considerations for the user of LPBF systems that use tubular polymeric recoaters.

- Recoater durometer had a significant impact on the wear rate with a clear trend showing that harder materials have less wear.
- Recoater diameter had no statistically determinable effect on wear rate.
- The recoater material and diameter had little impact on the dimensional accuracy of the printed parts.
- The material and diameter did have effects on the wear rate of the recoater.
- Being able to predict the response of the recoater material allows the operator to reliably plan for inconsistencies in the print and take preventative or corrective actions.

Although this study is specific to a single model LPBF machine and material feedstock combination, it is believed that the relationship found between recoater hardness and height change is transferable between different systems. Future work can be conducted with a larger variety of diameter and hardness recoater materials to further validate these findings.

When determining which recoater is optimal, multiple considerations must be made. The dimensional accuracy and the success of the print is critical. Even though all prints were successful and showed similar dimensional accuracy, a wall is a simple geometry and not a challenge to print. The large height changes in Recoater nos. 2 and 4 are expected to cause issues in more complex geometries due to their large height changes resulting in a significant deviation from the usual recoater build area gap, especially when printing taller and larger parts. Future studies should explore different geometries to test this.

Additionally, the desire for a uniform powder distribution throughout the print is important for consistent properties throughout the printed materials and confidence in success of completion of longer builds. The prevention of heterogenous wear is important as well as maintaining the correct recoater gap. Meaning that total cumulative, and localized height changes, are both important.

Our team plans to implement Recoater no. 1, the hardest recoater tested, instead of the OEM-supplied Recoater no. 3 for further evaluation while printing relevant parts with the primary goal being to decrease the rate of build failures, particularly in long (>5 days) builds with components having constant cross-sections being melted (e.g., tall tubes). This decision was based on the low height changes of the wiper material and the presence of a consistent and predictable trend between height change and contact time. An additional consideration arising from this decision is that due to the evidence of recoater material removal during the print, polymeric debris in excess of that created by the OEM wiper is expected to be introduced to the system. Additional work can be done to characterize the impact of this debris on the properties of printed parts and chemical composition of the feedstock.

Identifying the relationships between recoater properties, printed component performance, and build success rate is crucial. Being able to predict the wear behavior of soft elastomeric recoaters as a function of contact time is critical for certification of the build process and the quality of subsequent parts. This understanding enables repeatability of prints and reliability of the methods used to develop the process for subsequent printed metallic components.

6. References

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List of Symbols, Abbreviations, and Acronyms

2D	two-dimensional
3D	three-dimensional
AM	additive manufacturing
ARL	Army Research Laboratory
DEVCOM	US Army Combat Capabilities Development Command
LPBF	laser powder bed fusion
OEM	original equipment manufacturer

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