METHODS OF AUTOMATING THE LASER-FOIL-PRINTING ADDITIVE MANUFACTURING PROCESS

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Abstract

Laser Foil Printing (LFP) is a laser-based metal Additive Manufacturing (AM) method recently developed at Missouri University of Science and Technology. This study investigates and compares two different methods of automating part fabrication for the LFP process. Specifically, the edge elevation issue due to laser cutting is investigated. Edge elevation occurs after the foil cutting operation, which is an essential step of the LFP process. Previously, mechanical polishing was done to remove the elevated edges for the fabrication of each layer. However, as mechanical polishing is very time-consuming, the current study focuses on two other methods to eliminate the elevated edges. One of them uses laser polishing to remove the elevated edges. Another method is changing the order of the fabrication steps between pattern welding and contour cutting in the LFP process. Comparisons are made to observe the differences in part quality, properties, and building time between these two methods.

Introduction

It is known that the additive manufacturing (AM) processes were developed starting in the mid-1980s, however, AM techniques have more than 150 years of historical roots from topography and photo sculpture [1]. Since then, AM technology has gone through continuous innovation and further research to satisfy the needs of industry [1]. Therefore, within the insight of technological novelties, the improvements of AM technologies can be observed. In recent years, various industries (i.e., aerospace, energy, medical, etc.) have shown increased interest specifically in laser additive manufacturing (LAM) technology [2]. LAM is mainly used for fabricating metal parts, and this technology primarily focuses on powder and wire as the feedstock [3]. However, a novel method developed at Missouri University of Science and Technology called Laser Foil Printing (LFP), which uses metal foil as the feedstock, has brought a new perspective to LAM [4]. Because this method of fabrication uses a different type of feedstock, i.e., metal foil, it has various advantages and limitations over other powder or wire-based technologies.

To begin with the practical advantages of LFP, the material type can be changed faster and easier than powder-fed systems. In powder-bed systems, before the material change, the entire system needs to be cleaned, and the system needs to be prepared for the new powder type. For the

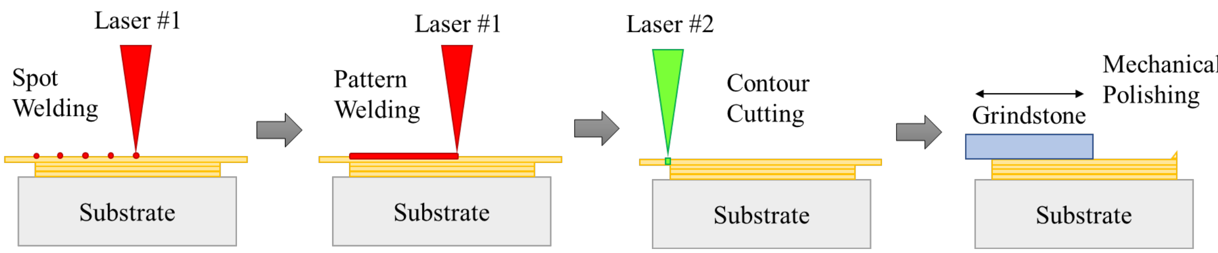
LFP system, the change of foil feed takes only a couple of minutes, and then the system is ready for the new type of material fabrication. Moreover, LFP has a clean fabrication environment without producing any dust that would cause a serious health hazard. In addition, the material cost for foils is generally much lower than powders. Furthermore, the scrap materials of foils can be easily recycled unlike the powders [5]. As a result of these practical advantages, it can be said that LFP is a functional and user-friendly method that potentially can be used easily and safely. In addition to the practical advantages, there are also some technical advantages of LFP. A comparative study showed that laser-foil-printed parts have finer grains and higher tensile strength than laser powder bed fusion (LPBF) parts [6]. In another comparative study between LFP welding modes, the keyhole and conduction welding modes were presented [7]. As a result of that study, conduction mode is preferred for obtaining laser-foil-printed parts with lower porosity, finer grains, and higher tensile strength [7].

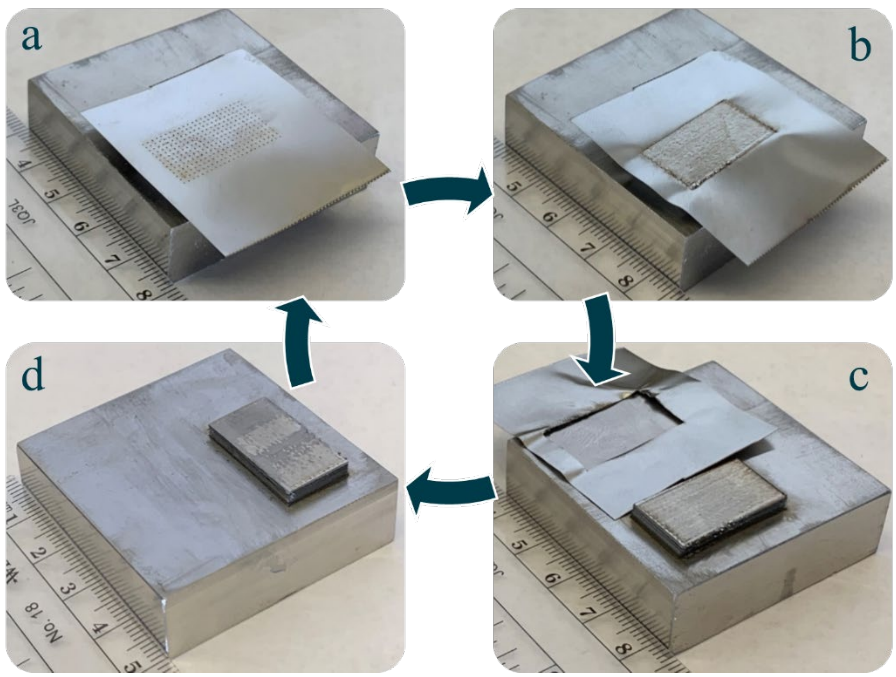
In terms of the current limitations of LFP, because the system is in-house developed without using advanced lasers, the process is relatively slow and needs to be improved to become more productive. Additionally, because foils are not as flexible as powders in layered building of parts, the LFP process is currently lacking in building parts with highly complex geometries, such as lattice [8] or honeycomb [9] structures, which can be done without difficulty with laser powder-fed AM methods.

Recently, our LFP system has been automated and the whole process can be completed without any manual steps. Before the development of a fully automated LFP system, only the laser processing steps (laser spot-welding, laser pattern-welding, and laser cutting) of LFP were automated. On the other hand, the excess foil removal and mechanical polishing steps were done manually. The automated LFP system's repeatability and ease of application reduce the time spent on the human-machine interaction. Additionally, the semi-automated process is likely to cause some human errors. Thus, all these potential errors are eliminated after automation. However, there are still some issues to be further investigated in order to increase the machine's productivity, such as the current study's focus on edge elevation after the laser cutting operation.

Overview of LFP Process Steps and System

To successfully perform an LFP process to build one metal foil on the substrate or previous layer, a four-step process needs to be completed. This process steps include (1) spot welding to fix the metal foil, (2) pattern welding to perform foil bonding, (3) laser cutting to remove the excess material from the layer, and (4) mechanical polishing to remove elevated edges caused by the previous step of laser contour cutting. These four steps are illustrated in Fig. 1 and Fig. 2.

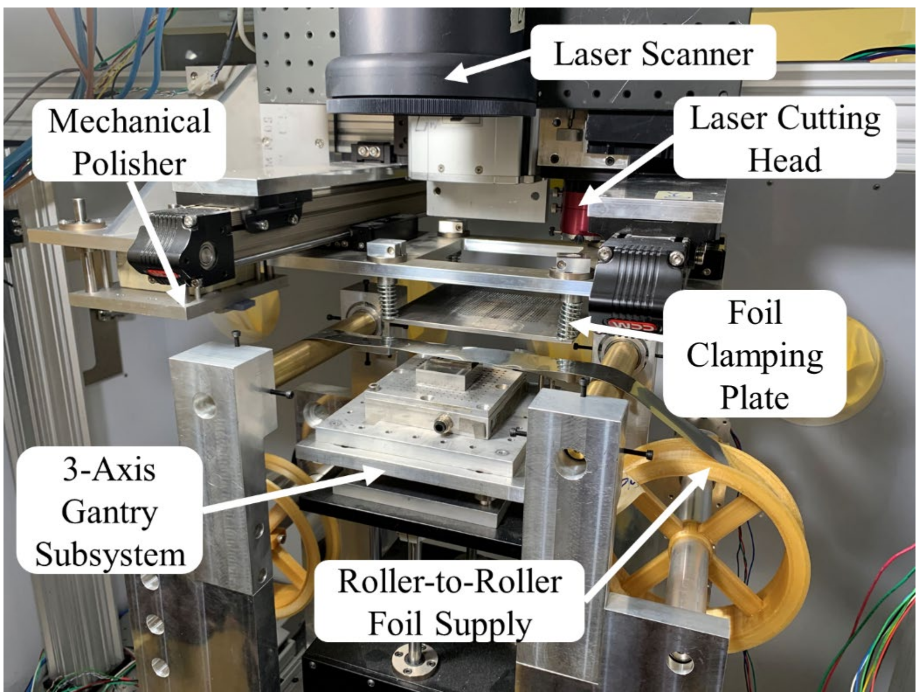




The LFP system consists of a dual-laser system to perform foil bonding and excess foil removal operations. In addition to the dual-laser system, a roller-to-roller foil supply subsystem, a foil clamping subsystem, and a 3-axis gantry subsystem are used to transport, position, and manipulate the foil. Before this study, a mechanical polisher (grindstone) was used to remove the elevated edges after each layer building.

In detail, the first step is spot-welding, which is done to temporarily fix the foil to the previous layer to prevent any potential distortion during the pattern-welding operation. During the spot welding, the clamping plate, which is a plate with holes to let the weld spots pass through the plate, applies pressure on the foil to ensure that the foil is flat and properly staying on top of the previously built layer. Afterward, the clamping plate is moved away to let the laser scanner perform the pattern-welding operation to achieve permanent bonding of the foil to the previous layer. This step is followed by UV laser cutting, which is performed by the second laser (UV pulsed laser) to remove the excess foil. Finally, the part is moved to the mechanical polisher to polish the elevated edges to flatten the layer surface. This completes the building of a laser-foil printed layer. After building each layer, all the above-mentioned steps are completed without any human interaction using the automated LFP system.

Figure 3 shows the LFP system, including all subsystems used to perform a fully automated LFP process. The laser scanner is a continuous-wave infrared (IR) fiber laser (IPG YLP-1000) with a maximum power of 1000 W, used for laser spot and pattern welding operations with the laser beam directed by a galvo-mirror scanner (SCANLAB hurrySCAN-30). The laser used for cutting is an ultraviolet (UV) pulsed laser with a maximum power of 10 W. The foil clamping plate is used for applying pressure on top of the foil to temporarily fix the foil before the spot-welding operation. The roller-to-roller foil supply mechanism is driven by a stepper motor to feed the foil. The 3-axis gantry system is used to move the part between the laser scanner, the laser cutting head, and the mechanical polisher for building each layer.



Motivation and Methods

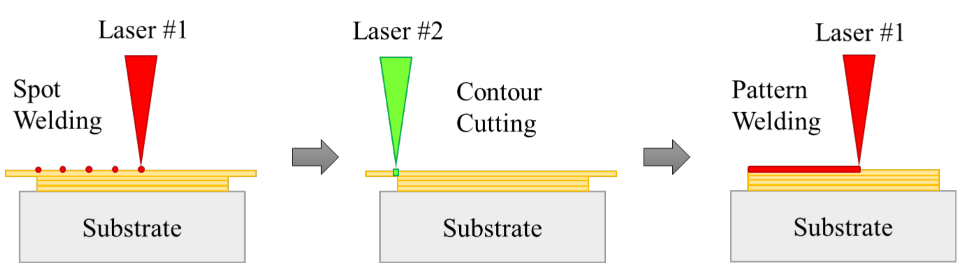
The most significant matter considered to achieve in this study is to suppress the edge elevation that occurs after cutting the excess foil. Before this study, mechanical polishing was used as a step for flattening the elevate edges after cutting. However, this step takes about one-third of the total processing time for each layer and thus an alternative solution is needed to shorten the time needed for eliminating the elevated edges. Mechanical polishing was developed and employed in the previous fully automated LFP system because the elevated edges caused foil burning, and this burning prevents successful bonding between layers. Therefore, the elevated edges were removed by mechanical polishing before building the next layer.

The main goal of this study is to increase the productivity of the LFP system. It has been proven that mechanical polishing is a valid option to remove elevated edges, but it is not a productive approach. Thus, the current aim is to use the same system in a more productive manner. To do that, this study aims to remove the mechanical polisher and thus the system would become more compact. As a result, the LFP system will be simplified, and the part building time will be about 2/3 of the current fabrication steps.

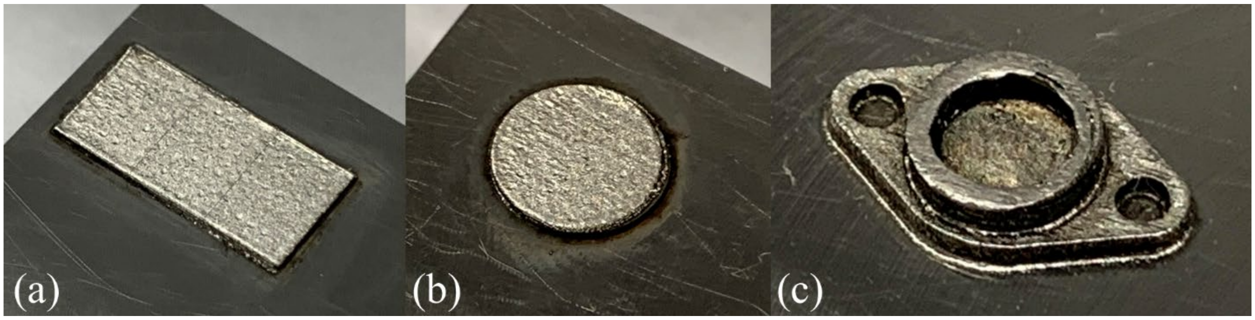
The experimental parts are built with two different approaches. During the part building for both approaches, the laser process parameters used are 400W in laser power and 300mm/s laser in scanning speed for 304L stainless-steel material for LFP with the foil thickness of 125 µm. The reason for using these parameters is to achieve conduction welding mode with lower porosity and higher strength in the fabricated part [7]. The investigation of edge elevation and levels of edge suppression was the output data of surface scanning. The surface is scanned with a laser surface profiler (Gocator 2300 Series). The surfaces are analyzed with the output data of the surface profiler and MATLAB plots.

<u>Method 1: Changing the Order of Fabrication</u>

The first approach to solve the edge elevation phenomenon used is changing the order of fabrication. This is a simpler approach but effective. Due to the reason that elevated edges occur after laser cutting, and application of laser on the elevated edges can suppress them, the sequence of LFP process steps is changed to investigate its effect. The main idea is that, if the order of laser cutting and pattern welding in the LFP process is reversed, there might not be any elevated edges due to the applied laser power on the foil to perform the pattern welding. Figure 4 is an illustration of this method.

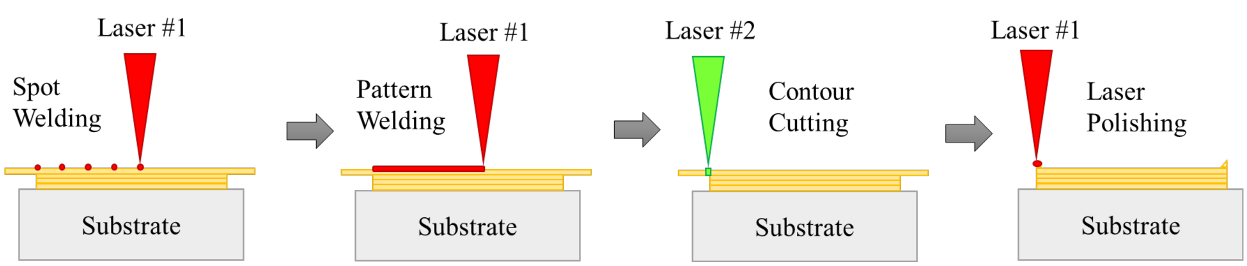


Experiments were conducted to build parts with this new sequence of LFP process steps, without any mechanical polishing or laser polishing operation. Figure 5 shows parts with three different geometries (rectangular plate, circular plate, and a flange part) built with this new process steps. The edges were controlled after each layer was built, and the subsequent layer can be bonded on top of the previous layer successfully.



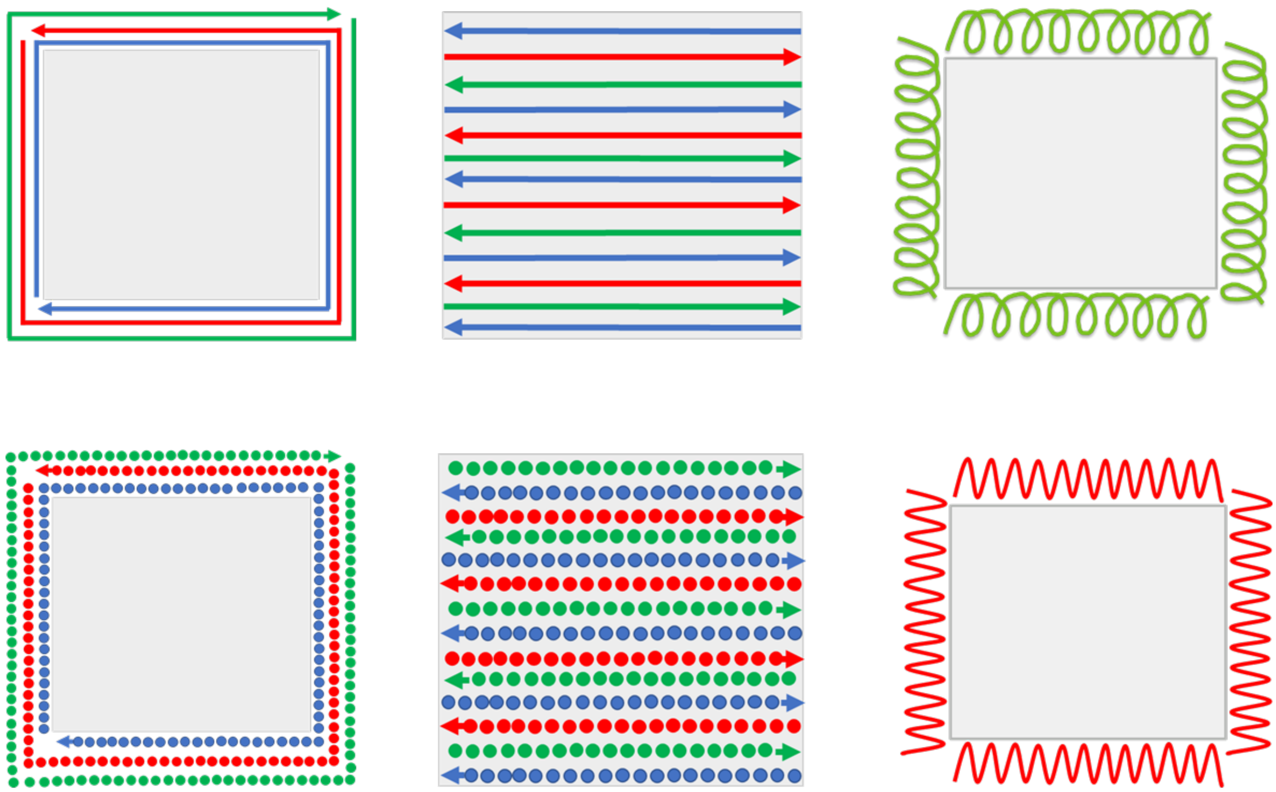
Method 2: Laser Polishing

The second approach to solve the edge elevation phenomenon is replacing mechanical polishing with laser polishing. Laser polishing is a well-known process, and it has been used for polishing various additively manufactured parts with different types of materials including steels (tool steel, stainless steel, etc.), aluminum alloys (AlSi10Mg), cobalt-chromium alloys (CoCr), Inconel alloys, and titanium alloys (Ti-6Al-4V, Ti-6.5Al-3.5Mo-1.5Zr-0.3Si) [10]. In specific, the investigation of edge elevation for parts built by the laser powder bed fusion (LPBF) additive manufacturing process has shown that laser polishing may be an alternative for post-process correction of the elevated edges generated by laser cutting [11]. Therefore, laser polishing could be an alternative for the mechanical polishing step of LFP. The laser polishing can be done by the laser which is responsible for spot and welding operations, and this means that the current system could be used without any need for additional sub-systems. Figure 6 is an illustration of this method.



Pattern welding, Contour cutting, and Laser polishing.

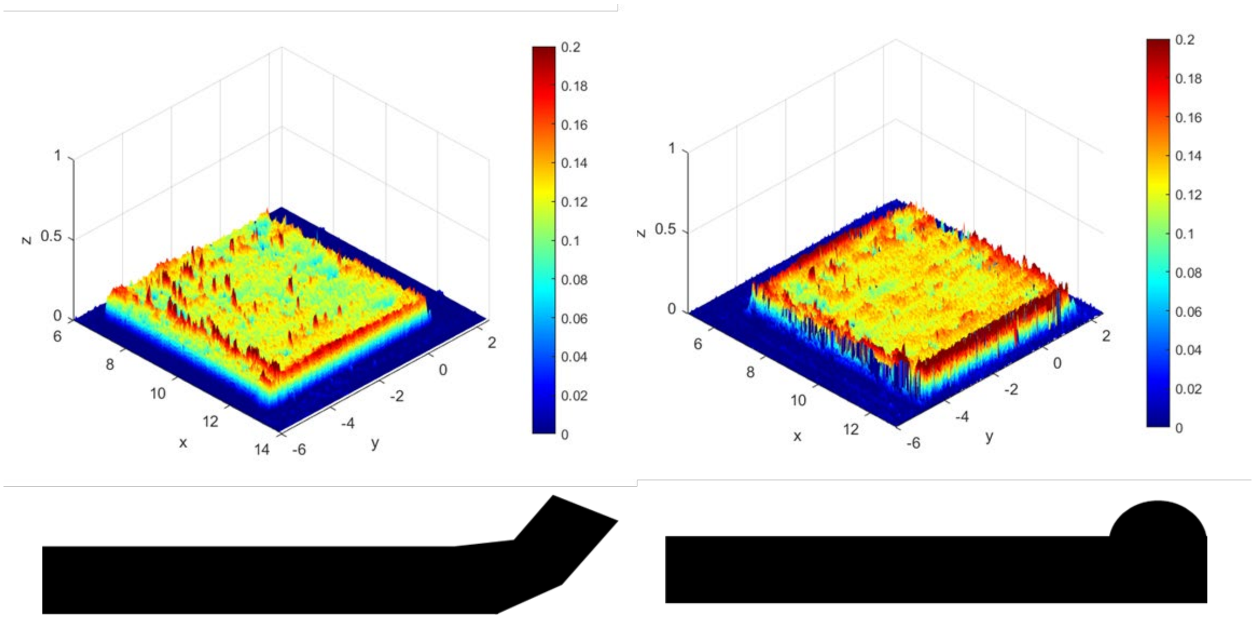
To remove the elevated edges, different laser parameters need to be determined. These parameters include the laser polishing pattern, laser power, laser scanning speed, and point time duration. To determine these parameters, some experiments were carried out. Various polishing patterns, laser scanning speed, and point time duration showed that the most dominant and effective among these is the laser polishing pattern. Figure 7 is an illustration of laser polishing patterns applied during the experimental work.



Line Edge (Top Left), Line Surface (Top Center), Helical Edge (Top Right),
Spot Edge (Bottom Left), Spot Surface (Bottom Center), Zigzag Edge (Bottom Right)

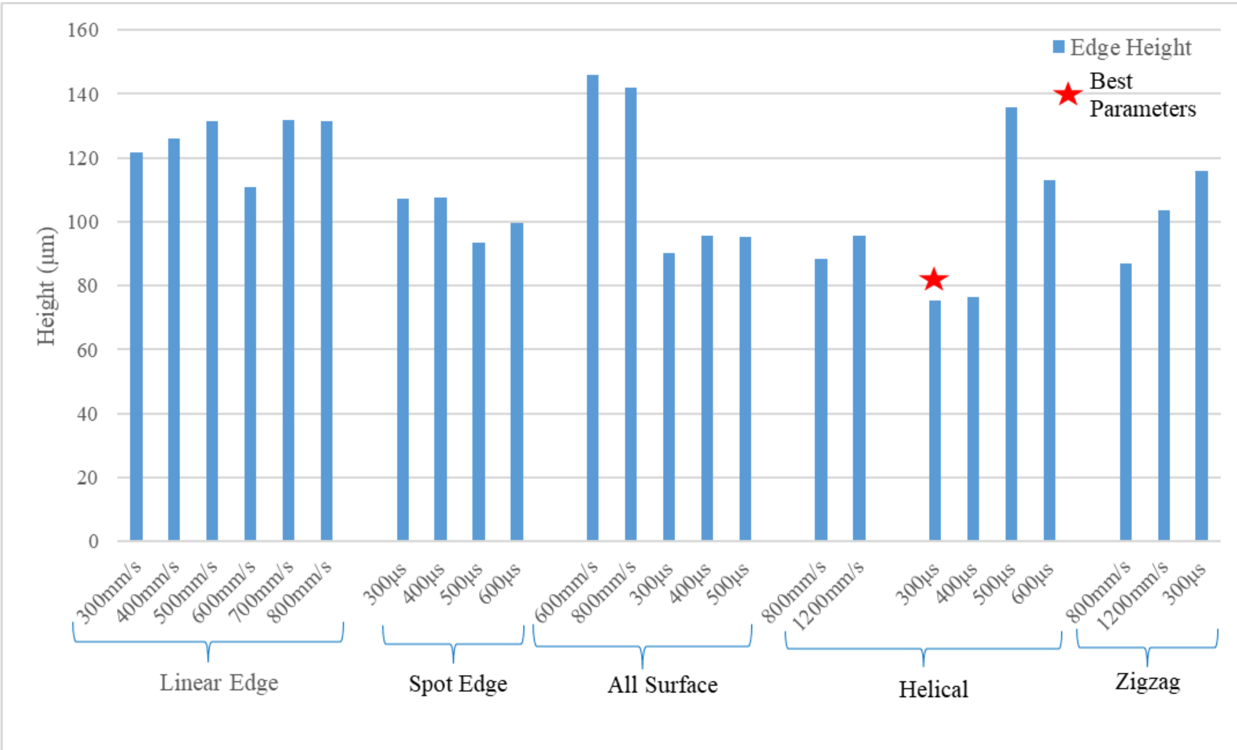
During the experimental work, to be able to observe the effects of various parameters, 6x6 mm^2 square-shaped samples were printed on a substrate with stainless steel 304L material. All samples were laser polished and scanned before and after with a laser surface profiler. The laser polishing was applied as lines and spots for each pattern, and it was seen that in general, spot type polishing is more effective than line type polishing.

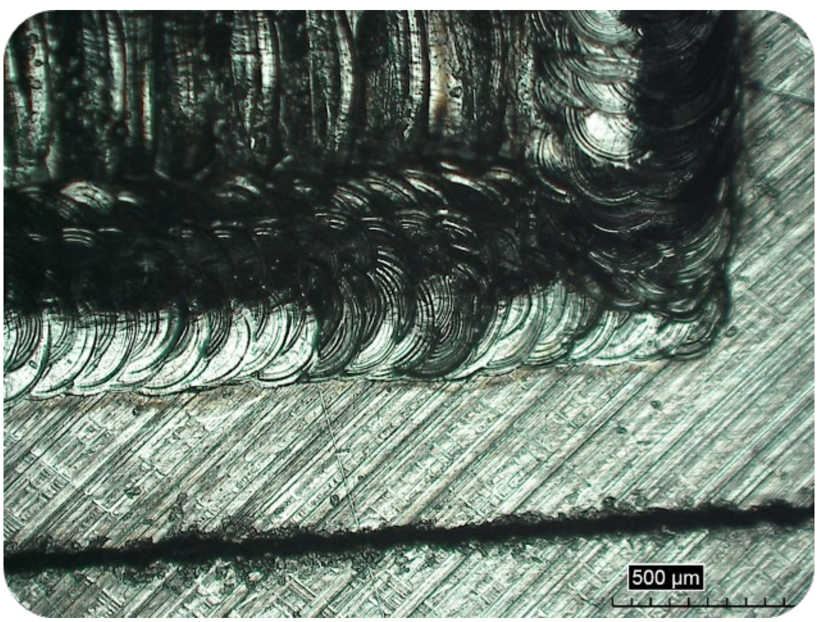
Among the results of different laser polishing patterns, the Linear Edge pattern was an ineffective polishing pattern in general and resulted in bulge formation at the edges. Various scanning speeds for line type polishing (300-400-500-600-700-800 mm/s), and point time durations for spot type polishing (300-400-500-600 µs) made no progress and the results for these are given as an example in Fig. 8. In this figure, the bottom images are illustrations for before/after edge protrusion. In addition to those, the top images in Fig. 8 are the resulted surface profiles generated by an in-house developed MATLAB program.



Afterward, the all-surface polishing was experimented. Theoretically, if the bulge formation occurs because remelted portion has no space to flow into, the all surface polishing pattern should provide enough space to flow into. Thus, all surface polishing has been experimented with for both spot and line type laser polishing. The line polishing speeds were varied using 600 and 800 mm/s, and spot type polishing point time durations were 300 and 500 µs. The line type polishing resulted in a rougher surface, but the spot type polishing appeared applicable. However, all surface polishing is not a productive method as time spent on non-elevated surface polishing is considered not a productive use of time.

The next polishing patterns considered were zigzag and helical patterns. As a result of this study, the zigzag pattern was not successful for sharp corners. However, the helical spot pattern laser polishing gave satisfactory results. Figure 9 provides a chart including the edge heights for all different laser polishing parameters. Based on this figure, our finalized laser polishing parameters were the helical pattern spot polishing with 300 µs point time duration and 400 W laser power. These laser polishing parameters resulted in 5.968 J/mm^2 energy density based on the following equation $E = P \cdot t/(\frac{\pi d^2}{4})$, where E is the applied energy density over a specific area (J/mm^2), P is the laser power (W), t is the point time duration (s), and d is the laser beam spot size (0.16 mm). Figure 10 shows the resulted optical microscope image for this set of best laser polishing parameters. The overlapping of laser spots is visible in this figure.



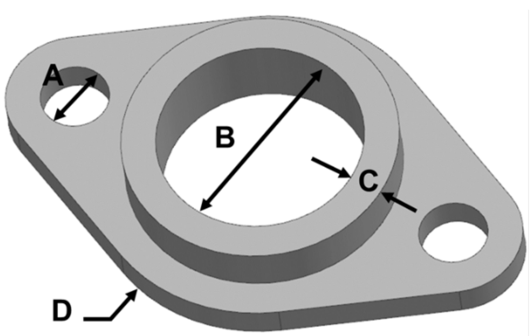


After finalizing the parameters, some different part geometries were built with the use of these laser polishing parameters. Figure 11 shows the three different geometries which are square and circular plate geometries and a more complex part geometry of flange part.

(b) Circular Plate, and (c) Flange Part.

Experimental Results: Method 1 vs. Method 2

To make a fair comparison between the two different methods, the same flange part geometry was printed with the use of the two different methods: Method 1 vs. Method 2. The dimensions of the CAD models and the accuracies of parts fabricated by the two methods are given in Fig. 12.



Measurements	A	B	C	D
CAD Design (mm)	2.00	6.00	1.00	10.00
Cutting First (mm)	1.97	5.75	1.19	9.82
Error Percentage	1.50%	4.16%	19.00%	1.80%
Laser Polishing (mm)	2.01	5.97	0.97	9.95
Error Percentage	0.50%	0.50%	3.00%	0.50%

In general, Method 2 (laser polishing) fabricates parts with higher accuracy and sharper edges. Although this method requires an additional step of polishing (the cutting first method contains no polishing step), this step leads to more accurate part dimensions and better surface finish. Thus, the time spent on laser polishing is required for an accurate part.

Method 1 (cutting first) is faster. However, this method depends on spot welding to keep the foil non-distorted during the cutting process. In addition, during the excess foil removal, thin-walled part quality is lower for this approach as the foil attachment depends only on the spot-welding step. During the excess foil removal, the spots should not be detached from the part surface, but it is not possible to be sure if the foil is still attached to the previous layer until the pattern welding is applied. Any dislocation or distortion of the foil will likely cause lower-quality parts. To illustrate this phenomenon, it can be seen in Fig. 5 that the flange part built with the use of Method 1 has lower accuracy in the flange's thickness due to the surface and part finish issues.

Conclusion

Mechanical polishing is an effective solution for removing edge elevation due to laser contour cutting in the automated Laser Foil Printing (LFP) process, but it not productive. In this study, two different methods of automating laser-foil-printing are presented. The cutting first method (Method 1), i.e., cutting before pattern welding, is an approach without any additional step of edge polishing, and the laser polishing method (Method 2) is another approach. The cutting first method is a more productive automation method but results in parts with less accuracy. This is because when the excess foil detachment is done prior to permanent foil bonding, the foil is likely to have been moved slightly. In the laser polishing method, the polishing pattern, laser power, laser scanning speed, point time duration need to be specified. Among them the laser polishing pattern is the dominant factor. Linear edge type polishing pattern could cause bulge formation at the edges and thus worsened the elevated edges. The all-surface spot polishing gave better results, but it is not productive polishing the entire surface takes much time. The zigzag pattern is not a good solution since the corners of the polished part are still elevated. The smallest height of edge elevation was achieved with the spot type polishing with the helical path and 300µs point time duration. Therefore, between the two different methods (cutting first and laser polishing) to address the edge elevation due to laser contour cutting in the automated LFP process, the laser polishing method is a more effective method of automation and the spot polishing with a helical pattern gives the best results among the various laser polishing patterns.

Acknowledgment

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References

[1] Huang, Y., Leu, M. C., Mazumder, J., and Donmez, A., 2015, "Additive Manufacturing: Current State, Future Potential, Gaps and Needs, and Recommendations," ASME. J. Manuf. Sci. Eng. February 2015; 137(1): 014001.

[2] Schmidt, M., Merklein, M., Bourell, D., Dimitrov, D., Hausotte, T., Wegener, K., Overmeyer, L., Vollertsen, F., Levy, G.N., 2017, "Laser Based Additive Manufacturing in Industry and Academia," CIRP Annals – Manufacturing Technology, 66(2):561-583.

[3] Frazier, W.E., 2014, "Metal Additive Manufacturing: A Review," J. of Materi Eng and Perform 23, 1917–1928.

[4] Chen, C., Shen, Y., and Tsai, H., 2017, "A Foil-Based Additive Manufacturing Technology for Metal Parts," ASME. J. Manuf. Sci. Eng. 139(2): 024501.

[5] Jacob, G., Brown, C., Donmez, A., Watson, S., Slotwinski, J., 2017, "Effects of powder recycling on stainless steel powder and built material properties in metal powder bed fusion processes," NIST Advanced Manufacturing Series 100-6.

[6] Hung, C.-H., Sutton, A., Li, Y., Shen, Y., Tsai, H., Leu, M.C., 2019, "Enhanced mechanical properties for 304L stainless steel parts fabricated by laser-foil-printing additive manufacturing," Journal of Manufacturing Processes, Vol. 45, pp. 438-446.

[7] Hung, C.-H., Chen, W.-T., Sehhat, M.H., Leu, M.C., 2020, "The effect of laser welding modes on mechanical properties and microstructure of 304l stainless steel parts fabricated by laser-foil-printing additive manufacturing," The International Journal of Advanced Manufacturing Technology.

[8] Liu, Xiaoyang; Sekizawa, Keito; Suzuki, Asuka; Takata, Naoki; Kobashi, Makoto; Yamada, Tetsuya. 2020. "Compressive Properties of Al-Si Alloy Lattice Structures with Three Different Unit Cells Fabricated via Laser Powder Bed Fusion" Materials 13, no. 13: 2902.

[9] Kaijie Lin, Dongdong Gu, Kaiming Hu, Jiangkai Yang, Haoran Wang, Luhao Yuan, Xinyu Shi, Liang Meng, "Laser powder bed fusion of bio-inspired honeycomb structures: Effect of twist angle on compressive behaviors", Thin-Walled Structures, Volume 159, 2021, 107252.

[10] Basha, S.M., Bhuyan, M., Basha, M.M., Venkaiah, N., Sankar, M.R., 2020, "Laser polishing of 3D printed metallic components: A review on surface integrity," Materials Today: Proceedings, Volume 26, Part 2, pp. 2047-2054.

[11] Metelkova, J., de Formanoir, C., Haitjema, H., Witvrouw, A., Pfleging. W., Van Hooreweder, B., 2019, "Elevated edges of metal parts produced by laser powder bed fusion: characterization", Joint Special Interest Group meeting between euspen and ASPE Advancing Precision in Additive Manufacturing Ecole Centrale de Nantes, France.

[12] Hung, C.-H., Li, Y., Sutton, A., Chen, W.-T., Gong, X., Pan, H., Tsai, H.-L., Leu, M. C., 2020. "Aluminum Parts Fabricated by Laser-Foil-Printing Additive Manufacturing: Processing, Microstructure, and Mechanical Properties" Materials 13, no. 2: 414.