University of Texas Rio Grande Valley

ScholarWorks @ UTRGV

Manufacturing & Industrial Engineering Faculty Publications and Presentations

College of Engineering and Computer Science

9-2022

Ultrafast Laser Ablation of Inconel 718 for Surface Improvement

Sampson Canacoo
The University of Texas Rio Grande Valley

Enrique Contreras Lopez
The University of Texas Rio Grande Valley

Oscar Coronel
The University of Texas Rio Grande Valley

Farid Ahmed
The University of Texas Rio Grande Valley

Jianzhi Li
The University of Texas Rio Grande Valley

See next page for additional authors

Follow this and additional works at: https://scholarworks.utrgv.edu/mie_fac

Part of the Industrial Engineering Commons, and the Manufacturing Commons

Recommended Citation

Canacoo, Sampson, et al. "Ultrafast Laser Ablation of Inconel 718 for Surface Improvement." Manufacturing Letters 33 (2022): 410-414. https://doi.org/10.1016/j.mfglet.2022.07.054

This Article is brought to you for free and open access by the College of Engineering and Computer Science at ScholarWorks @ UTRGV. It has been accepted for inclusion in Manufacturing & Industrial Engineering Faculty Publications and Presentations by an authorized administrator of ScholarWorks @ UTRGV. For more information, please contact justin.white@utrgv.edu, william.flores01@utrgv.edu.

Authors

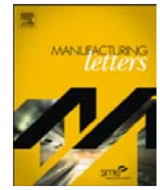
Sampson Canacoo, Enrique Contreras Lopez, Oscar Coronel, Farid Ahmed, Jianzhi Li, and Anil K. Srivastava

This article is available at ScholarWorks @ UTRGV: https://scholarworks.utrgv.edu/mie_fac/40

Available online at www.sciencedirect.com

Manufacturing Letters

Manufacturing Letters 33 (2022) 410–414



50th SME North American Manufacturing Research Conference (NAMRC 50, 2022)

Ultrafast Laser Ablation of Inconel 718 for Surface Improvement

Sampson Canacoo[a], Enrique Contreras Lopez[a], Oscar Coronel[a], Farid Ahmed[a], Jianzhi Li[a]*, Anil Srivastava[a]

[a]*University of Texas Rio Grande Valley, 1201 W University Dr, Edinburg, TX 78539, United States of America*

* Corresponding author. Tel.: +1-956-279-0906; *E-mail address:* jianzhi.li@utrgv.edu

Abstract

Inconel 718 is considered difficult to machine because of its ability to maintain its properties at high temperatures. The low thermal conductivity of the alloy causes accelerated tool deterioration when machining. Selective laser melting (SLM) additive manufacturing introduces a possibility of eliminating these difficulties, and producing complex shapes with this difficult-to-machine material. However, high surface roughness and porosity usually occur at the surface of components produced through additive manufacturing. In this study, the surfaces of Inconel 718 samples produced through selective laser melting were treated using laser ablation. The process parameters for the laser ablation process were analyzed in order to achieve a minimum surface roughness. The surfaces of the samples were observed after printing and after the laser ablation process using a microscope and the roughness average was measured using a profilometer. Optimized process parameters were achieved, and have the capability to reduce the surface roughness to a minimum R_a of 3.024 μm.

© 2022 Society of Manufacturing Engineers (SME). Published by Elsevier Ltd. All rights reserved.
This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/)
Peer-review under responsibility of the Scientific Committee of the NAMRI/SME.
Keywords: laser ablation; additive manufacturing; surface roughness; material removal

1. Introduction

Inconel 718 is a nickel-based alloy and it is widely used in aircrafts, gas turbines, nuclear and fossil fuel power plants because of its superior mechanical properties. Aerospace parts are subjected to high mechanical and thermal loads during their service life, therefore parts used are required to have high density and high surface integrity [1]. Inconel 718 possesses high strength, corrosion resistance, fatigue resistance at high temperatures up to 650◦C [2]. Though these properties are desired in applications with extreme conditions, they also make Inconel 718 difficult to machine.

Nomenclature

SLM	Selective Laser Melting
IN718	Inconel 718
ANOVA	Analysis of Variance
R_a	Roughness Average

For traditional machining processes on Inconel 718, the low thermal conductivity of the alloy would cause heat concentration at the tool tip during the machining process, which leads to accelerated tool wear and deterioration.

Additive manufacturing introduces the possibility of producing complex shapes with this difficult-to-machine material, while avoiding the difficulties associated with traditional machining. Selective Laser Melting (SLM) is an additive manufacturing technique that uses a high-power laser to melt and fuse metallic powders [3]. A component is built by selectively melting and fusing powders layer by layer, till a 3D object is produced according to the CAD model of the object. In general, additive manufactured parts suffer from high surface roughness and porosity that usually occur at the surface of components due to staircase effect which stems from the layer-by-layer building process, balling effects [4], hatch marks, and cracks [5]. Post processing is a crucial step for additive manufactured parts to remove undesired imperfections from the surface.

2213-8463 © 2022 Society of Manufacturing Engineers (SME). Published by Elsevier Ltd. All rights reserved.
This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/)
Peer-review under responsibility of the Scientific Committee of the NAMRI/SME.

Laser surface treatment is a non-contact method to reduce the surface roughness and improve the surface of a material. In laser ablation, the material under laser irradiation absorbs laser energy, and is heated to melting temperature, and subsequently to vaporization temperature leading to the removal of material from the surface [6]. The laser ablation process can be controlled to remove a layer from the surface of additive manufactured parts to remove undesired imperfections. Some studies have been carried out on the use of laser ablation to improve the surface of additive manufactured parts. Mohammad et al. [7] investigated the effect of laser ablation parameters on surface improvement of electron beam melted Ti-6Al-4V alloy. A range of laser fluences were applied on the surface. The best possible surface finish obtained was a roughness of about 13 μm. About 60% reduction in surface roughness was obtained. Campanelli et al. [8] investigated the optimization of the surface finish obtained by laser ablation on selective laser molten AISI 316L steel parts. The Taguchi method was used to find out the optimal process parameters for reducing the surface roughness. They found out that the higher scan speeds affected the surface finish. The laser power and repetition rates had to be set to the maximum value to optimize roughness. Kruth et al. [9] used optimized parameters for laser erosion to reduce the roughness of SLM CL20ES stainless steel from Ra of 15 μm to 6 μm, which was a 60% reduction.

Limited literature exists on the use of femtosecond laser ablation to improve the surface of selective laser melted Inconel 718. A good amount of literature focuses on the use of microsecond, picosecond and nanosecond lasers for surface improvement in a process called laser polishing. In laser polishing, the laser melts the surface of the material and the liquid in the molten pool redistributes to the same level under the influence of surface tension and gravity. The liquid then solidifies and the surface roughness is reduced [10]–[14] .

In this study, a femtosecond laser was applied to the surface of selective laser melted Inconel 718 using different combinations of laser energy, scanning speed and hatch distance. The purpose was to investigate the effects of the laser ablation parameters on the SLM IN718 surface, and determine the optimum parameters after analysis.

2. Materials and Methods

2.1. Experimental Setup

The laser used for the laser ablation study was a Spectra-Physics Spirit One Laser. The laser system delivers a pulse energy of up to 40 μJ at a repetition rate of 200 kHz, and an output of 1040 nm. The pulse width is 400 fs.

Inconel 718 samples (10 × 10 × 10 mm) were manufactured using SLM. The composition of the as received Inconel 718 powder used is shown in Table 1. The surface roughness of all the faces of the samples were measured, and the roughness average R_a was 13.04±0.5 μm.

Table 1. Chemical composition of received IN718.

Element	Ni	Cr	Fe	Nb	Mo
%	52.34	18.22	Balance	4.8	2.94
Element	Ti	Al	Co	C	Mn
%	0.34	0.41	0.7	0.04	0.20
Element	Si	P	S	B	Cu
%	0.012	0.09	0.05	0.05	0.25

2.2. Focal Length Selection

Before the laser ablation experiment was run, a test was conducted in order to select the appropriate focal distance of the laser system to match the height of the printed samples. Using the right focal distance ensures that the focal point of the laser falls exactly on the surface of the sample. The focal point is the point at which the laser beam diameter is the smallest. Laser fluence is defined as laser energy per unit area, therefore the smaller the incident diameter of the laser beam on the surface, the larger the fluence, and more material is removed. The focal length of the system was altered by changing the z-value in the g-code. The effect of the z-values was tested by applying single pulses on the IN718 surface with a pulse energy 40 μJ and z-values ranging from 114.5 mm to 114.95 mm with 50 μm increments between them. The craters produced by the pulses were observed and measured using the microscope. The depths of the craters were measured, and z-value of 114.8 mm was selected, because it produced the crater with the smallest diameter of 20.61 μm and the largest depth of 92.81 μm.

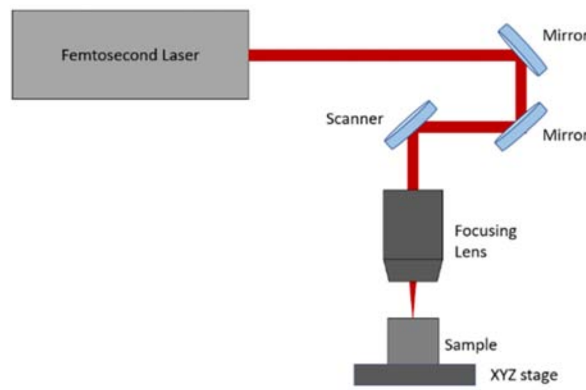


Fig. 1. Schematic of the laser setup

2.3. Femtosecond Laser Ablation

Three laser parameters were selected for this laser ablation study with three levels. The variables are pulse energy, scanning speed, and hatch distance. These parameters were selected based on literature and the results from previous experiments. Table 2 shows the parameters and their various levels. A full factorial experiment was used, with 3 replicates of each combination of the processing parameters. 81 runs were performed in total. The laser ablation was applied on 3 x 6 mm areas on the vertical surfaces of the SLM samples.

Table 2. Parameters used with levels.

Parameters	Levels		
Pulse Energy (μJ)	4	20	36
Scanning Speed (mm/s)	5	10	15
Hatch Distance (μm)	10	30	50

After the experiment, the surfaces of the samples were observed using a VHX 5000 microscope and the surface roughness average Ra was measured using a Mahr M 300 C profilometer.

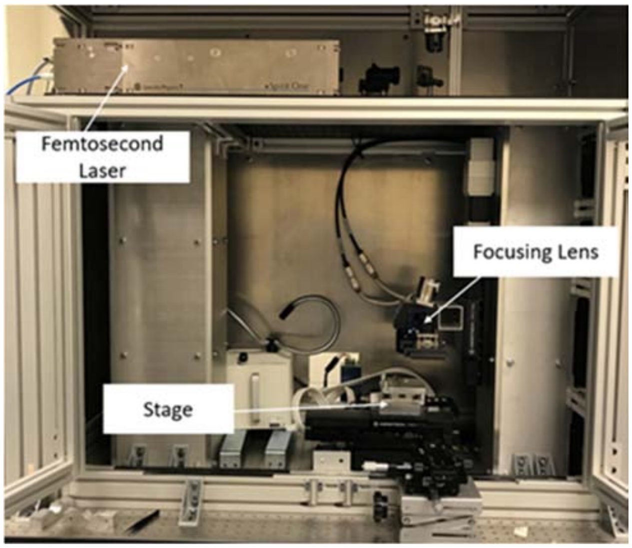


Fig. 2. Laser setup used for the experiment

3. Results and Discussion

The roughness averages of the ablated surfaces of the samples were measured. The lowest roughness value recorded was R_a of 3.098 µm. An analysis of variance was performed to observe the significant of each of the parameters on the surface roughness. Table 3 shows the results of the ANOVA.

Table 3. ANOVA results

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	18	80.105	4.4503	28.38	0.000
Linear	6	70.628	11.7713	75.06	0.000
Pulse Energy	2	14.481	7.2404	46.17	0.000
Scanning Speed	2	9.279	4.6394	29.58	0.000
Hatch Distance	2	46.868	23.4341	149.44	0.000
2-Way Interactions	12	9.477	0.7897	5.04	0.000
Pulse Energy*Scanning Speed	4	5.976	1.4941	9.53	0.000
Pulse Energy*Hatch Distance	4	1.638	0.4095	2.61	0.044
Scanning Speed*Hatch Distance	4	1.863	0.4656	2.97	0.026
Error	62	9.723	0.1568		
Lack-of-Fit	8	2.059	0.2573	1.81	0.095
Pure Error	54	7.664	0.1419		
Total	80	89.827			

The significance level selected for the analysis was 0.05 [15]. Factors with p-values less than 0.05 are statistically significant, and factors with p-values greater than 0.05 are not statistically significant and do not have any effect on the output, which in this case was surface roughness. From the table, laser energy, hatch distance and the interaction between laser energy and scanning speed have an effect on the surface roughness. The Pareto chart in Figure 3 shows that the pulse energy and hatch distance both have the greatest effect on the roughness, followed by the laser energy.

The plot in Figure 4 shows that the hatch distance is directly proportional to surface roughness. When the hatch distance is smaller, the degree of overlap between the individual laser tracks increases. An area on the material surface receives more laser pulses, and more material is removed, causing a greater reduction in roughness. A hatch distance too large leaves some portions of the material untouched by the laser in between laser tracks, leaving a minimal reduction in roughness.

It was observed in Figure 5 that the roughness R_a was low with lower scanning speeds, and increased with higher scanning speeds. At slower speeds, the individual laser pulses are closer to each other and overlap, therefore an area on the

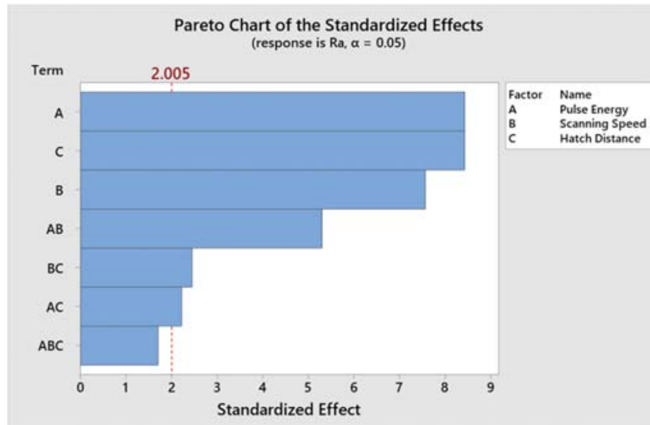


Fig. 3. Pareto chart of the standardized effects

substrate is exposed to more laser pulses. This causes more material to be ablated, reducing surface roughness. A high scanning speed increases the distance between the pulses and reduces the number of pulses the material receives per unit area, so the material is not evaporated as desired.

At high pulse energy in Figure 6, the surface roughness produced is high. At low pulse energy, the roughness values are lower, and at intermediate level of laser pulse, the surface roughness values are at their lowest. Similar results have been observed in other surface improvement studies [16]–[18]. At low pulse energy, the laser only removes a minimal amount of material leaving some peaks on the material surface. The high pulse energy removes a relatively large amount of material per pulse, causing deep grooves on the surfaces, increasing surface roughness.

Optimization of parameters was carried out using statistical software to achieve the optimal process parameters to minimize roughness [19]. The optimized parameters are shown in Figure 5 in red colored text. They are; pulse energy of 20 µJ, scanning

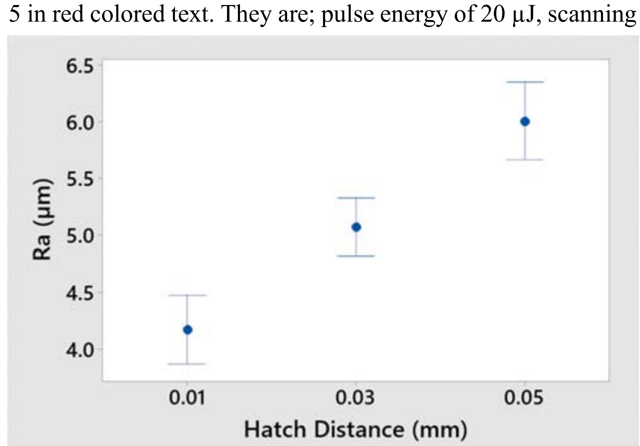


Fig. 4. Plot of hatch distance against average Ra with standard deviation

speed of 5 mm/s, and hatch distance of 10 µm. Under the optimized parameters, a minimum roughness of 3.024 µm can be achieved after the laser ablation process.

Figure 8 shows the surface of the IN718 sample before and after laser ablation using the optimized parameters during the experiment. Before the application of the laser, the surface of the material was covered with balling effects and the surface was visibly rough. After the laser treatment, the roughness and the balling were reduced significantly.

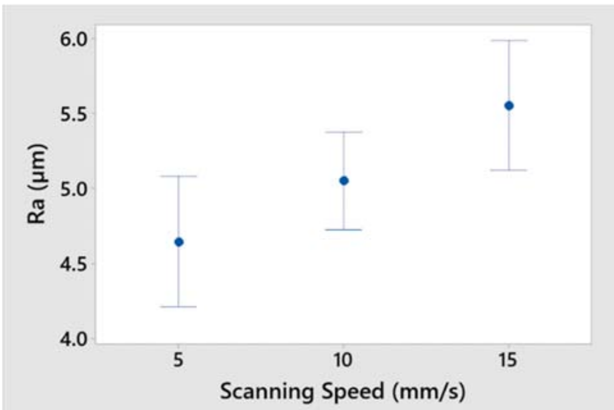


Fig. 5. Plot of scanning speed against average Ra with standard deviation

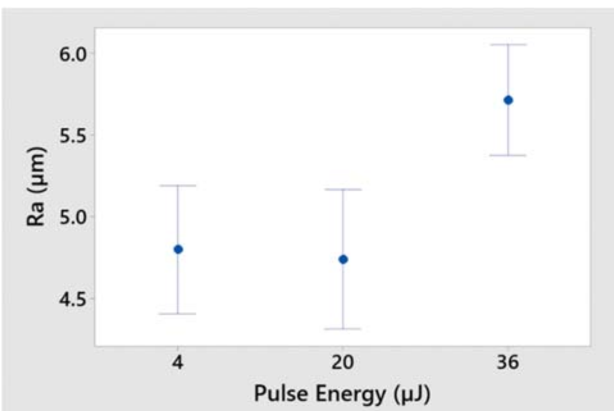


Fig. 6. Plot of pulse energy against average Ra with standard deviation

4. Conclusions

Femtosecond laser ablation for improving the surface roughness of SLM Inconel 718 was investigated by varying laser energy, scanning speed, and hatch distance. The performance measure for this investigation was surface roughness (Ra). The optimal process parameters were found using statistical analysis. Based on the results, the following conclusions were made:

- Pulse energy, scanning speed and hatch distance are all significant to the surface roughness of the part after laser ablation.
- Pulse energy and hatch distance have the strongest effect on the surface roughness.
- Pulse energy set to 20 µJ, scanning speed set to 5 mm/s, and hatch distance set to 10 µm produced the lowest surface roughness.
- The surface roughness reduced significantly after only one cycle of laser ablation using the optimal parameters. Multiple passes should further improve the surface roughness.

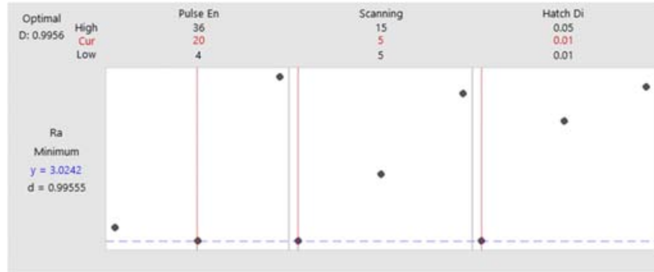


Fig. 7. Optimality plot of laser parameters for minimum Ra

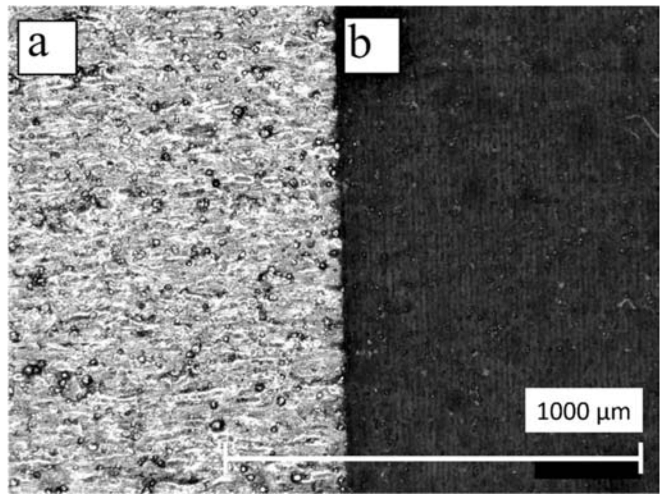


Fig. 8. (a) IN718 surface after printing, (b) IN718 surface after laser ablation with optimal parameters.

5. Acknowledgement

This work was supported by the U.S. Department of Defense Manufacturing Engineering Education Program (MEEP) under Award No. N00014–19-1–2728.

6. References

[1] M. Rahman, W. K. H. Seah, and T. T. Teo, “The machinability of inconel 718,” *Journal of Materials Processing Technology*, vol. 63, no. 1–3, pp. 199–204, Jan. 1997, doi: 10.1016/S0924-0136(96)02624-6.

[2] E. O. Ezugwu, Z. M. Wang, and A. R. Machado, “The machinability of nickel-based alloys: a review,” *Journal of Materials Processing Technology*, vol. 86, no. 1–3, pp. 1–16, Feb. 1999, doi: 10.1016/S0924-0136(98)00314-8.

[3] C. Y. Yap, C. K. Chua, and Z. L. Dong, “An effective analytical model of selective laser melting,” *http://dx.doi.org/10.1080/17452759.2015.1133217*, vol. 11, no. 1, pp. 21–26, Jan. 2016, doi: 10.1080/17452759.2015.1133217.

[4] G. Strano, L. Hao, R. M. Everson, and K. E. Evans, “Surface roughness analysis, modelling and prediction in selective laser melting,” *Journal of Materials Processing*

Technology, vol. 213, no. 4, pp. 589–597, Apr. 2013, doi: 10.1016/J.JMATPROTEC.2012.11.011.

[5] E. Wycisk, A. Solbach, S. Siddique, D. Herzog, F. Walther, and C. Emmelmann, “Effects of Defects in Laser Additive Manufactured Ti-6Al-4V on Fatigue Properties,” *Physics Procedia*, vol. 56, no. C, pp. 371–378, Jan. 2014, doi: 10.1016/J.PHPRO.2014.08.120.

[6] X. Liu, D. Du, and G. Mourou, “Laser ablation and micromachining with ultrashort laser pulses,” *IEEE Journal of Quantum Electronics*, vol. 33, no. 10, pp. 1706–1716, Oct. 1997, doi: 10.1109/3.631270.

[7] A. Mohammad, M. K. Mohammed, and A. M. Alahmari, “Effect of laser ablation parameters on surface improvement of electron beam melted parts,” *The International Journal of Advanced Manufacturing Technology 2016 87:1*, vol. 87, no. 1, pp. 1033–1044, Mar. 2016, doi: 10.1007/S00170-016-8533-4.

[8] S. L. Campanelli, G. Casalino, N. Contuzzi, and A. D. Ludovico, “Taguchi Optimization of the Surface Finish Obtained by Laser Ablation on Selective Laser Molten Steel Parts,” *Procedia CIRP*, vol. 12, pp. 462–467, Jan. 2013, doi: 10.1016/J.PROCIR.2013.09.079.

[9] J. Kruth, E. Yasa, J. D.-P. of the 3rd international, and undefined 2008, “Roughness improvement in selective laser melting,” *lirias.kuleuven.be*, Accessed: Nov. 23, 2021. [Online]. Available: https://lirias.kuleuven.be/retrieve/117846

[10] H. Guoqing, S. Yang, and G. Yingchun, “Tailoring metallic surface properties induced by laser surface processing for industrial applications,” *Nanotechnology and Precision Engineering*, vol. 2, no. 1, p. 29, Dec. 2020, doi: 10.1016/J.NPE.2019.03.003.

[11] Y. Li, Z. Zhang, and Y. Guan, “Thermodynamics analysis and rapid solidification of laser polished Inconel 718 by selective laser melting,” *Applied Surface Science*, vol. 511, p. 145423, May 2020, doi: 10.1016/J.APSUSC.2020.145423.

[12] S. Dadbakhsh, L. Hao, and C. Y. Kong, “Surface finish improvement of LMD samples using laser polishing,” *https://doi.org/10.1080/17452759.2010.528180*, vol. 5, no. 4, pp. 215–221, Dec. 2010, doi: 10.1080/17452759.2010.528180.

[13] S. Marimuthu, A. Triantaphyllou, M. Antar, D. Wimpenny, H. Morton, and M. Beard, “Laser polishing of selective laser melted components,” *International Journal of Machine Tools and Manufacture*, vol. 95, pp. 97–104, Aug. 2015, doi: 10.1016/J.IJMACHTOOLS.2015.05.002.

[14] F. Zhihao, L. Libin, C. Longfei, and G. Yingchun, “Laser Polishing of Additive Manufactured Superalloy,” *Procedia CIRP*, vol. 71, pp. 150–154, Jan. 2018, doi: 10.1016/J.PROCIR.2018.05.088.

[15] D. Montgomery, *Design and analysis of experiments*. 2017. Accessed: Nov. 26, 2021. [Online]. Available: https://books.google.com/books?hl=en&lr=&id=Py7bDgAAQBAJ&oi=fnd&pg=PA1&dq=design+and+analysis+of+experiments&ots=X7s6l2NQ26&sig=ni9tOcnFEhGKwhV6kjeoOpYHstY

[16] T. L. Perry, D. Werschmoeller, X. Li, F. E. Pfefferkorn, and N. A. Duffie, “Pulsed laser polishing of micro-milled Ti6Al4V samples,” *Journal of Manufacturing Processes*, vol. 11, no. 2, pp. 74–81, Jul. 2009, doi: 10.1016/J.JMAPRO.2009.10.001.

[17] T. L. Perry, D. Werschmoeller, N. A. Duffie, X. Li, and F. E. Pfefferkorn, “Examination of selective pulsed laser micropolishing on microfabricated nickel samples using spatial frequency analysis,” *Journal of Manufacturing Science and Engineering, Transactions of the ASME*, vol. 131, no. 2, pp. 0210021–0210029, Apr. 2009, doi: 10.1115/1.3075874/468477.

[18] T. A. Mai and G. C. Lim, “Micromelting and its effects on surface topography and properties in laser polishing of stainless steel,” *Journal of Laser Applications*, vol. 16, no. 4, p. 221, Dec. 2004, doi: 10.2351/1.1809637.

[19] A. Alin, “Minitab,” *Wiley Interdisciplinary Reviews: Computational Statistics*, vol. 2, no. 6, pp. 723–727, Nov. 2010, doi: 10.1002/WICS.113.