Available online at www.dergipark.org.tr/en

INTERNATIONAL ADVANCED RESEARCHES
and
ENGINEERING JOURNAL

Journal homepage: www.dergipark.org.tr/en/pub/iarej

e-ISSN: 2618-575X

International Open Access

Volume 07
Issue 02

August, 2023

Research Article

Investigating the influence of shielding gas stability of laser polished Ti-6Al-4V alloy using image processing

Tolgahan Ermergen [a,*], Fatih Taylan [a], İsmail Serkan Üncü [b] and Ersin Kayahan [c]

[a] *Department of Mechanical Engineering, Isparta University of Applied Sciences, Isparta, Turkey*
[b] *Department of Electric-Electronics Engineering, Isparta University of Applied Sciences, Isparta, Turkey*
[c] *Laser Technologies Research and Application Center (LATARUM), Kocaeli University, Kocaeli, Turkey*

ARTICLE INFO

Article history:
Received 02 May 2023
Accepted 02 August 2023
Published 15 August 2023

Keywords:
Laser polishing
Shielding gas stability
Surface roughness
Surface coloring
Image processing

ABSTRACT

The use of Additive Manufacturing methods in modern manufacturing is increasing rapidly. However, the high surface roughness of the manufactured parts is a major drawback for Additive manufacturing methods. Therefore, additively manufactured parts need subsequent surface treatment. Laser polishing (LP) is one of the nontraditional polishing techniques, where a shielding gas is also used during the process to eliminate the adverse effects of the atmosphere. In this study, additively manufactured Ti-6Al-4V samples were laser polished by using Argon as shielding gas. During the operation, the flow stability of shielding gas was changed to observe the consequences of gas flow instability during LP. This observation was carried out by using Image Processing techniques. Even though surface quality alteration is possible even with an unstable gas flow, the output of surface modification may differ along with the material, especially in terms of surface roughness. The surface quality of the sample which processed under a stable Argon flow gave homogenous results, while the sample which processed under an unstable Argon flow gave non-homogenous results on its surface.

1. Introduction

Additive manufacturing (AM) methods enable the manufacturing of complex geometries which cannot be manufactured easily by conventional machining processes. As Ergene [1] stated, the application of additive manufacturing (AM) is crucial in industries that require the production of intricate structures and customizable components, particularly in the fields of aeronautics, medicine, and automotive manufacturing. However, the use of additively manufactured components may cause some drawbacks, since the surface quality of the manufactured components cannot be in a favorable range as a result of layer-by-layer manufacturing. Yasa et al. [2] indicated that as a result of the nature of AM methods, the surface quality of as-built parts is lower compared to conventionally manufactured counterparts.

To eliminate that specific limitation of AM methods mentioned above, post-processes after manufacturing should be performed to enhance the surface quality of the AM parts. In different previous studies by Mohammadian et al. [3], Ma et al. [4], Li et al. [5], and Wang et al. [6], various surface finish processes were discussed for parts produced by additive manufacturing. Among all these finishing methods, a laser-based surface modification method called Laser Polishing (LP) dominates the industry due to its superior features.

Laser polishing employs a laser as the primary source for a thermal-based process aimed at enhancing the quality of a surface. This process involves the re-melting and subsequent solidification of the surface through the application of laser radiation, as demonstrated by Temmler et al. [7] in their research and depicted in Figure 1.

The objective of LP is to eliminate surface irregularities by using a laser beam to re-melt and smooth out peaks on the surface of the material, as shown in Figure 2. By exposing a material surface to a laser beam of adequate energy density, the high points on the surface are liquefied and flow

* Corresponding author. Tel.: *+90 246 214 67 88*; Fax: +90 246 214 68 99.
E-mail addresses: tolgahanermergen@isparta.edu.tr (T. Ermergen), fatihtaylan@isparta.edu.tr (F. Taylan), serkanuncu@isparta.edu.tr (İ.S. Üncü), kayahan@kocaeli.edu.tr (E. Kayahan)
ORCID: 0000-0001-6831-1268 (T. Ermergen), 0000-0002-4518-0645 (F. Taylan), 0000-0003-4345-761X (İ.S. Üncü), 0000-0001-8657-2947 (E. Kayahan)
DOI: 10.35860/iarej.1291164

downward to lower areas due to gravity and surface tension. Upon cooling, these molten pools solidify, resulting in robust structures that are devoid of any porosity. By minimizing the morphological discontinuities on the surface, surface roughness is eventually reduced. This phenomenon has also been confirmed by Temmler et al. [8] in their previous studies.

In order to improve the results acquired from LP, an assist gas can be used as a shielding medium to protect the heated zone from atmospheric effects such as oxidation. Various gases such as Argon (Ar) and Nitrogen are used as the shielding gas for the LP process. In a past study by Giorleo et al. [9], Nitrogen was used as the shielding gas for LP operation. During the polishing process, Nitrogen was repelled to the melting zone under different pressures; thus, the effect of gas pressure was investigated. In another study done by Temmler et al. [10], Argon and Nitrogen were used during LP to understand the difference between various shielding gases. Apart from the economic aspect, no significant difference between Ar and N was observed. Along with these studies, there are numerous amounts of papers in which Argon or Nitrogen is used as a shielding gas during LP. On the other hand, studies which investigated the effect of LP operated in the open air are available as well. In such a study, Cwikla et al. [11] reported that LP operation was carried out with and without Ar shielding gas. Even though an increment in surface quality was acquired for both conditions, LP under open-air caused oxidation on the material surface. Although there are a significant number of studies available on LP which point out the importance of shielding gas, no study in the literature emphasizes the prominence of shielding gas flow stability during LP.

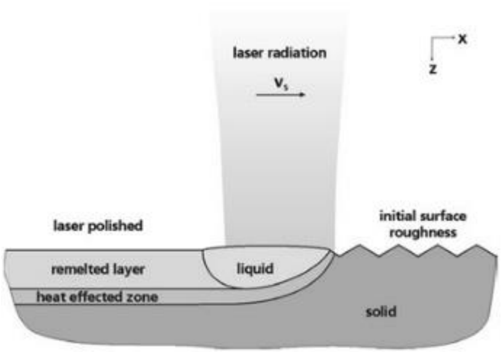


Figure 1. Schematics of Laser Polishing Process [7]

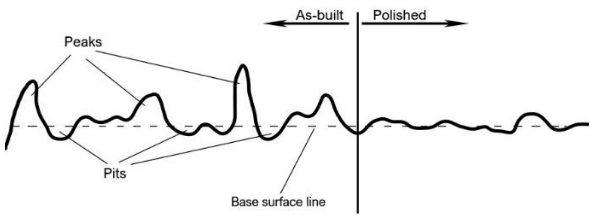


Figure 2. Principle of Laser Polishing

During laser polishing, oxidation can be effectively prevented by using shielding gas. However, when operations are performed in open-air or with low-density shielding gas flow, complete prevention of oxidation becomes challenging. As a result, several oxide phases, such as Ti_2O, TiO, Ti_2O_3, and TiO_2, inevitably form on the material surface. These oxide layers are responsible for the coloration observed on the surface (see Figure 3).

Various studies by Sun et al. [12], Perez del Pino et al. [13-15], Diamanti et al. [16], and Kurniawan et al. [17] have shown that the color of the sample surfaces is directly related to the composition of the oxide layer coating. For instance, Ti_2O provides a brighter surface compared to the as-built material, while TiO predominantly creates a golden surface appearance. Similarly, Ti_2O_3 and TiO_2 crystalline coatings result in purple and bluish colors, respectively. These Titanium Oxide coatings exhibit different mechanical properties due to their distinct chemical structures.

In cases where unstable shielding gas is used during the laser polishing process, non-uniform discoloration occurs on the material surface. The presence of different colors indicates the formation of Titanium Oxide coatings with varying mechanical properties. Consequently, the surface will have areas with different mechanical properties after the laser polishing process when unstable shielding gas is employed. This non-uniform behavior can affect the sample's response under mechanical and thermal loads, leading to varying performance characteristics across the surface.

In summary, the use of shielding gas helps prevent oxidation during laser polishing, leading to a more uniform surface appearance and consistent mechanical properties. However, without stable shielding gas flow, the presence of oxide coatings with different colors results in varied mechanical properties across the material surface, potentially impacting its performance under different conditions.

In this study, additive manufactured Ti-6Al-4V samples underwent laser polishing with Argon as the shielding gas. To examine the effects of gas flow instability during laser polishing, the researchers intentionally altered the gas flow stability. Image processing techniques were used to observe the consequences of this instability on the polished surfaces.

Furthermore, to induce surface coloring, the density of the shielding gas was kept low, resulting in oxidation on the polished surfaces. The researchers photographed the polished surfaces and used custom-coded software to process the images. This analysis helped in understanding how the stability of the shielding gas influences the final surfaces.

Notably, this research addresses a gap in the existing literature, as no previous study has specifically focused on the stability of the shielding gas during laser polishing. By filling this gap, the study contributes to a better understanding of the impact of gas flow stability on the surface quality of additively manufactured components.

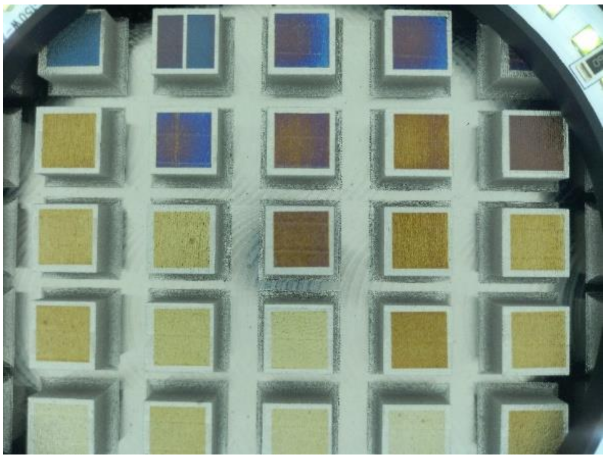


Figure 3. Surface Coloring due to Oxidation after LP

2. Materials and Methods

In this study, Ti-6Al-4V specimens manufactured using Selective Laser Sintering (SLM) device EOSsint M280 were polished by a laser source to get betterment in surface quality. In the study, Argon was selected as the protective gas in the polishing process. For the homogenous process, the flow rate of Ar gas was kept stable at 18 L/min; while it was also fluctuated to create the non-homogenously-processed specimen surface on the test specimen.

The laser source used in the study was a Gaussian Type 20W pulsed fiber laser with a 100 kHz frequency and 1080 nm wavelength. The polishing parameters for both homogeneously (HP) and non-homogenously processed (nHP) samples were kept the same except for the flow rate of Ar gas. In Table 1 below, the process parameters for laser polishing were given.

Table 1. Laser Polishing Parameters for HP and nHP Samples

Laser Power (P)	Pulse Repetition Rate (f)	Scan Speed (V)	Beam Diameter (d)	Beam Overlap
20 W	100 kHz	40 mm/s	40 µm	60%

After laser polishing, the surface roughness of specimens was measured by using Hommel Tester T500 from Hommel Werke (Germany). During roughness measurements, 10 different Ra were taken from different areas on the sample, and the geometric mean of these values was considered as the surface roughness value of that specimen.

Subsequently, surface images of the test specimens were photographed for image processing. In order to acquire sound images, a 6500K Wordop SD-120 model dome light source and a 24-megapixel camera were used. Then, images of the specimen surfaces were processed in custom software coded by the authors to draw RGB Histogram diagrams, and analyze surface homogeneity via color codes.

3. Results

3.1 Histograms and Homogeneity Analysis

At homogeneous surfaces, the color of the surface should be the same or quite similar along the area. To understand the differences between hues, recorded images were evaluated using histogram graphs. Histogram graphs show the frequency of the RGB colors; thus, giving us hints about the homogeneity of the color range at the surface. In Figure 4, a histogram graph for a sample color block has been presented.

The sample color block shown in Figure 4 was prepared via MS Paint to create a fully (100%) homogenous surface. The X-axis of RGB histograms represents the number of different color tones within that color, while Y-axis shows the amount of that tone. By looking at the RGB Histogram of the sample color block, it is seen that RGB colors within the sample color block draw a straight line through the y-axis, and their pixel values through the x-axis are quite narrow; which means red, green, and blue color values within the sample have single color codes leading to a fully homogenous surface. In order to formulate the homogeneity through RGB histogram, Equation (1) was created.

$$HR = \frac{n_{max}}{pv_{max} - pv_{min}} \quad (1)$$

In Equation 1, n_{max} is the maximum value in y-axis while pv_{max} is the maximum and p_{vmin} is the minimum pixel values for that color.HR gives the homogeneity rate of that color. In that case, HR values for the sample color block are the same for all colors and equal to 12.5. This value is standard for all fully homogenous colors. Since it is the ideal value, HR values for as-built or HP samples will be lower than 12.5.

To evaluate the homogeneity of the surfaces in another way, custom-designed software has been used in addition. In this software, images of the surfaces are divided into 10x10 square blocks by the software, then color codes of the square blocks are analyzed individually. Ultimately, the homogeneity of the surface is determined by a group of color codes. In Figure 5, the homogeneity of the sample color block determined via this software has been given.

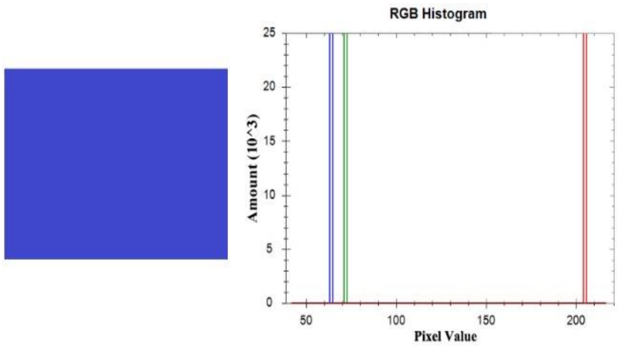
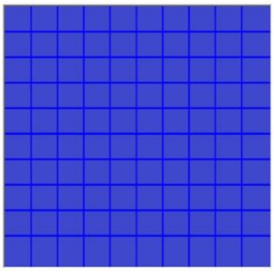


Figure 4. RGB histogram of the sample color block



108	108	108	108	108	108	108	108	108	108
108	108	108	108	108	108	108	108	108	108
108	108	108	108	108	108	108	108	108	108
108	108	108	108	108	108	108	108	108	108
108	108	108	108	108	108	108	108	108	108
108	108	108	108	108	108	108	108	108	108
108	108	108	108	108	108	108	108	108	108
108	108	108	108	108	108	108	108	108	108
108	108	108	108	108	108	108	108	108	108
108	108	108	108	108	108	108	108	108	108

Figure 5. Color code homogeneity of the sample color block

From Figure 5, it is seen that the color code for this sample color block has been chosen as 108 by the software. Since all of the square blocks have the same color code, this image can be considered as a fully homogenous surface.

In this study, the as-built sample along with the homogeneously (HP) and non-homogeneously processed (nHP) samples have been evaluated by using the technique as explained above. Macro images of the samples used in this study were given in Figure 6, while surface images of these samples were shown in Figure 7.

As shown in Figure 7 above, as-built and homogenously processed samples can be considered as having a small volume of color hues. On the other hand, the non-homogeneously processed sample has a wide color range on its surface. To investigate in detail, RGB histograms of the specimen surface were drawn, and color code homogeneity software was applied to surface images. In Figure 8, the RGB histogram of the as-built sample was given.

RGB histogram of the as-built sample shows a similar behavior as the RGB histogram of the sample color block given in Figure 4. Pixel values of red, green, and blue colors are in a small range, and they have only one peak; which means hue on the as-built material surface is very close to being fully homogenous. To observe the hues on the material surface in an elaborate way, the results of the color code homogeneity software were given in Figure 9 .

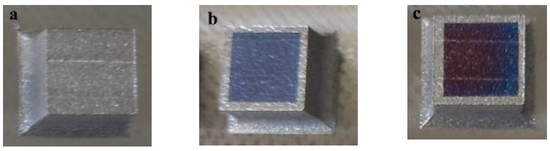


Figure 6. Macro Images After Laser Polishing of a) As-built Sample, b) HP Sample, c) nHP Sample

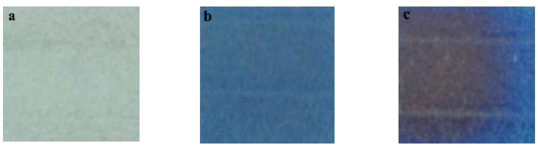


Figure 7. Surface Images After Laser Polishing for a) As-built Sample, b) HP Sample, c) nHP Sample

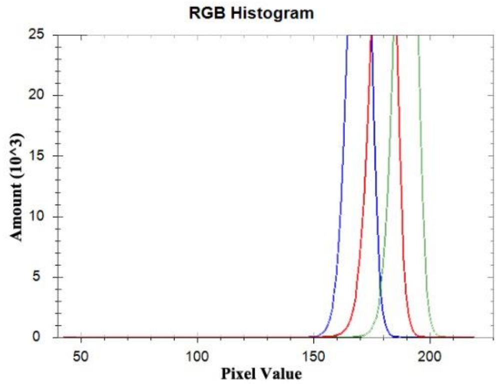
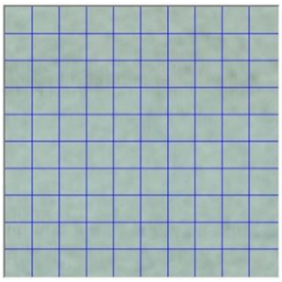


Figure 8. RGB histogram of the as-built sample



176	176	174	175	175	174	174	173	175	175
174	171	171	174	172	171	169	169	171	174
169	168	170	168	170	170	170	171	167	172
173	173	174	174	175	171	173	172	171	174
176	177	175	176	174	171	175	173	174	176
177	177	175	176	176	175	174	177	173	176
178	176	177	176	176	175	175	176	175	176
175	174	176	175	174	173	174	174	173	175
175	173	173	172	173	171	172	174	171	173
175	172	173	173	173	172	172	171	173	175

Figure 9. Color code homogeneity of the as-built sample

As seen from the figure, the color code scale for the as-built specimen is between 168 and 178; which can be considered quite narrow compared to the non-homogenously processed sample discussed later.

After assessment of the as-built sample, the material was polished under the laser to enhance its surface roughness. During laser polishing, the flow of the Argon gas was kept stable; thus, enabling a homogenous process. After the polishing process, the surface quality of the HP sample was measured and the image of the surface was taken to be analyzed. In Figure 10, the RGB histogram of the HP sample was shown.

Similar to the RGB histogram of the as-built sample, pixel values of the HP sample are relatively in a small range and only one peak is apparent on the graph. That proves to us that the material surface of the HP is almost fully homogenous. For a complete analysis, separate color histograms were given in Figure 11, and results of the color code homogeneity software in Figure 12 below. Similar to the color code range of the as-built material, the range for the HP sample (between 97-108) can be considered narrow as well, especially compared to the nHP sample.

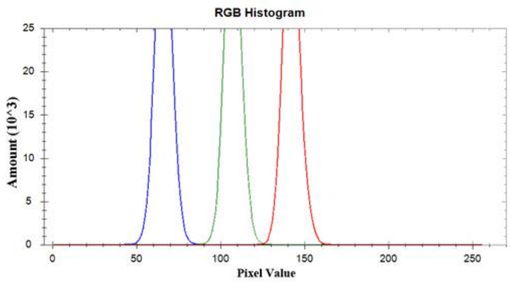


Figure 10. RGB Histogram of the HP Sample

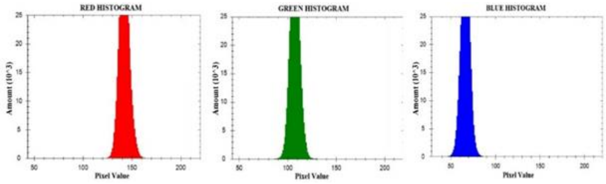
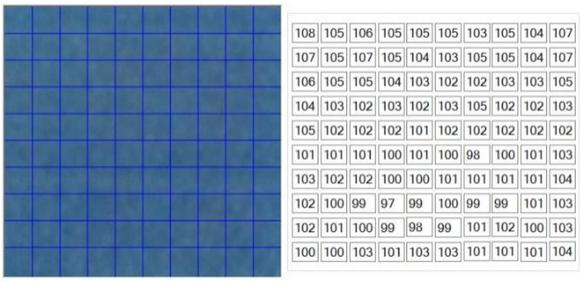


Figure 11. Separate color histograms of the HP sample



108	105	106	105	105	105	103	105	104	107
107	105	107	105	104	103	105	105	104	107
106	105	105	104	103	102	102	103	103	105
104	103	102	103	102	103	105	102	102	103
105	102	102	102	101	102	102	102	102	102
101	101	101	100	101	100	98	100	101	103
103	102	102	100	100	101	101	101	101	104
102	100	99	97	99	100	99	99	101	103
102	101	100	99	98	99	101	102	100	103
100	100	103	101	103	103	101	101	101	104

Figure 12. Color code homogeneity of the HP sample

Table 2. HR values of as-built and HP samples

Homogeneity Rate (HR)	As-Built Sample	HP Sample
Red	0.714	0.714
Green	0.714	0.714
Blue	0.714	0.714

Apart from these, homogeneity rates obtained through Equation 1 were given in Table 2 below. As shown in Table 2, HR values of colors within As-built and HP specimens are the same. That is the evidence showing that the specimen which was polished under a stable shielding gas flow created a homogeneous surface; since the HR values of red, green, and blue colors are equal to each other as it is in the as-built sample.

For assessment of the nHP sample, the material was polished under laser while the flow of the Argon gas was not stable; thus, led to a non-homogenous process. After the polishing process, the surface quality of the nHP sample was measured and the image of the surface was taken to be analyzed. In Figure 13 RGB histogram, and in Figure 14 separate color histograms of the nHP sample were given.

Unlike the HP sample, RGB histograms behave differently for the nHP sample. Due to the color hues, which can be clearly seen on the material surface in Figure 7, various peaks in histogram diagrams were expected to appear. As shown in Figure 13, the RGB histogram of the nHP sample proves the non-homogeneity on the material surface, since a wide range of pixel values along with multiple peaks can be observed.

In Figure 15, the result of the color code homogeneity software was presented. The color code range for the nHP sample varies between 80 and 109; which demonstrates a wider range than the as-built and HP samples.

As the final assessment, Table 3 below shows the HR values of each color within the nHP sample. As can be seen, values differ for nHP sample. This difference is evidence of non-homogeneous processes occurring across the surface of the sample.

3.2 Surface Roughness

The laser polishing process utilizes laser radiation to re-melt and solidify the surface, with the objective of enhancing the surface quality of the material by decreasing its roughness. During this process, inert gases such as Argon and Nitrogen can be used to enhance the output of the process. However, the flow stability of those protective gases is of importance in surface enhancement. As explained previously in Figure 7, stable gas flow during laser polishing enables a homogenous surface modification while lack of stability in gas flow occurs non-homogeneity on the material surface. Thus, a surface quality alteration that occurred on the material surface depends on the stability of the gas flow. Surface qualities of the as-built material prior to the laser polishing, along with the HP and nHP samples were given in Figure l6.

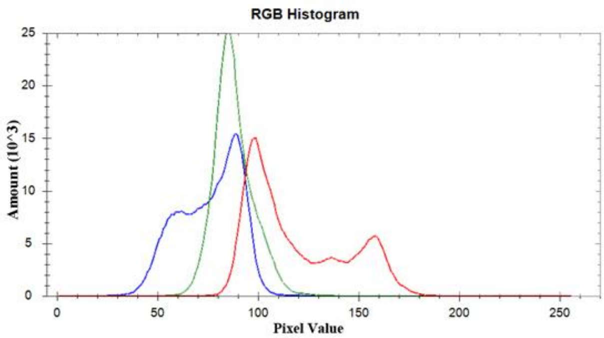


Figure 13. RGB Histogram of the nHP Sample

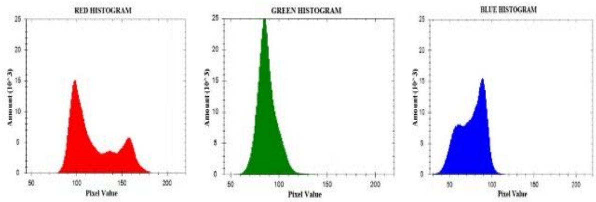
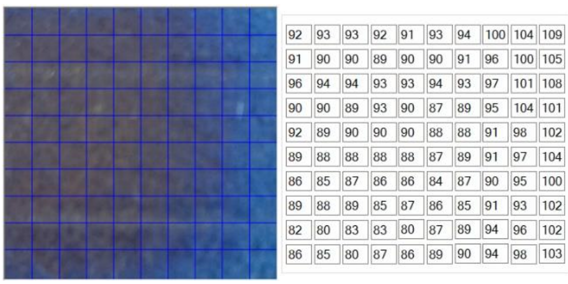


Figure 14. Separate color histograms of the nHP sample

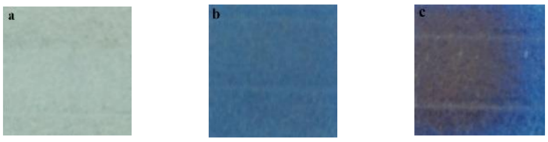


92	93	93	92	91	93	94	100	104	109
91	90	90	89	90	90	91	96	100	105
96	94	94	93	93	94	93	97	101	108
90	90	89	93	90	87	89	95	104	101
92	89	90	90	90	88	88	91	98	102
89	88	88	88	88	87	89	91	97	104
86	85	87	86	86	84	87	90	95	100
89	88	89	85	87	86	85	91	93	102
82	80	83	83	80	87	89	94	96	102
86	85	80	87	86	89	90	94	98	103

Figure 15. Color code homogeneity of the nHP sample

Table 3. HR values of nHP sample

Red	0.141
Green	0.357
Blue	0.183



Ra = 8.1 ± 0.05 µm   Ra = 4.81 ± 0.1 µm   Ra = between 4.82 - 6.93 µm

Figure l6. Surface Roughness Values of a) As-built Material, b) HP Sample, and c) nHP Sample

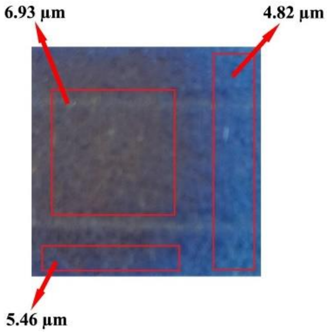


Figure 17. Non-Homogeneous Surface Qualities on nHP Sample

As an expected result of laser polishing, the surface quality of the HP sample shows a constant 40% betterment all over the surface. On the other hand, final Ra values on the nHP sample fluctuate between 4.82 µm and 6.93 µm. As detailed in Figure 17 below, different color regions represent specific surface qualities on that particular material. Even though an improvement in surface quality is observed, the betterment rate varies depending on the flow rate of the Ar gas during laser polishing.

3. Conclusions

In this study, the researchers investigated the importance of maintaining a stable protective gas flow during laser polishing of additively manufactured Ti-6Al-4V samples. The goal was to achieve a homogenously processed material surface. Some specimens had a constant and stable flow rate of argon (Ar) gas during laser polishing, while others experienced fluctuations in the gas flow for experimental purposes.

After the laser polishing process, the researchers photographed the surface of the specimens. These photographs were then analyzed using image processing techniques, including RGB histograms, and a custom-coded homogeneity analysis software. The roughness values of the material surfaces were also measured.

The results of the study demonstrate that the stability of the protective gas flow during laser polishing plays a significant role in achieving a homogenous material surface. Although surface quality alterations can occur even with an unstable gas flow, the outcome of the surface modification may vary depending on the material.

The study highlights the importance of surface roughness, as certain mechanical properties, such as fatigue strength, are directly affected by it. The researchers suggest that the fatigue strength of the specimens subjected to an unstable gas flow (nHP sample) might suffer and produce unexpected results. Conversely, the homogenous surface and better Ra (surface roughness) values of the specimens with stable gas flow (HP sample) are expected to result in superior fatigue strength compared to the as-built and nHP samples.

The study acknowledges that further investigations are necessary to validate these findings. This particular study solely focuses on the consequences of protective gas flow instability during laser polishing in terms of surface semblance and roughness and does not delve into the direct mechanical property evaluations.

Declaration

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article. The authors also declared that this article is original, was prepared in accordance with international publication and research ethics, and ethical committee permission or any special permission is not required

Author Contributions

Methodology, T.E, F.T. and İ.S.Ü.; formal analysis, F.T. and T.E.; investigation, T.E.; resources, T.E. and E.K.; data curation, T.E. and İ.S.Ü; writing—original draft preparation, T.E.; writing—review and editing, F.T. and İ.S.Ü.; visualization, T.E; supervision, F.T. and E.K.

Acknowledgment

This work supported by the Laser Technologies Research and Application Center (LATARUM) at Kocaeli University in Turkey.

Nomenclature

AM	: Additive Manufacturing
LP	: Laser Polishing
SLS	: Selective Laser Sintering
HP	: Homogeneously Processed
nHP	: Non-homogeneously Processed
HR	: Homogeneity Rate
Ar	: Argon
P	: Laser Power
V	: Scan Speed
f	: Pulse Repetition Rate
d	: Beam Diameter

References

1. Ergene B., *Simulation of the production of Inconel 718 and Ti6Al4V biomedical parts with different relative densities by selective laser melting (SLM) method.* Journal of the Faculty of Engineering and Architecture of Gazi University, 2022. **37**(1): p. 469-484.
2. Yasa E., J.P. Kruth and J. Deckers, *Manufacturing by combining selective laser melting and selective laser*

erosion/laser re-melting. CIRP Annual, 2011, **60**(1): p. 263–266.

3. Mohammadian N., S. Turenne and V. Brailovski, *Surface finish control of additively-manufactured Inconel 625 components using combined chemical-abrasive flow polishing.* Journal of Material Processing Technology, 2018, **252**: p. 728–738.
4. Ma C., M.T. Andani, H. Qin, N.S. Moghaddam, H. Ibrahim, A. Jahadakbar and C. Ye, *Improving surface finish and wearresistance of additive manufactured nickel-titanium by ultrasonicnano-crystal surface modification.* Journal of Material Processing Technology, 2017. **249**: p. 433-440.
5. Li J., W. Huayang, L. Haixu and Z. Dunwen, *Surface and property characterization of selective laser-melted Ti-6Al-4V alloy after laser polishing*. The International Journal of Advanced Manufacturing Technology, 2023. **127**: p. 9-10.
6. Wang Y., L. Yuhang and G.Yingchun, *Surface modification and mechanical properties of laser powder bed fusion Inconel 718 after magnetic-assisted laser polishing*. Optics & Laser Technology, 2023, 162.
7. Temmler A., E. Willenborg E and K. Wissenbach, *Design surfaces by laser remelting.* Physics Procedia, 2011, **12**: p. 419–430.
8. Temmler A., E. Willenborg E and K. Wissenbach, *Laser Polishing.* Proc. SPIE 8243, Laser Applications in Microelectronic and Optoelectronic Manufacturing (LAMOM) XVII, 2012. 82430.
9. Giorleo L., E. Ceretti E and C. Giardini, *Ti surface laser polishing: effect of laser path and assist gas.* Procedia CIRP, 2015, **33**: p. 446–451.
10. Temmler A., I. Ross, J. Luo, G. Jacobs and J.H. Schleifenbaum, *Influence of global and local process gas shielding on surface topography in laser micro polishing (LμP) of stainless steel 410.* Surface & Coatings Technology, 2020. 403.
11. Cwikla M., R. Dziedzic and J. Rainer, *Influence of Overlap on Surface Quality in the Laser Polishing of 3D Printed Inconel 718 under the Effect of Air and Argon.* Materials, 2021, **14**(6): p. 1479.
12. Sun X., W. Wang, X. Mei, A. Pan, Y. Chen and J. Cui, *High Capacity color code preapred on titanium alloy using femtosecond laser.* Optics & Laser Technology, 2022, 145.
13. Perez del Pino A., P. Serra and J.L. Morenza, *Coloring of titanium by pulsed laser processing in air.* Thin Solid Films, 2002. **145**: p. 201-205.
14. Perez del Pino A., P. Serra and J.L. Morenza, *Oxidation of titanium through Nd:YAG laser irradation*. Applied Surface Science, 2002. **197**(198): p. 887-890.
15. Perez del Pino A., J.M. Fernandez-Pradas, P. Serra and J.L. Morenza, *Coloring of titanum through laser oxidation: comparative study with anodizing*. Surface and Coatings Technology, 2004. **187**: p. 106-112.
16. Diamanti M.V., D.C. Barbara and P. MariaPia, *Anodic oxidation of titanium: from technical aspects tobiomedical applications*. Journal of Applied Biomater Biomechanic, 2011, **9**(1): p. 55-69.
17. Kurniawan K.F., I.M. Ulfah and K. Muhammad, *The Effect of Anodic Oxidation Voltages on the Color and CorrosionResistance of Commercially Pure Titanium (CP-Ti).* Evrimata: Engineering and Physics, 2023, **1**(1): p. 18-23.