Tribol. Lubr., Vol. 39, No. 6, December 2023, pp. 244~249
Tribology and Lubricants

ISSN 2713-8011(Print) • 2713-802X(Online)
http://Journal.tribology.kr

DOI https://doi.org/10.9725/kts.2023.39.6.244

Influence of Surface Roughness on Friction and Wear Characteristics of SUS 321 for Hydraulic Cylinder Parts Application

Sung-Jun Lee[1], Yonghun Jang[2] and Chang-Lae Kim[3†]

[1]Ph.D. Student, Graduate School, Dept. of Mechanical Engineering, Chosun University
[2]Senior Research Engineer, Innovation Process Development Team, KEPCO KPS Global Institute of Technology
[3]Associate Professor, Dept. of Mechanical Engineering, Chosun University

(Received December 13, 2023 ; Revised December 19, 2023 ; Accepted December 21, 2023)

Abstract – This paper presents a comprehensive analysis of the impact of surface roughness on the friction and wear properties of SUS 321, an austenitic stainless steel variant produced using the laser powder bed fusion (LPBF) technique, which is a prevalent additive manufacturing method. After the LPBF fabrication, the specimens go a heat treatment process aimed at alleviating residual stress. Subsequently, they are polished extensively to achieve a refined and smooth surface. To deliberately introduce controlled variations in surface roughness, an etching process is employed. This multi-step method encompassed primary etching in a 3M hydrochloric acid solution, followed by secondary etching in a 35 wt% ferric chloride solution, with varying durations applied to different specimens. A comprehensive evaluation of the surface characteristics ensued, employing precise techniques such as surface roughness measurements and meticulous assessments of water droplet contact angles. Following the surface treatment procedures, a series of friction tests are performed to explore the tribological behavior of the etched specimens. This in-depth investigation reached its peak by revealing valuable insights. It clarified a strong correlation between intentionally altered surface roughness, achieved through etching processes, and the resulting tribological performance of LPBF-fabricated SUS 321 stainless steel. This significantly advances our grasp of material behavior in tribological applications.

Keywords – Laser powder bed fusion, Friction/wear characteristics, Hydraulic cylinder, Surface roughness

1. Introduction

The advent of additive manufacturing has revolutionized material processing and component manufacturing, enabling the creation of intricate geometries with unparalleled ease and efficiency[1]. Among various additive manufacturing techniques, Laser Powder Bed Fusion (LPBF), a powder bed fusion process, has gained substantial traction due to its precision and suitability for a wide range of materials[2]. LPBF operates by selectively melting powder layers using a high-energy laser beam, progressively constructing the desired part. This study focuses on applying the LPBF method to SUS 321, an austenitic stainless steel known for excellent corrosion resistance and mechanical properties.

SUS 321, with its superior resistance to intergranular corrosion, finds extensive applications across diverse industries[3]. One such focus in this study is its application in hydraulic cylinder parts. Hydraulic cylinders are critical components in various machinery and vehicles, and their performance heavily relies on material properties, especially the friction and wear characteristics of constituent parts[4].

[†]Corresponding author: Chang-Lae Kim
Tel: +82-62-230-7048, Fax.: +82-62-230-7048
E-mail: kimcl@chosun.ac.kr
https://orcid.org/0000-0002-1983-0181

Surface characteristics, notably surface roughness, play a crucial role in determining material friction and wear behavior. Surface roughness refers to micro-level surface irregularities significantly impacting tribological performance by affecting friction, wear, and lubrication. Hence, understanding surface roughness's effect on the friction and wear characteristics of SUS 321 is vital for its application in hydraulic cylinder parts.

Numerous studies have investigated material friction and wear characteristics concerning surface roughness. In a study by Rahaman et al., the influence of surface roughness on friction and wear of bulk metallic glasses was examined[5]. Their findings revealed that asperity deformation before contact sliding crucially alters material friction properties. It was reported that the material's friction coefficient and wear resistance increase with surface roughness. In another study, Lee et al. explored the impact of surface roughness on the tribological characteristics of silicone rubber, a material used in hydraulic rod seals[6]. Silicone rubber specimens with varied surface roughness were fabricated through silicone powder coating, and their friction and wear characteristics were evaluated via reciprocating sliding friction tests. The study demonstrated that increased surface roughness led to reduced surface energy, absorbing and dispersing contact pressure, resulting in reduced friction. Particularly, silicone rubber coated with silicone powder exhibited a friction coefficient over 70 % lower than pure silicone rubber, displaying minimal wear patterns.

This study aims to investigate the effect of surface roughness on the friction and wear characteristics of LPBF-fabricated SUS 321. Furthermore, it has been recognized that considering contact angle measurements is crucial. The contact angle serves as an important measurement standard for understanding the wetting behavior of material surfaces. The interaction between the liquid and solid surfaces quantified by the contact angle can reveal complex relationships between surface characteristics such as surface energy and wettability, and friction performance. To induce controlled surface roughness variations, SUS 321 samples underwent etching processes using hydrochloric acid (HCl) and ferric chloride ($FeCl_3$). Etching, a chemical milling process, selectively removes surface material, altering surface roughness. By varying etching time, SUS 321 samples with different surface roughness were prepared.

The surface properties of etched SUS 321 samples were comprehensively characterized, and their friction and wear characteristics were evaluated under controlled conditions. The findings from this study will offer valuable insights into the correlation between surface roughness and the tribological performance of SUS 321. This understanding will inform the design and manufacturing processes of hydraulic cylinder parts, enhancing their performance and lifespan.

2. Materials and Experiments

In this study, SUS 321 specimens were prepared using 3D printing with the LPBF method to assess surface, friction, and wear characteristics based on the surface roughness of SUS 321. Fig. 1 illustrates a schematic diagram of the LPBF process. Test specimens were created using specific process parameters: 180 W output, 650 mm/s scanning speed, 0.105 mm scanning spacing, and 30 μm layer thickness. The SUS 321 specimens underwent heat treatment to eliminate residual stress and were then polished to achieve a smooth surface. An etching process was employed to generate specimens with varying surface roughness. Initially, SUS 321 specimens were cleaned ultrasonically in ethanol and dried using a hot air dryer. The cleaned substrates were immersed in a 3M hydrochloric acid solution for 30 minutes for primary etching, followed by immersion in a 35 wt% ferric chloride solution for different durations. Subsequently, the SUS 321 specimens were dried in an oven at temperatures exceeding 60°C for at least 30 minutes. The specimens etched in hydrochloric acid were labeled as “Bare”, while those etched in ferric chloride solution were designated as “3 min”, “8 min”, “15 min”, and “30 min”, corresponding to the duration of etching.

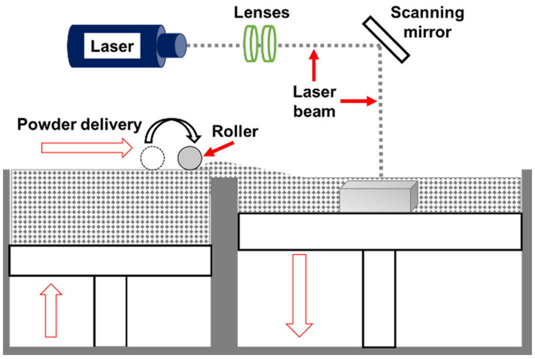

Fig. 1. Schematic diagram of laser powder bed fusion process.

Table 1. Tribo-test conditions

Tribo-test	
Tip material	SUS 304 (D : 1 mm)
Normal load	100 mN
Sliding speed	16 mm/s
Sliding stroke	2 mm
Sliding cycle	5,000 cycles

To assess the surface characteristics of the SUS 321 specimens based on their surface roughness, measurements of surface roughness and water droplet contact angles were conducted. The contact angle was determined by depositing 10 μL of DI water onto the specimen surface and measuring the resulting angle formed by the water droplet using a microscope. Surface roughness (R_a) for each specimen was measured utilizing a 2D profiler. The surface roughness was determined by scanning a 2 mm evaluation length at a speed of 0.5 mm/s after applying the stylus tip onto the specimen surface with a load of 0.75 mN.

A friction test was performed to assess the friction and wear characteristics of the SUS 321 specimens produced through the etching process, contingent upon their surface roughness. The test conditions for the friction evaluation of SUS 321 are outlined in Table 1. This involved a sliding friction test wherein a 1 mm diameter SUS 304 sphere was brought into contact with the specimen, applying a load of 100 mN. The experiment comprised 5,000 cycles conducted at a speed of 16 mm/s and a sliding distance of 2 mm. The friction test took place in an environment with a temperature of 20°C and 30% humidity. Post the friction test, the wear track formed on the surface underwent analysis using an optical microscope.

3. Results and Discussion

This study aimed to explore the influence of surface roughness on the friction and wear characteristics of LPBF-fabricated SUS 321, with the intent of assessing its potential application in hydraulic cylinder components.

Fig. 2 depicts the surface morphology of each specimen based on the etching conditions. Despite some scratch marks, the Bare specimen displayed a relatively smooth surface. However, the 3 min, 8 min, 15 min, and 30 min specimens, subjected to ferric chloride etching, exhibited increased roughness, showcasing micrometer-sized particles on the surface. This indicates that the ferric chloride etching process results in a rougher surface compared to sole hydrochloric acid etching[7].

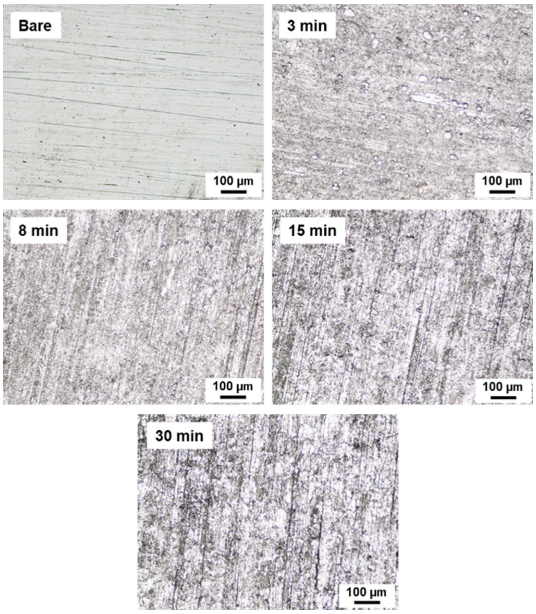

Fig. 2. Microscope images of SUS 321 according to etching conditions.

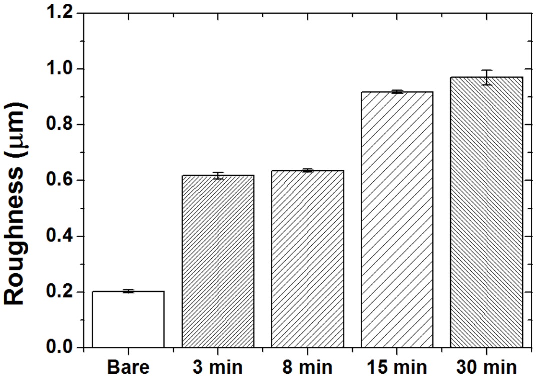

Fig. 3. Surface roughness values of SUS 321 according to etching conditions.

Fig. 3 showcases the surface roughness (R_a) values of each specimen. The Bare specimen presented the smallest surface roughness value at 0.2 μm, whereas the 3 min, 8 min, 15 min, and 30 min specimens, treated with ferric chloride etching, displayed surface

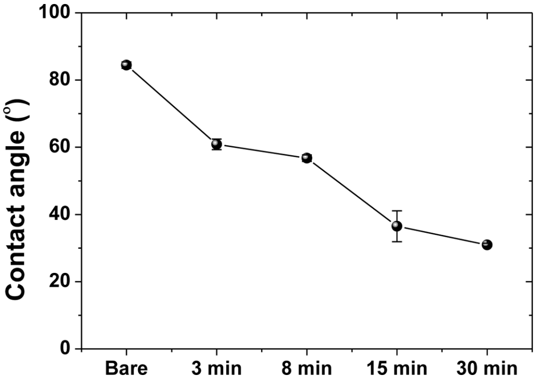

Fig. 4. Contact angles of SUS 321 according to etching conditions.

roughness values of 0.62, 0.64, 0.92, and 0.97 μm, respectively. Among these, the 30 min specimen, enduring the lengthiest ferric chloride etching duration, exhibited the highest surface roughness value of 0.97 μm, indicating the most aggressive etching process.

Fig. 4 presents the contact angle outcomes for each specimen. The Bare specimen exhibited the highest contact angle, measuring 84.5°, whereas the 30 min specimen, subject to the longest etching duration, demonstrated the lowest contact angle at 31.0°. Among the 3 min, 8 min, and 15 min specimens treated with ferric chloride etching, contact angles of 60.8°, 56.8°, and 36.5° were observed, respectively. These results indicate that as surface roughness increases, surface wettability improves, resulting in decreased contact angles[8].

Fig. 5 depicts the variations in the friction coefficient for each specimen across 5,000 cycles. Both the Bare and 3 min specimens initiate around 0.2 but exhibit a rapid surge to approximately 0.35 after about 200 cycles. This abrupt rise might stem from the adhesive wear mechanism, wherein their relatively smooth surfaces foster a larger real contact area, consequently generating heightened adhesive forces[9]. Subsequently, the friction coefficient gradually increases, signifying a shift from adhesive to fatigue wear as the surface roughness accommodates deformation.

The 8 min and 15 min specimens demonstrate a similar pattern, swiftly escalating to around 0.3 within the initial 200 cycles. However, post this swift rise, their friction coefficient stabilizes, implying the attainment of a steady-state wear regime wherein asperity deformation and recovery rates balance out[10].

In contrast, the 30 min specimen initiates with a friction coefficient of 0.22. However, after approximately 1,500 cycles, it sharply climbs beyond 0.35. This surge could be attributed to the abrasive wear mechanism, where increased surface roughness intensifies asperity interlocking, leading to accelerated material removal from the surface[11].

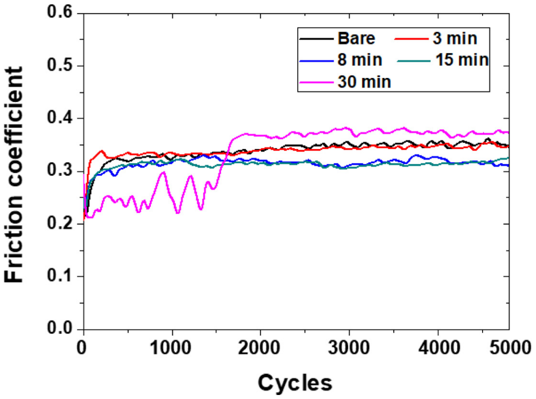

Fig. 5. Friction coefficient history of SUS 321 according to etching conditions.

Fig. 6 displays the average friction coefficient for each specimen. The Bare and 3 min specimens exhibit the highest average friction coefficient at 0.34, followed by the 30 min specimen at 0.33. The 8 min and 15 min specimens show the lowest average friction coefficient at 0.31. This trend in the average friction coefficient aligns with the wear mechanisms depicted in Fig. 5, illustrating a transition from adhesive to fatigue to abrasive wear, causing a decrease in the average friction coefficient.

Fig. 7 offers a detailed view of the observed wear

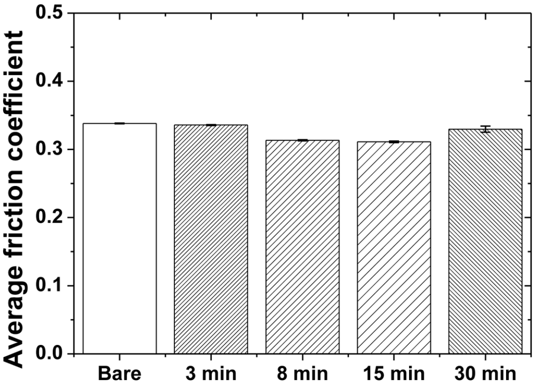

Fig. 6. Average friction coefficients of SUS 321 according to etching conditions.

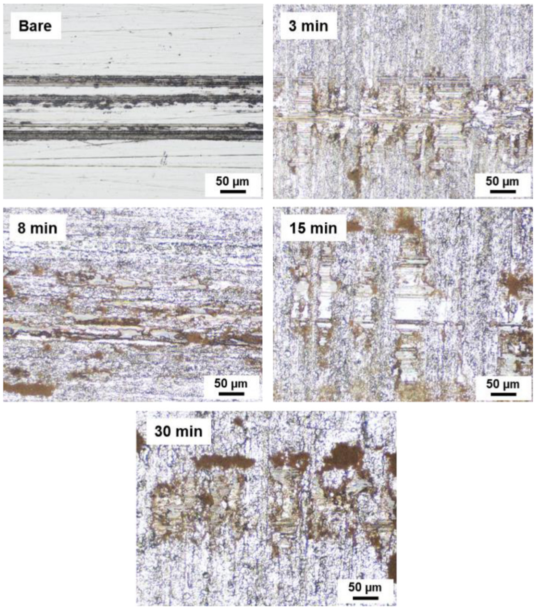

Fig. 7. Microscope images of wear tracks formed on the surfaces of SUS 321 according to etching conditions.

tracks on each specimen. It is evident that wear mechanisms significantly vary among the specimens, primarily due to differences in their surface roughness resulting from varied etching process durations[12].

The Bare specimen, subject to the mildest etching process, displayed a rough scratch pattern at both the center and edges of the contact area. This wear pattern indicates adhesive wear, a common mechanism occurring when solid surfaces slide under significant loads[13]. This type of wear is likely due to the Bare specimen's relatively smooth surface, resulting in a larger real contact area and consequently, higher adhesive forces. Material transfer between surfaces occurs, leading to the observed scratch patterns.

Conversely, the 3 min and 8 min specimens, etched for relatively short durations, exhibited scratch marks at the wear shape’s edges, displaying a wear pattern that appeared pitted at the center. This pattern suggests fatigue wear, occurring under cyclic loading conditions [14]. The slightly increased surface roughness of the 3 min and 8 min specimens likely contributes to more stress risers, initiating crack formation. Over time, these cracks propagate, causing material detachment from the surface and forming the observed pitted wear pattern.

In contrast, the 15 min and 30 min specimens, subjected to longer etching durations, displayed a wider wear width with localized grinding shapes on the surface. This pattern indicates abrasive wear, occurring when hard asperities or particles adhering to a surface plow material from the opposing surface [15]. The significantly increased surface roughness of the 15 min and 30 min specimens likely results in heightened asperity interlocking, leading to accelerated material removal from the surface.

In summary, this study offers valuable insights into how etching duration impacts the surface properties and wear behavior of LPBF-fabricated SUS 321. These findings can guide the optimization of surface treatment processes to achieve desirable friction and wear properties for hydraulic cylinder components. Future studies should delve deeper into understanding wear mechanisms and their relationship with the etching process.

4. Conclusion

The study offers a comprehensive understanding of how surface roughness influences the friction and wear characteristics of LPBF-fabricated SUS 321. The etching process effectively modified specimen surface roughness, providing a range of levels for evaluation. Surface roughness and water droplet contact angle measurements characterized specimen surface properties, revealing a correlation between increased roughness and improved wettability. Friction tests, conducted under controlled conditions, showcased how varying roughness levels affected friction and wear behaviors. Results suggest an optimal roughness level could enhance friction and wear properties in LPBF-fabricated SUS 321, offering crucial insights for hydraulic cylinder part design and manufacturing. However, additional studies are recommended to explore wear mechanisms under diverse operating conditions and validate these findings. This research serves as a valuable resource for future work aimed at optimizing the surface treatment processes to enhance the performance and lifespan of hydraulic cylinder parts.

Acknowledgement

This work was supported by project for ‘Customized technology partner’ funded Korea Ministry of SMEs and Startups in 2023. (RS-2023-00253146)

References

[1] Ngo, T. D., Kashani, A., Imbalzano, G., Nguyen, K. T. Q., Hui, D., "Additive manufacturing (3D printing): A review of materials, methods, applications and challenges", *Composites Part B: Engineering*, Vol.143, pp.172-196, 2018.

[2] Oliveira, J. P., Lalonde, A. D., Ma, J., "Processing parameters in laser powder bed fusion metal additive manufacturing", *Mater. Des*., Vol.193, pp.108762, 2020.

[3] Wang, J., Su, H., Chen, K., Du, D., Zhang, L., Shen, Z., "Effect of δ-ferrite on the stress corrosion cracking behavior of 321 stainless steel", *Corrosion Sci*., Vol.158, pp.108079, 2019.

[4] Qiu, Z., Min, R., Wang, D., Fan, S., "Energy features fusion based hydraulic cylinders seal wear and internal leakage fault diagnosis method", *Measurement*, Vol.195, pp.111042, 2022.

[5] Rahaman, M. L., Zhang, L., Liu, M., Liu, W., "Surface roughness effect on the friction and wear of bulk metallic glasses", Wear, Vol.332, pp.1231-1237, 2015.

[6] Lee, S. J., Kim, C. L., "Influence of surface structure on friction and wear characteristics of silicone rubber for hydraulic rod seals", *RSC Adv*., Vol.13, pp.33595-33602, 2023.

[7] Zhang, Y., Zhang, Z., Yang, J., Yue, Y., Zhang, H., "Fabrication of superhydrophobic surface on stainless steel by two-step chemical etching", *Chem. Phys. Lett*., Vol.797, pp.139567, 2022.

[8] Wang, X., Zhang, Q., "Role of surface roughness in the wettability, surface energy and flotation kinetics of calcite", *Powder Technol*., Vol.371, pp.55-63, 2020.

[9] Lee, S. J., Kim, C. L., "Evaluation of friction and wear characteristics of carbon-based solid lubricant films for surface application of compressor parts", *Tribol. Lubr*., Vol.38, No.5, pp.222-226, 2022, https://doi.org/10.9725/kts.2022.38.5.222

[10] Lee, S. J., Kim, C. L., "Evaluation of scratch characteristics of diaphragm for application of hydrogen compressor parts", *Tribol. Lubr*., Vol.39, No.5, pp.212-215, 2023, https://doi.org/10.9725/kts.2023.39.5.212

[11] Kim, H. J., Kim, C. L., "Effect of nanomesh structure variation on the friction and wear characteristics of carbon nanotube coatings", *Tribol. Lubr*., Vol.36, No.6, pp.315-319, 2020, https://doi.org/10.9725/kts.2020.36.6.315

[12] Kumar, M., Sidpara, A., Racherla, V., "Analysis of tool wear and counter surface roughness in the flexible abrasive tool finishing", *Lubricants*, Vol.10, pp.318, 2022.

[13] Terwey, J. T., Fourati, M. A., Pape, F., Poll, G., "Energy-based modelling of adhesive wear in the mixed lubrication regime", *Lubricants*, Vol.8, pp.16, 2020.

[14] Johnson, C. L., Dunn, A. C., "Wear mode control of polydimethylsiloxane (PDMS) by load and composition", *Wear*, Vol.438, pp.203066, 2019.

[15] Li, Y., Schreiber, P., Schneider, J., Greiner, C., "Tribological mechanisms of slurry abrasive wear", *Friction*, Vol.11, pp.1079-1093, 2023.