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Enhancing Surface Integrity of Additively Manufactured Inconel 718 by Roller Burnishing Process

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Abstract

This work presents the effect of burnishing process including burnishing force, burnishing speed and burnishing conditions on surface properties of Inconel 718 alloy fabricated by laser powder based fusion additive manufacturing. As-built, sand blasted and heat-treated specimens are burnished and final surface properties such as surface roughness, surface topography, and microhardness are presented. The performance of the burnished surface is tested through wear test. This study reveals that burnishing process makes substantial contribution to reduce surface roughness of additively manufactured Inconel 718 alloy. Moreover, surface hardness is notably increased resulting from burnishing process and hence wear resistance of this alloy improved. Wear resistance of as-built specimens was increased by 38% through implementing roller burnishing. Wear resistance of heat-treated specimens is increased by 55% through implementing roller burnishing process.

Keywords: Additive manufacturing, Surface integrity, Inconel 718, Burnishing process

1. Introduction

Inconel 718 material is a nickel-based superalloy with high strength, high oxidation resistance, high fatigue properties and good wear resistance [1]. Due to these properties, Inconel 718 is widely used in oil & gas, aerospace and defense industry [2] and generally has complex geometries. However, Inconel 718 is classified as "hard-to-cut materials" [3]. For this reason producing Inconel 718 using traditional manufacturing is quite hard and also has quite high cost [2]. Inconel 718 has good weldability with the small amount of aluminum and titanium in its content, which allows its production with AM [4]. PBF-LB uses a focused laser beam to fuse metal powders layer by layer according to a 3D CAD model, is one of the most widely used AM methods [5]. It has a unique advantage over traditional technologies such as high geometric complexity, reduction of production steps, low material consumption, reduction of lead time and low production cost [6, 7]. In addition to these advantages, the PBF-LB method also has some disadvantages such as tensile residual stress [8, 9], porosity and cracks [10]. Although parameter optimization in AM aims to produce the final product within the specified tolerances, this is usually not the case, and the surface qualities and mechanical properties may not be as desired level [11]. It may be necessary to apply post-processes to improve the surface quality and mechanical properties of the parts [12, 13]. Roller burnishing process is one of the mechanical post-process methodology which is an easy-to-use, fast, cost-effective surface improvement process, often performed without stock removal to improve the surface integrity of mechanical parts, making workpieces smooth and hard [14-16]. The roller burnishing process is the process of eliminating the peaks on the surface and filling the gaps under the surface by applying pressure to the workpiece surface, depending on the force, feed, and rotation parameters determined according to the desired surface roughness of the cylindrical balls connected to the roller burnishing tool connected to the CNC center. The roller burnishing process is a method applied to aerospace materials produced by traditional methods in the literature, especially because it

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improves the surface quality and creates compressive residual stresses [17].

In this study, it is aimed to improve surface integrity aspects of additively manufactured Inconel 718 parts by controlling surface and subsurface characteristics and hence increasing wear resistance.

Nomenclature	
AM	Additive Manufacturing
PBF-LB	Laser-Beam Powder-Based Fusion

2. Experimental procedures

The workpieces used in this study was PBF-LB manufactured Inconel 718 nickel-based superalloy cylinder with a dimension of Ø20 x 80 mm. PBF-LB process was performed in ENAVISION 250 3D Additive Manufacturing Machine and process parameters presented in Table 1.

Table 1. Parameter set used in the manufacturing of specimens by PBF-LB method.

Laser Spot Diameter, d (µm)	85
Laser Scanning Speed, v (mm/s)	700
Laser Power, P (W)	190
Hatch Distance, h (µm)	70
Layer Thickness, tlayer (µm)	20
Recoater Time, (s)	11
Scanning Strategy	Chessboard (5x5 mm) Strip Rotate 67° Pattern
Base Plate Material	S316L

In order to reveal the effects of the roller burnishing process parameters on the workpiece, the parameter values are selected with high range. Accordingly, the roller burnishing process was applied under two burnishing forces (250 N, 750 N), two burnishing speeds (350 RPM, 1050 RPM) and two machining conditions (dry, air). Also in the build direction of the as-built PBF-LB Inconel 718 parts, feed rate was taken as constant 0.1 mm/rev throughout the roller burnishing process.

After the roller burnishing process, the parameters that gave the lowest (250 N, 1050 RPM, dry condition) and highest (750 N, 350 RPM, air condition) surface microhardness were determined. These parameters were applied to separately heat-treated and sandblasted specimens to observe the effectiveness of the two post-processes used consecutively.

Fig. 1. Roller burnishing process in dry condition.

Sandblasting was applied to the produced parts with the SK-500 Benchtop Shot Blasting Machine, which is produced in accordance with TS EN 12100:2010 and TS EN 60204-1 standards. A mixture of Al_2O_3 abrasive media (F70: 180-250 µm average particle size) and air applied by a nozzle with distance of 75 mm from the part and at a 45° angle under 6 bar pressure for 3 minutes on each part.

Inconel 718 alloy parts are heat treated with a 7-step programmable oven that can reach high temperatures (0-1200°C), 5000 W power (23 A/Phase). The heat treatment condition is 980 °C for 1 hour/cooling in air, 8 hours at 720 °C, cooling to 620 °C in the furnace with a cooling rate of 55°C/h, aging at 620 °C for 8 hours (precipitation) heat treatment/air cooling.

A 3D Keyence VHX-6000 optical microscope was used to examine the surface topography, roughness and wear marks. The ASTM E 384 standard was followed for the hardness test using Future-Tech FM310e. An average of 5 measurements determined the hardness of each specimen with a load dwelling time of 15 s and a testing load of 100 gf was used.

Wear tests were applied to determine the effect of second treatments on wear resistance. TURKYUS RTW Linear Wear Machine was used for these tests. This machine, with its reciprocation mechanism, can work with under different loads (from 1N to 30N), different ball types (such as steel, Si3N4, WC, Al_2O_3) and different sliding speeds (from 5 mm/s to 40 mm/s) according to ASTM G133 standards. The parts were subjected to wear test at optimum room temperature and humidity, under 5N load, 6 mm friction distance and 40 minutes. As the abrasive material, 6 mm diameter tungsten carbide ball (WC 94%, CO 6%) was used.

3. Results and discussions

3.1. Surface Topographies

The roller burnishing process is a very effective method to improve surface quality of additively manufactured parts. The pressure created by the applied force reduces the difference between peaks and troughs by plastically deforming the peaks. This results in a brighter surface with less roughness. Table 2 shows the surface roughness values measured after the roller burnishing process applied through various parameters. While the surface roughness of the as-built parts was measured about 15 µm, it was possible to reduce this value to 0.32 µm by applying roller burnishing.

Table 2 indicates that both parameters, namely burnishing force and speed alters the surface roughness of additively manufactured parts. Increasing burnishing speed results in decreasing average surface roughness of parts. Similarly, the high the burnishing force, the lower the surface roughness. It seems these parameters provide regular plastic flow with high deformation [18].

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Table 2. Surface roughness values of Inconel 718 parts under different roller burnishing parameters.

	Burnishing Force (N)	Burnishing Speed (RPM)	Ra (µm)
Dry	250	350	0,91
		1050	0,76
	750	350	0,62
		1050	0,51
Air	250	350	0,85
		1050	0,7
	750	350	0,5
		1050	0,32

Table 3 shows the influence of heat treatment and sandblasting on surface quality. Once as-built specimen is burnished at 250 N force and 1050 RPM under dry condition, the measured average surface roughness is 0.76 µm. However, once as-built specimen is subjected to heat treatment and followed by burnishing process, measured surface roughness is 0,94 µm. It indicates that implementing roller burnishing to heat treated specimen results in much higher surface roughness. Another as-built specimen is burnished through 750 N force and 350 RPM speed. The surface roughness of this specimen is 0.5 µm; but, once the specimen is heat treating and followed by burnishing using same parameters, the measured average roughness is approximately 0.55 µm. This also confirms that once heat treatment is implemented before burnishing process, roughness is much higher. On the other hand, sandblasting to as-built specimen and followed by burnishing seems to be much effective way to reduce average surface roughness as shown in Table 3.

Table 3. Surface roughness values of Inconel 718 parts under different roller burnishing parameters.

Roller Burnishing Parameters	Surface Roughness Values, Ra (µm)		
	As-Built + Roller Burnishing	Sandblasted + Roller Burnishing	Heat-Treated + Roller Burnishing
250 N, 1050 RPM, Dry	0,76	0,46	0,94
750 N, 350 RPM, Air	0,5	0,3	0,55

In Fig.2, topography images taken after roller burnishing operations with determined parameters applied to as-built, sandblasted and heat-treated parts are included.

It is clearly seen that the results of the roller burnishing operation applied in 750 N burnishing force, 350 RPM burnishing speed and air condition are better than the results of the roller burnishing operation applied in 250 N burnishing force, 1050 RPM burnishing speed and dry condition. The increase in the load and the decrease in the burnishing speed in the roller burnishing operation performed after both heat treatment and sandblasting showed an improvement in the surface of the part.

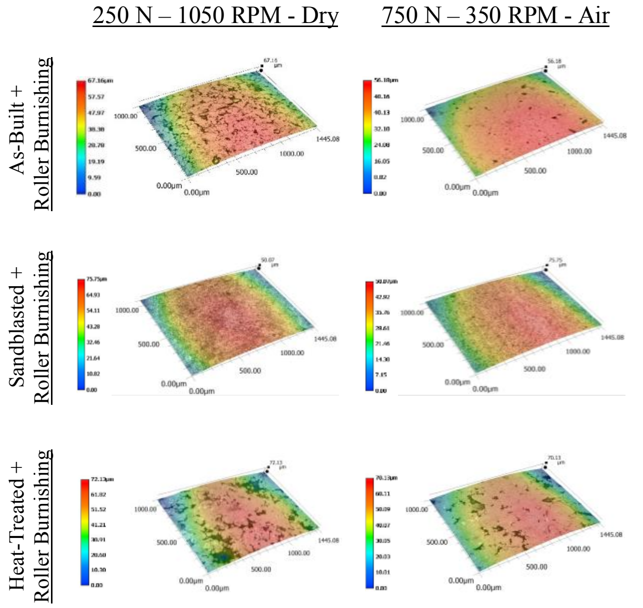

Fig. 2. Topography images of different post-processed Inconel 718 parts by manufactured with PBF-LB.

3.2. Microhardness

While one of the great advantages of burnishing process is to improve surface quality of parts as finishing processes, it also influences beneath the surface. While microhardness of as-built specimen is approximately 365 HV, burnishing process results in this value increased remarkably for all conditions. Fig. 3 shows microhardness values of specimens burnished under various burnishing force and speed. The effect of burnishing speed on hardness variation for both burnishing forces is evident.

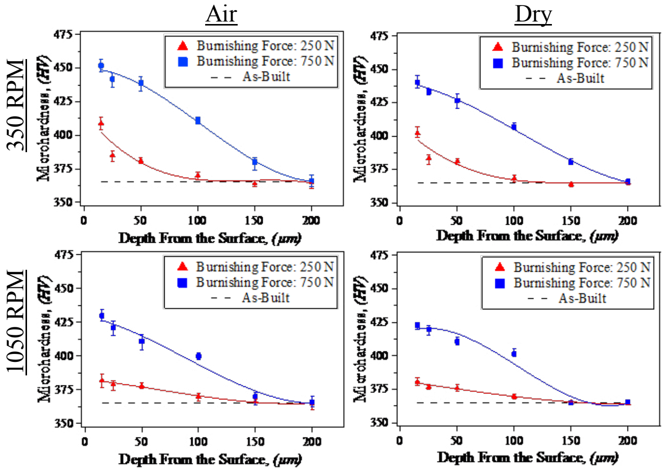

Fig. 3. Microhardness values of the Inconel 718 parts under various roller burnishing parameters.

At lower burnishing speed, higher microhardness is measured. Besides, larger burnishing force leads to much harder surface and subsurface layer as compared to smaller burnishing force. This is an expected result as the specimen is subjected to much larger mechanical effect and hence strain hardening takes place and eventually this can be seen via

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measured hardness. On the other hand, increased speed also increases temperature on the contact area that might causes annihilation of mechanical effect. Reduced hardness is the reason of such annihilation and softening at higher burnishing speed. Another evidence supporting this argument is the comparison the hardness result of specimens burnished under dry and air-cooling condition. Once air is used during burnishing to cool down the contact region between roller and specimen, then the hardness becomes slightly higher than dry condition. Another point needs to be discussed is the depth of strain hardened layer. When burnishing force is 250 N, the depth of hardened layer is approximately 100 µm, however, when 750 N force is used, the hardened layer reaches more than 150 µm depth from the surface. Such thick layer on the surface is expected to influence surface aspect against physical and chemical interaction. Thus, the performance of Inconel 718 components fabricated by additive manufacturing can be controllable through such surface properties.

The role of sandblasting and heat treatment on the surface and subsurface hardness is shown in Fig.4. Moreover, these specimens are subjected to roller burnishing to create final surface. This final hardness values of the surface and subsurface is also shown in Fig.4. It is an expected to obtain harder specimens after heat treatment. But, sandblasting process also results in increased hardness on the surface and subsurface of additively manufactured specimens. Followed by burnishing process created much harder surface and subsurface as shown in Fig.4. It is an obvious that the surface hardness of heat-treated + roller burnished specimen reaches to approximately 500 HV when 750 N burnishing force is applied.

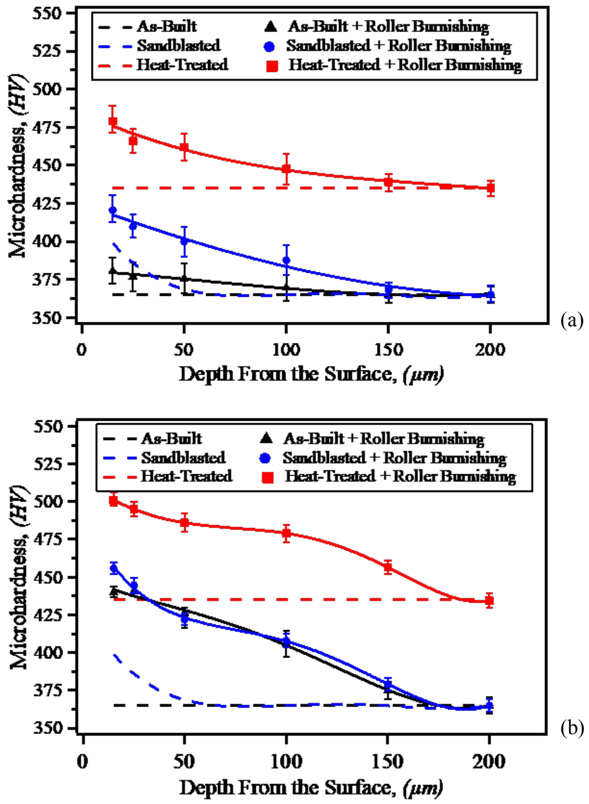

Fig. 4. Measured microhardness values of as-built and treated specimens, a) 250 N, 1050 RPM at dry condition, b) 750 N, 350 RPM at air condition.

3.3. Wear Behavior

The role of altered surface through burnishing process on performance is measured via wear test. Previous studies showed that wear behavior is directly proportional to microhardness of the parts [19]. The two-dimensional wear profile obtained from experiments are shown in Fig.5. Maximum depth is measured from as-built specimen as expected. While wear width of specimens does not show substantial difference, wear depth of specimens shows notable difference. The smallest wear depth is observed on the specimen that was subjected to heat treatment and burnishing. Wear depth of burnished specimen and sandblasted+ burnished specimen does not show remarkable difference.

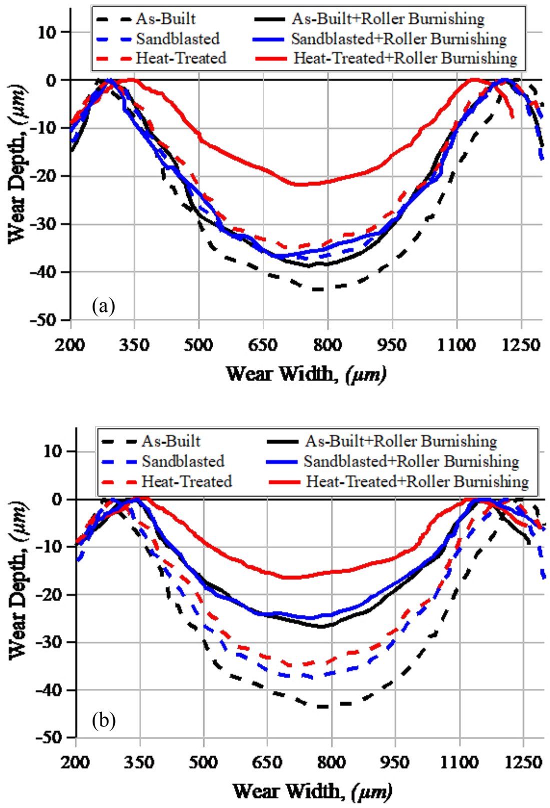

Fig. 5. Surface profiles measured across wear tracks of specimens after roller burnishing applied to as-built, sandblasted and heat-treated Inconel 718 parts a) 250 N, 1050 RPM and dry condition b) 750 N, 350 RPM and air condition.

Depending on the wear depth and wear width values obtained, the wear volume can be found by using following equation (1) [20]:

$$V = L\left[r^2 sin^{-1}\left(\frac{w}{2r}\right) - \frac{w}{2}\left(r^2 - \frac{w^2}{4}\right)^{\frac{1}{2}}\right] + \frac{\pi}{3}\left[2r^3 - 2r^2\left(r^2 - \frac{w^2}{4}\right)^{\frac{1}{2}} - \frac{w^2}{4}\left(r^2 - \frac{w^2}{4}\right)^{\frac{1}{2}}\right] \qquad (1)$$

where V is the wear volume in mm^3, L is the distance traveled by the ball in one burnishing speed (stroke length) in mm, w is the wear track width in mm, and r is the radius of the carbide ball in mm. The specific wear rate is defined as equation (2) [21]:

$$k = \frac{V}{Fxs} \tag{2}$$

where k is the specific wear rate in mm^3/Nm, F is the applied normal force in Newtons and s is the total sliding distance in m.

Fig.6. shows the specific wear rates of as-built, sandblasted and heat-treated parts. Specific wear rates of as-built, sandblasted and heat-treated parts were found as $6.7x10^{-4}$ mm^3/Nm, $5.71x10^{-4}$ mm^3/Nm and $5.04x10^{-4}$ mm^3/Nm, respectively. The specific wear rate decreased to $5.83\ x10^{-4}$ mm^3/Nm when roller burnishing was applied to the as-built part with 250 N, 1050 RPM in dry condition. Furthermore, when roller burnishing applied to the heat-treated part with the same parameters, the specific wear rate was calculated $3.53x10^{-4}$ mm^3/Nm. It is obvious that applying roller burnishing to the heat-treated parts increases the wear resistance.

Specific wear rate was found as $4.12x10^{-4}$ mm^3/Nm when as-built specimen was roller burnished through 750 N, 350 RPM in air condition. Once the specimen is heat-treated and followed by burnishing using same parameters, the measured specific wear rate becomes $3.04x10^{-4}$ mm^3/Nm. This result confirms that heat treatment followed by roller burnishing increases wear resistance of specimens. It was determined that the increase in microhardness improved the wear resistance.

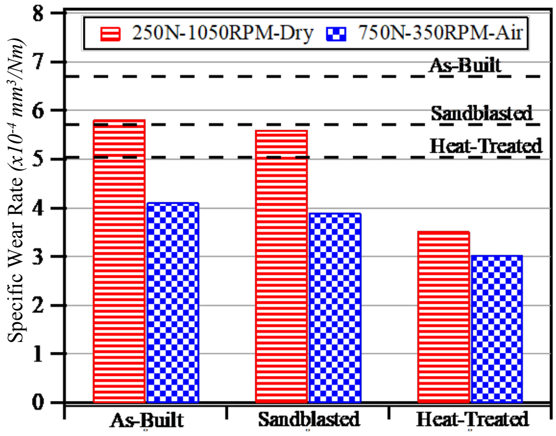

Fig. 6. Specific wear rates of Inconel 718 parts after roller burnishing applied to as-built, sandblasted and heat-treated parts with 250 N, 1050 RPM, dry condition and 750 N, 350 RPM, air condition.

4. Conclusions

According to the results obtained from the study, roller burnishing is an important post-process that affects the microhardness and, accordingly, the wear resistance of Inconel 718 parts produced with PBF-LB. The heat treating followed by the roller burnishing operation significantly improves the wear resistance of PBF-LB specimens. Although sandblasting is not effective as heat treatment on the wear resistance, it plays an important role in reducing the surface roughness.

Wear performance increased by 38% when the roller burnishing process was applied to the as-built part. The increase in wear performance was 42% when sandblasting was applied before roller burnishing, while it was 55% when roller burnishing was applied before heat treatment.

This study also showed that roller burnishing parameters such as burnishing force and burnishing speed are critical parameters to make the burnishing process more effective. In subsequent studies, roller burnishing can be applied with wider parameters to parts produced by additive manufacturing in order to obtain lower surface roughness values and high wear resistance. In addition, the consecutive use of various post-processes can be tried.

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References

[1] Q. Jia, and D. Gu, “Selective laser melting additive manufacturing of Inconel 718 superalloy parts: Densification, microstructure and properties,” *Journal of Alloys and Compounds,* vol. 585, pp. 713-721, 2014.

[2] Z. Baicheng, L. Xiaohua, B. Jiaming *et al.*, “Study of selective laser melting (SLM) Inconel 718 part surface improvement by electrochemical polishing,” *Materials & Design,* vol. 116, pp. 531-537, 2017.

[3] T. Sugihara, and T. Enomoto, “High speed machining of Inconel 718 focusing on tool surface topography of CBN tool,” *Procedia Manufacturing,* vol. 1, pp. 675-682, 2015.

[4] M. Xia, D. Gu, G. Yu *et al.*, “Influence of hatch spacing on heat and mass transfer, thermodynamics and laser processability during additive manufacturing of Inconel 718 alloy,” *International Journal of Machine Tools and Manufacture,* vol. 109, pp. 147-157, 2016.

[5] A. Mostafa, I. Picazo Rubio, V. Brailovski *et al.*, “Structure, texture and phases in 3D printed IN718 alloy subjected to homogenization and HIP treatments,” *Metals,* vol. 7, no. 6, pp. 196, 2017.

[6] Q. B. Nguyen, M. L. S. Nai, Z. Zhu *et al.*, “Characteristics of inconel powders for powder-bed additive manufacturing,” *Engineering,* vol. 3, no. 5, pp. 695-700, 2017.

[7] V. Popovich, E. Borisov, A. Popovich *et al.*, “Impact of heat treatment on mechanical behaviour of Inconel 718 processed with tailored microstructure by selective laser melting,” *Materials & Design,* vol. 131, pp. 12-22, 2017.

[8] I. Serrano-Munoz, T. Mishurova, T. Thiede *et al.*, “The residual stress in as-built Laser Powder Bed Fusion IN718 alloy as a consequence of the scanning strategy induced microstructure,” *Scientific Reports,* vol. 10, no. 1, pp. 1-15, 2020.

[9] M. Kaya, N. Sunay, and Y. Kaynak, “Comparison of finite element and empirical model prediction of surface residual stress in inconel 718 parts fabricated by laser powder bed fusion additive manufacturing,” *Journal of Additive Manufacturing Technologies,*

This is a resupply of March 2023 as the template used in the publication of the original article contained errors. The content of the article has remained unaffected.

vol. 1, no. 3, pp. 592-592, 2021.

[10] K. Prashanth, S. Scudino, T. Maity *et al.*, “Is the energy density a reliable parameter for materials synthesis by selective laser melting?,” *Materials Research Letters,* vol. 5, no. 6, pp. 386-390, 2017.

[11] Y. Kaynak, and O. Kitay, “The effect of post-processing operations on surface characteristics of 316L stainless steel produced by selective laser melting,” *Additive Manufacturing,* vol. 26, pp. 84-93, 2019.

[12] D. Bourell, J. P. Kruth, M. Leu *et al.*, “Materials for additive manufacturing,” *CIRP annals,* vol. 66, no. 2, pp. 659-681, 2017.

[13] N. Sunay, K. Mert, And Y. Kaynak, “Chemical Post-Processing Methods For Enhancing Surface Properties Of Parts Fabricated By Additive Manufacturing: A Review,” *Sigma Journal of Engineering and Natural Sciences,* vol. 38, no. 4, pp. 2027-2042, 2020.

[14] N. Loh, and S. Tam, “Effects of ball burnishing parameters on surface finish—a literature survey and discussion,” *Precision Engineering,* vol. 10, no. 4, pp. 215-220, 1988.

[15] F. Klocke, and J. Liermann, “Roller burnishing of hard turned surfaces,” *International Journal of Machine Tools and Manufacture,* vol. 38, no. 5-6, pp. 419-423, 1998.

[16] L. Luca, S. Neagu-Ventzel, and I. Marinescu, “Effects of working parameters on surface finish in ball-burnishing of hardened steels,” *Precision engineering,* vol. 29, no. 2, pp. 253-256, 2005.

[17] A. Sequera, C. Fu, Y. Guo *et al.*, “Surface integrity of inconel 718 by ball burnishing,” *Journal of materials engineering and performance,* vol. 23, no. 9, pp. 3347-3353, 2014.

[18] N. El-Tayeb, K. Low, and P.V. Brevern, “The influence of roller burnishing process on hardness and roughness of cylindrical polymer surfaces,” *Part J: Journal Of Engineering Tribology*, Vol. 222, No. 7, Pp. 947-955, 2008.

[19] Y. Karabulut, E. Tascioglu, and Y. Kaynak, “Heat treatment temperature-induced microstructure, microhardness and wear resistance of Inconel 718 produced by selective laser melting additive manufacturing,” *Optik*, pp. 163907, 2019.

[20] S. Sharma, S. Sangal, and K. Mondal, “On the optical microscopic method for the determination of ball-on-flat surface linearly reciprocating sliding wear volume,” *Wear,* vol. 300, no. 1-2, pp. 82-89, 2013.

[21] J. F. Archard, and W. Hirst, “The wear of metals under unlubricated conditions,” *Proceedings of the Royal Society of London. Series A. Mathematical and Physical Sciences,* vol. 236, no. 1206, pp. 397-410, 1956.

This is a resupply of March 2023 as the template used in the publication of the original article contained errors. The content of the article has remained unaffected.