Chapter

Surface Integrity of Ball Burnished 316L Stainless Steel

Selma Attabi, Abdelaziz Himour, Lakhdar Laouar and Amir Motallebzadeh

Abstract

316L is a type of austenitic stainless steel that offers a good combination of mechanical properties, corrosion resistance, and biocompatibility. In some industrial applications, it is necessary to proceed to finish treatments to extend the lifetime of the mechanical parts. In the present chapter, ball burnishing treatment is applied to improve the surface integrity of 316L since the performance behavior of parts is directly dependant on the surface properties of the used material. Both surface topography and surface microhardness of 316L after subjection to ball burnishing are studied. The number of burnishing passes is varied by up to five to investigate its effect on the results. Optical profilometer and atomic force microscopy (AFM) were used to analyze the surface roughness and surface topography texture while measurements of microhardness Vickers were proceeded to investigate the changes in surface hardening.

Keywords: 316L, ball burnishing, surface topography, microhardness

1. Introduction

Austenitic stainless steels, particularly 316L grade, have received much attention because of their good mechanical properties and high corrosion resistance [1]. This material contains a maximum carbon content of 0.03 by weight, which provides an extra level of corrosion resistance as well as the high rate of weldability. Several domains, notably marine and petrochemical industry, architecture, chemical production, and also biomedical sector, use this stainless steel due to its superior tensile strength, fracture toughness, and good formability [2]. 316L is non-magnetic and has excellent biocompatibility, which makes him a good candidate in the production of biomedical parts such as knee joints of total hip replacements [3]. In addition, 316L became very attractive to the industry owing to its low-cost and easy fabrication.

In almost engineering applications, an important interest is directed to the aspect of surface as it strongly influences the functional properties of mechanical parts such as their corrosion resistance, tribological behavior, and fatigue durability. Most failures of manufactured parts initiate from the outer layers which are exposed to the environmental conditions of service [4]. Mechanical, metallurgical, or chemical changes are the most common causes of the initiation of alterations in the surface [5]. In the case of wear, repeated contact actions between surfaces lead to the abrasion and/or delamination of the superficial layer which causes a loss in material quantity as well as in wear resistance. This loss is also produced in the case of corrosion where chemical changes in the surface are provoked after the contact between the surface and the environment under which the material operates. As a result, of these phenomena, the properties of surfaces become poor and unacceptable to fulfill the intended requirements of service. Some examples of components because of surface damages are: (a) environmental stress cracking of plastics by some chemical environments [6], (b) turbine vane and blade material surface deterioration caused by erosion [7], (c) surface corrosion [8], etc. The surface quality of materials therefore greatly needs attention to guarantee a good longevity of manufactured products.

The surface integrity notion, as it is understood is manufacturing processes, was defined by Field and Kahles [9] as *the inherent or enhanced condition of a surface produced in machining or other surface generation operation*. This term concerns many parameters:

- Topological characteristics (surface roughness, geometric aspects…);
- Mechanical characteristics (microhardness, residual stresses…);
- Metallurgical characteristics (phase transformation, grains size, …);
- Chemical characteristics (changes in the chemical composition of the surface, …).

Among the aforementioned parameters, surface roughness and microhardness are the major ones influencing the functional properties of parts. By far, the two parameters are remaining extensively studied to achieve better surface integrity. Surface roughness is a measurement of surface texture. A lower surface roughness indicates a smaller contact area with other materials, which is advantageous to improve corrosion resistance, frictional resistance, and fatigue life. Generally, the high quality of surface roughness is highlighted by the low values of amplitude parameters of surface topography. These parameters clarify the aspect of the topography which is related to the distance of a point on the surface from the mean plane, i.e., it gives information about the height or depth of a surface [10]. Hardness is the ability of a material to resist deformation. It is commonly preferred to produce surfaces with high values of microhardness as it prevents failures by wear and fatigue.

One way of improving the surface roughness and microhardness of parts is by applying surface treatments during the finishing step. Ball burnishing is a common mechanical surface treatment that has been widely applied on engineering parts for the finishing of their functional surfaces. This post-machining process is based on causing plastic deformation of the superficial layers through compressing a hard ball on the surface of the workpiece (**Figure 1**). As the ball is continuously moving, it transfers a material flow from peaks to valleys of superficial asperities. As a result, surface irregularities are reduced and compressive residual stresses are induced in the deformed layer. These two simultaneous actions improve the physical and mechanical characteristics of the surface which becomes smoother and also harder. Ball burnishing is easy, simple, and fast process which enhance the long-term properties of materials with low energy and almost no environmental pollution.

At present, there are rich literature sources about the effect of ball burnishing on surface roughness and microhardness of materials and also on the service performance of manufactured parts. The positive effect of this treatment in reducing the surface roughness [12–16] and raising the microhardness [12, 15–18] was widely reported. As a result, of these changes caused in surface characteristics, wear delamination was restricted as the interlocking movements of micro-irregularities were limited during friction [4, 19]. Fatigue resistance, yield and tensile strength, and also corrosion resistance were improved [20, 21].

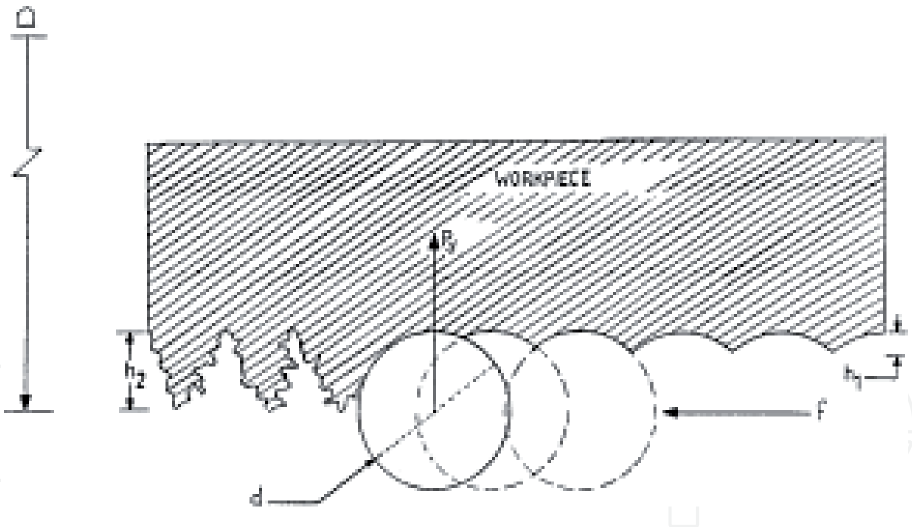

Figure 1.
Ball burnishing concept [11].

High surface finishing after ball burnishing is dependant on whether appropriate parameters of the process were well chosen or not. While the penetration depth and the initial state of the surface play a secondary role in obtaining good surface integrity, other parameters such as the burnishing force, the feed rate, and the number of passes contribute fundamentally to the final aspect of the treated surface [22]. Thus, it is very necessary to choose the right combination of process parameters and to master their effect on the surface integrity.

This research tackles the surface integrity of 316L after being subjected to the ball burnishing process. The effect of the number of burnishing passes, as an important process parameter, will be investigated. The results will be analyzed in terms of surface texture and microhardness after processing. At the sight of the results, an appropriate combination between burnishing force, feed rate, ball size, and a number of passes shall be proposed to execute the operation according to the right objective. This is important for 316L to confer its parts the special properties intended in the different industrial applications.

2. Experimental

2.1 Ball burnishing treatment

In this study, 316L stainless steel was used as workpiece material. The chemical composition of the alloy was determined as: the wt% is 0.02% C, the wt% is 16.64% Cr, the wt% is 10.35% Ni, the wt% is 2.03% Mo, and the rest is Fe. In the first step, a pre-machining operation was applied on a TOS TRENSIN machine to prepare the surface to be treated. Ball burnishing was then proceeded on the prepared surface with fixing the parameters regrouped in **Table 1**. The mentioned parameters were fixed after optimization of the process using the response surface "RSM" method based on BOX-Behnken design. The methodology of the optimization, as well as the

Parameter	Burnishing force (P_x)	Feed rate (f)	Ball diameter (D_b)
Value	87.1 N	0.18 mm/tr	13 mm

Table 1.
Burnishing parameters.

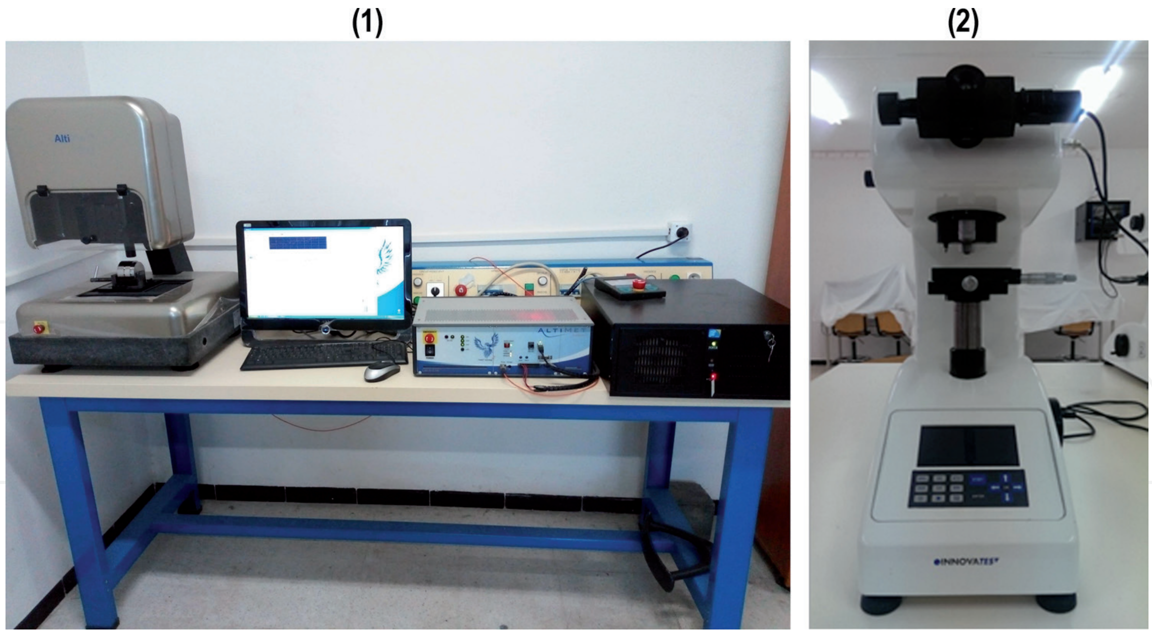

Figure 2.
Altisurf500 profilometer (1); Innovatest microdurometer (2).

analysis, were precisely described in our previous work [23]. After fixing the cited parameters, a number of passes (i) was varied by up to i = 5.

2.2 Characterization

The surface roughness of burnished surfaces was measured using Altisurf500 profilometer (**Figure 2**(1)). For each sample, an area of 3 × 2 mm^2 was scanned with a cutoff length of 0.8 mm. Altimap software was used to extract the following surface texture parameters. Atomic force microscopy (Bruker Dimension) was used to analyze the 3D topography of some selected surfaces.

Innovatest microdurometer, showed in **Figure 2**(2), was used to measure the surface microhardness of pre-machined and burnished samples. All tests were carried out using a load of 100 kgf applied for 10 s. The average diameters of five indentations were calculated to get reliable data.

3. Results and discussion

3.1 Effect of ball burnishing on the surface topography

The values surface topography parameters of the height of the five burnished samples, in comparison to the turned one, are regrouped in **Table 2**.

As a consequence of the ball burnishing process, the root means square height of the surface Sq was decreased in all samples as compared to the untreated one. During ball burnishing, the first two passes significantly reduced the Sq parameter from 2.212 μm to 0.715 and 0.729 μm respectively. After three passes (i = 3), the Sq still decreased achieving 0.583 μm. However, further augmentation in the number of passes provoked an increase in the Sq parameter which can attain a value higher than the initial one after five passes (i = 5). The turned surface is characterized by a more negative skewness Ssk and higher kurtosis Sku than all burnished samples. The highest skewness and the lowest kurtosis are registered in the surface burnished with three passes (i = 3/Ssk = −0.784 Sku = 2.77). The other amplitude parameters (Sp, Sv, Sz, and Sa) of all samples decreased after ball burnishing. These parameters follow

Surface topography parameters of height		Sample					
		Turned	Burnished (i = 1)	Burnished (i = 2)	Burnished (i = 3)	Burnished (i = 4)	Burnished (i = 5)
Root mean square height	Sq [μm]	2.212	0.715	0,729	0.583	0.978	2.62
Skewness	Ssk	−1.121	−0.758	−0,856	−0.784	−0.799	−1.09
Kurtosis	Sku	5.83	3.62	3.48	2.77	5.34	3.24
Maximum peak height	Sp [μm]	5.89	3.37	3.37	1.35	2.83	3.60
Maximum pit height	Sv [μm]	9.52	5.76	3.85	2.16	3.79	7.50
Maximum height	Sz [μm]	15.41	9.14	7.23	3.51	6.62	11.1
Arithmetic mean height	Sa [μm]	1.552	0.574	0.590	0.450	0.733	2.12

Table 2.
Comparison of height surface topography parameters of ground and ball-burnished samples.

the same tendency with respect to the number of passes as the Sq parameter. Hence, it can be noted that three passes (i = 3) are the most appropriate if surface topography is aimed to be improved. Further augmentation in this parameter can lead to the deterioration of surface quality, which is indicated by the increase in the amplitude parameters. The main objective of ball burnishing is the reduction of the heights of surface irregularities. Effectively, this objective was reached because the results show that the height parameters of the surface structure were reduced by more than three-fold, which is indicated in the results listed in **Table 2**.

The sample burnished with three passes (i = 3) shows the best height surface topography parameters. As a result, this surface is selected to be studied in terms of the other surface topography parameters. **Table 3** regroups the measured parameters of this surface as compared to the turned sample. Comparing these results, significant differences in the measurements can be highlighted between the turned and the burnished surface. After ball burnishing, the areal material ration Smr was significantly increased while the Smc and Sxp indicators were reduced. The Smr parameter of the turned sample was very low indicating a high peaky topography. After the application of ball burnishing, the value of Smr was sharply increased which impacts positively on the wear properties of the material. Indeed, a good bearing ratio indicates a good bearing capacity which improves the tribological behavior of the workpiece [10]. The Sxp parameter was reduced indicating reducing in surface roughness [24].

The spatial parameter Str of the burnished sample was almost similar to that of the turned sample indicating the micro-anisotropic texture of both surfaces. The micro-anisotropy is a natural result of the machining process [10]. In turning, and similarly burnishing, the single point cutting tool will generate a high degree of anisotropy to the machined surface. The std. parameter is used to indicate the marked direction of the surface texture for the y-axis, which means indicating the lay direction of the surface [25]. This parameter is applicable only for surfaces which does not have a uniform texture, i.e., when the Str > 0.5. It can be observed from **Table 3** that both turned and burnished surfaces have a lower value of Str < 0.5, which means that both surfaces have a pronounced lay pattern. The Std parameter gives the direction angle of the texture, which in the present results has increased from 72.01° for the turned sample to 106° after burnishing.

Surface topography parameters			Sample	
			Turned	Burnished (i = 3)
Functional	Areal material ratio	Smr [%]	0.826	28.8
	Inverse areal material ratio	Smc [μm]	2.263	0.660
	Extreme peak height	Sxp [μm]	6.045	1.47
Spatial	Texture-aspect ratio	Str	0.292	0.312
	Texture direction	Std [°]	72.015	106
Hybrid	Root mean square gradient	Sdq	0.070	0.159
	Developed interfacial area ratio	Sdr [%]	0.247	1.11
Functional (volume)	Material volume	Vm [mm^3/mm^2]	1.088×10^{-4}	1.95×10^{-5}
	Void volume	Vv [mm^3/mm^2]	0.00237	0.00068
	Peak material volume	Vmp [mm^3/mm^2]	1.088×10^{-4}	1.95×10^{-5}
	Core material volume	Vmc [mm^3/mm^2]	0.00168	0.0005
	Core void volume	Vvc [mm^3/mm^2]	0.00196	0.000588
	Pit void volume	Vvv [mm^3/mm^2]	4.096×10^{-4}	9.22×10^{-5}
Functional (stratified surfaces)	Core roughness depth	Sk [μm]	3.118	1.26
	Reduced summit height	Spk [μm]	1.849	0.302
	Reduced valley depth	Svk [μm]	3.613	0.722
	Upper bearing area	Smr1 [%]	14.34	6.81
	Lower bearing area	Smr2 [%]	77.61	86.5

Table 3.
Comparison of surface texture parameters of turned and ball-burnished surfaces.

All functional (volume) parameters were significantly reduced as a result of the ball burnishing process. The decrease in the material volume Vm indicates that an important part of surface irregularities was eliminated while the decrease in the void volume Vv refers to the elimination of valleys. This is also evident from the diminish of the other functional parameters Vmp and Vvc. The Vvv parameter characterizes the volume of fluid retention in the deepest valleys of the surface. Although this indicator was reduced for the burnished surface, this is not significant as this parameter is not affected by wear processes [26]. The wear resistance of components is directly related to the functional (volume) parameters and the enhancement resulting after BB impacts positively on reducing the quantity of material exposed to wear during the functioning of the workpiece.

For the functional parameters (stratified surfaces), all the parameters were reduced in the case of the burnished surface. The only exception is for the parameter Smr2. The lower value of Sk is desired for better sliding contact between contact surfaces while the decrease in the Spk parameter means that the volume of the material which is likely to be removed during the running in of the component was considerably restricted [26].

Based on the previously cited results, the effect of ball burnishing on surface topography can be remarked. As a consequence of the ball burnishing process, the functionality surface topography of 316L was efficiently improved which is characterized by the advantageous micro-geometric changes, namely: surface smoothness, elimination peaks and valleys and reduced peak heights and trough depths. The effect of a number of burnishing passes was also highlighted. It can be concluded that when the ball passes repeatedly over the surface of 316L, it deforms more asperities and produce smoother surface. However, this repetition should be limited 3 times to have the most improved surface, otherwise, surface flaking occurs due to excessive plastic deformation on the same surface layers [4].

Figure 2 represents isometric views of the selected burnished sample with three passes (i = 3) which showed the best-enhanced surface topography parameters. According to the 3D images of the untreated surface (**Figure 3**(1)), we can notice that it is characterized by higher peaks and deeper valleys compared to the burnished surface (**Figure 3**(2)). Hence it can be confirmed that the burnishing treatment by applying three passes produced a smoother surface. The visible scratches on the turned surface are due to the machining process which generates significant roughness (Ra = 134 nm μm and Rq = 172 nm). After burnishing with three passes over the surface of the 316L, the scratches as well as the peaks have almost disappeared, which reduces the roughness Ra to 14.1 nm and Rq to 18.3 nm, i.e., a decrease by 89.4% and 68.3% respectively.

3.2 Effect of ball burnishing on the surface microhardness

The effect of ball burnishing as well as the number of passes on surface microhardness Hv of the surfaces is presented in **Figure 4**. It can be remarked that all burnished surfaces show higher values of microhardness in comparison to the turned sample. This indicated the high efficiency of BB process in hardening the surface of

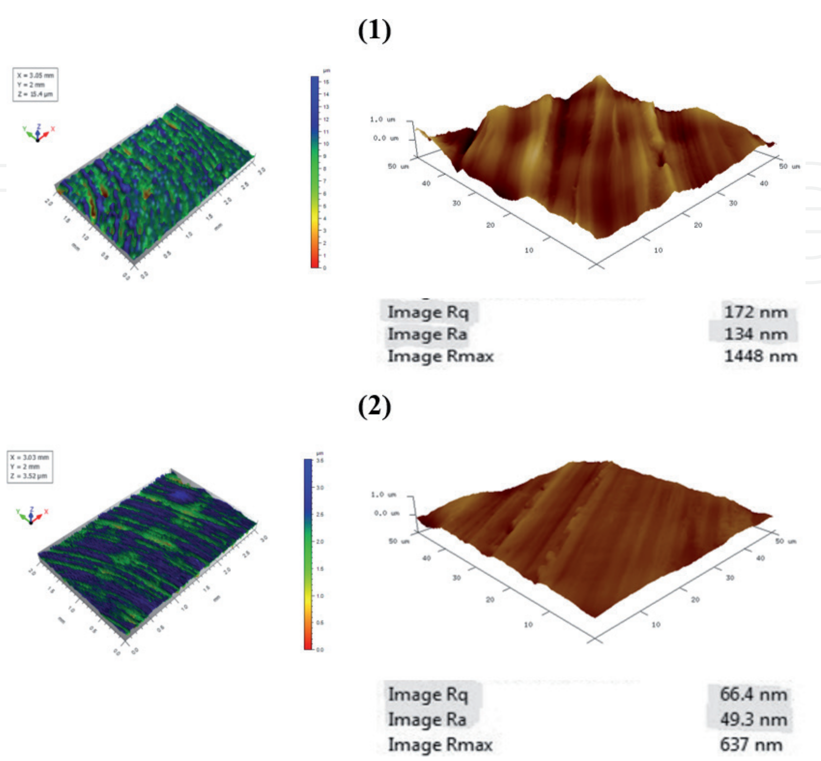

Figure 3.
3D images of (1) untreated surface and (2) burnished sample with i = 3.

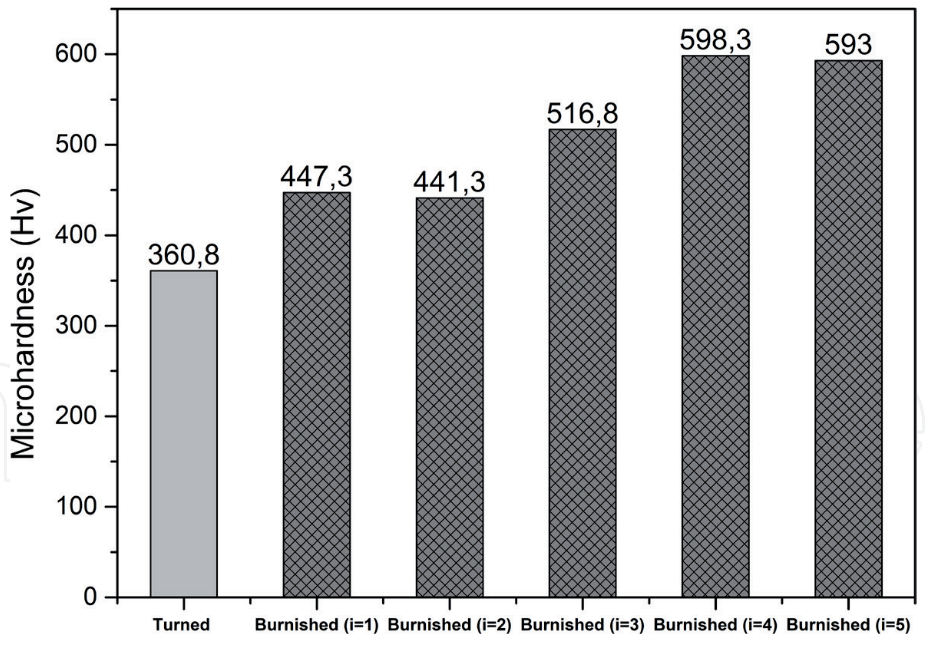

Figure 4.
Microhardness values of untreated and burnished surfaces.

316L. The impact of increasing the number of passes is manifested by a variation in the final microhardness. As a result, to one pass during ball burnishing (i = 1), an increment of approximately 90 Hv was obtained. While the increase in the number of passes to i = 2 did not really cause a remarkable change in the microhardness, the application of 3–5 passes generates a very significant hardening. The application of three passes has led to the increase in microhardness by 150 Hv while the most significant improvement in microhardness was recorded when four passes (i = 4) were applied. A similar hardening effect was caused after the application of five passes (i = 5) which is characterized by reaching a value of 593.0 Hv.

The impact of burnishing on the microhardness is interpreted by the plastic deformation which produces a structure with condensed grains and generates residual stresses loading the surface in compression. However, and contrary to the results of roughness, the increase in the number of passes does not cause any negative effect even if the ball passes 5 times successively over the same surface. Although, several works stipulate that repeating the burnishing operation several times, especially more than 3 times, destroy the surface because the surface is already saturated. We can explain our result by the high feed (0.18 mm/rev) and the low force (80 N) applied during the five passes. Indeed, since the ball is lowly loaded and moves quickly, it deforms more areas after each pass without affecting the already deformed areas. In other words, the repetitive passage of the ball over the same area will not have a detrimental effect since it does not have either the great force or the time sufficient to penetrate the surface and destroy the previously deformed layers.

4. Conclusions

In this study, the surface integrity of 316L stainless steel after ball burnishing was investigated. Based on the obtained results, the following conclusions can be drawn:

- The surface topography of 316L stainless steel was successfully improved after the ball burnishing process. The root means square Rq was reduced to less than 0.1 μm. Almost all the surface texture parameters were reduced after the application of ball burnishing treatment, which is an important advantage if the functional properties, such as the wear resistance, is aimed to be improved.

- The surface microhardness of the studied alloy was efficiently raised as a result of the ball burnishing process. An increment in microhardness by up to 150 Hv was recorded indicating the work hardening effect induced during the process.

- The number of passes is found to be an important parameter that influences on both surface topography and microhardness. The previously cited results are obtained in condition to the application of three number of passes. Further increase in the number of passes can lead to the deterioration of the surface.

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Conflict of interest

The authors declare no conflict of interest.

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References

[1] Fellah M, Labaïz M, Assala O, Iost A, Dekhil L. Tribological behavior of AISI 316L stainless steel for biomedical applications. Tribology—Materials, Surfaces and & Interfaces. 2013;7:135-149. DOI: 10.1179/1751584X13Y.0000000032

[2] Saboori A, Alberta A, Giulio M, Sara B, Mariangela L, Paolo F. Microstructure and mechanical properties of AISI 316L produced by directed energy deposition-based additive manufacturing: A review. Applied Sciences. 2020;**10**(9):3310. DOI: 10.3390/app10093310

[3] Chintan M. A review on parameters affecting properties of biomaterial SS 316L. Australian Journal of Mechanical Engineering. 2020:1-11. DOI: 10.1080/14484846.2020.1752975

[4] Attabi S, Himour A, Laouar L, Motallebzadeh A. Effect of Ball Burnishing on Surface Roughness and Wear of AISI 316L SS. Journal of Bio- and Tribo-Corrosion. 2021;7:7. DOI: 10.1007/s40735-020-00437-9

[5] Davim JP. Surface integrity in machining. In: Surface Integrity—Definition and Importance in Functional Performance. London: Springer; 2010. pp. 1-35. DOI: 10.1007/978-1-84882-874-2_1

[6] Characterization and Failure Analysis of Plastics. Materials Park, OH: ASM International; 2003. Available from: http://asmcommunity.asminternational.org/portal/site/www/AsmStore/ProductDetails/?vgnextoid=66b975dfae0f8110VgnVCM100000701e010aRCRD

[7] Sotnikov AA, Stepanov VN, Livshits AM, Bukchin SM. Improvement of turbine blade systems to reduce cavitation erosion. Power Technology and Engineering. 1994;**28**(12):746-750

[8] Masakazu O, Hiroshi M, Kazuyuki M, Tomoyoshi O, Masayuki U. Surface corrosion of various kinds of metals by atmospheric pollution. Bulletin of Hiroshima Kokusai Gakuin University. 2005;**38**:69-83

[9] Field M, Kahles JF. The surface integrity of machined and ground high strength steels. DMIC Report. 1964;**210**:54-77

[10] Waikar RA, Guo YB. A comprehensive characterization of 3D surface topography induced by hard turning versus grinding. Journal of Materials Processing Technology. 2008;**197**(1-3):189-199. DOI: 10.1016/j.jmatprotec.2007.05.054

[11] Hassan AM, Al-Bsharat AS. Influence of burnishing process on surface roughness, hardness and microstructure of some non-ferrous metals. Wear. 1996;**199**:1-8

[12] Revankar GD, Shetty R, Rao SS, Gaitonde VN. Analysis of surface roughness and hardness in ball burnishing of titanium alloy. Measurement. 2014;**58**:256-268

[13] Dzierwa A, Gałda L, Tupaj M, Dudek K. Investigation of wear resistance of selected materials after slide burnishing process. Eksploatacja i Niezawodnosc–Maintenance and Reliability. 2020;**22**(3):432-439

[14] Świrad S, Wydrzynski D, Nieslony P, Krolczyk GM. Influence of hydrostatic burnishing strategy on the surface topography of martensitic steel. Measurement. 2019;**138**:590-601

[15] Teimouri R, Amini S, Bami AB. Evaluation of optimized surface properties and residual stress in ultrasonic assisted ball burnishing of AA6061-T6. Measurement. 2018;**116**:129-139

[16] Jerez-Mesa R, Travieso-Rodríguez JA, Landon Y, Dessein G,

Lluma-Fuentes J, Wagner V. Comprehensive analysis of surface integrity modification of ball-end milled Ti-6Al-4V surfaces through vibration-assisted ball burnishing. Journal of Materials Processing Technology. 2019;**267**:230-240

[17] Dimitrov DM, Slavov SD, Dimitrov Z. Experimental research on the effect of the ball burnishing process, using new kinematical scheme on hardness and phase composition of surface layer of AISI 304L stainless steel. MATEC Web of Conferences. 2017;**112**:02001

[18] Basak HM, Ozkan T, Toktaset I. Experimental research and ANN modeling on the impact of the ball burnishing process on the mechanical properties of 5083 Al-Mg material sheets through vibration-assisted ball burnishing. Kovove Materialy. 2019; **57**(1):61-74

[19] Revankar GD, Shetty R, Rao SS, Gaitonde VN. Wear resistance enhancement of titanium alloy (Ti–6Al–4V) by ball burnishing process. Journal of Materials Research and Technology. 2017;**6**:1, 13-32

[20] Avilés R, Albizuri J, Rodríguez A, De Lacalle LL. Influence of low-plasticity ball burnishing on the high-cycle fatigue strength of medium carbon AISI 1045 steel. International Journal of Fatigue. 2013;**55**:230-244

[21] Sadeler R, Corak S, Atasoy S, Bulbul F. Evaluation of an electroless nickel-boron (Ni-B) coating on corrosion fatigue performance of ball burnished AISI 1045 steel. Kovove Materialy-Metallic Materials. 2013;**51**(6):351-356

[22] Laouar L, Hamadache H, Saad S, Bouchelaghem A, Mekhilef S. Mechanical surface treatment of steel-Optimization parameters of regime. Physics Procedia. 2009;**2**:1213-1221

[23] Attabi S, Himour A, Laouar L, Motallebzadeh A. Mechanical and wear behaviors of 316L stainless steel after ball burnishing treatment. Journal of Materials and Research Technology. 2021;**15**:3255-3267

[24] Marteau J, Bigerelle M, Mazeran P-E, Bouvier S. A Relation between roughness and processing conditions of AISI 316L stainless steel treated by ultrasonic shot peening. Tribology International. 2015;**82**:319-332

[25] Dong WP, Sullivan PJ, Stout KJ. Comprehensive study of parameters for characterizing three dimensional surface topography. IV. Parameters for characterizing spatial and hybrid properties. Wear. 1994;**178**:45-60

[26] Blateyron F. The areal field parameters. In: Leach R, editor. Characterization of Areal Surface Texture. London: Springer; 2013. DOI: 10.1007/978-3-642-36458-7_2