Determining the Significance of Surface Roughness and Hardness Outputs of Grinding Cylinders Specifically for Laser Processing Parameters

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Abstract: Surface roughness and hardness, critically important in industrial applications, are parameters that affect the performance and functionality of cast iron materials, particularly in various sectors. White cast iron is widely used in food milling due to its superior hardness and wear resistance. In parallel with all these advantages, grinding cylinders made of white cast iron wear to a certain extent due to the grinding of products such as wheat, barley, and coffee beans, necessitating periodic surface treatment. Laser processing has become widely used in recent years to modify the surface properties of metallic and composite materials. This experimentally significant study focused on investigating the effects of laser processing parameters on the surface roughness and hardness of grinding cylinders made of white cast iron. It was concluded that by using 10, 30 and 50 W, the desired hardness and roughness can be achieved by correctly selecting the process parameters. At the end of the experimental process, depending on the effect of power parameter variability, microscopic images showed a smooth surface texture, regional molten surface fluctuations and microcrater results in the presence of irregular solidification in the upper layer.

Keywords: Laser processing parameters, Surface roughness, Hardness, Grinding, Industrial applications.

INTRODUCTION

Cast iron, a basic material in engineering applications, is preferred due to its outstanding mechanical properties such as high hardness, wear resistance and thermal conductivity (Rocha *et al*. 2020, Zhang *et al*. 2020). Among various types of cast iron, white cast iron is known to stand out for its exceptional hardness and wear resistance, thanks to its microstructure consisting of hard, brittle carbides embedded in a pearlite or martensitic matrix (Liu *et al*. 2018, Liu *et al*. 2019). Besides, white cast iron, known for its excellent machinability and damping capacity, finds extensive use in automotive components, engine blocks, machine tools, mining equipment, crusher liners, and rolling mill rolls (Yadav *et al*. 2019, Jena *et al*. 2020, Rai *et al*. 2021).

Laser surface treatment has emerged as a promising technique to modify the surface properties of metallic materials, including cast iron (Fathi *et al*. 2017) in recent years. Laser surface treatment offers several advantages such as precise control over processing parameters, localized heating and minimal thermal distortion. Laser treatment can also enhance hardness, wear resistance and reduce surface roughness by altering the surface microstructure, (Gupta *et al*. 2020, Gupta *et al*. 2021). Despite the reported outstanding properties of white cast iron, its performance can significantly be affected in machines for grinding food products and similar applications where abrasive wear is common. High surface roughness can lead to increased friction, wear, and reduced dimensional accuracy, limiting the efficiency and life of components (Chen *et al*. 2019).

Laser applications are reported to offer a significant solution for improving the surface properties of metallic materials, including surface roughness and hardness, through controlled heating and rapid solidification (Ahmed *et al*. 2021). By adjusting processing parameters such as laser power, scanning speed, beam diameter, and pulse frequency, it is possible to tailor the microstructure and properties of the processed surface, thereby achieving desired surface characteristics. Some researchers (Khan *et al*. 2021, Ahmad *et al*. 2020, Deng *et al*. 2021) have investigated the effect of laser power upon surface coatings applied on cast iron materials. In the laser hardening process, the upper surface layer of cast irons is heated above the critical transformation (austenization or melting temperature) point to transform the original structure of the material into unstable austenite. Then, the austenitized layer is cooled at a high cooling rate together with the surrounding cold substrate and air. When the surface is irradiated by a powerful laser beam, it can heat the material to an austenitizing temperature and rapidly self-quenched. The

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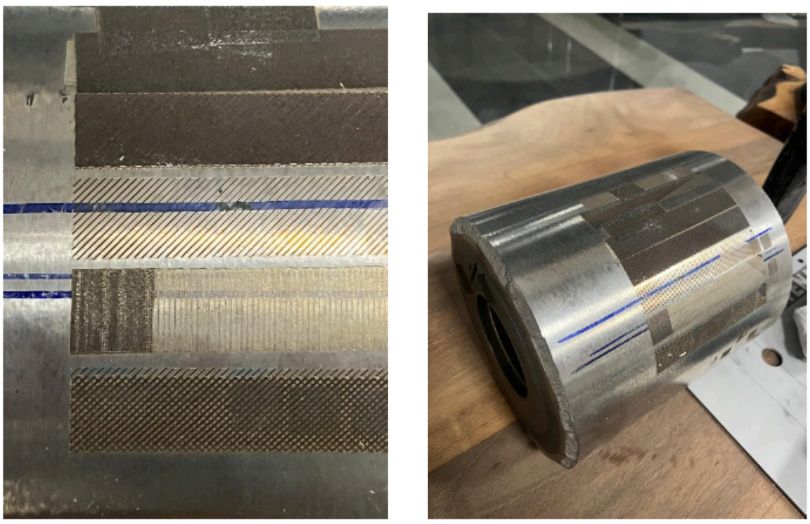
self-quenching process was reported to be a thermal cyclic loading because of high-speed heating and cooling (Abdulhadi *et al*. 2017). On the other hand, laser surface hardening improves wear resistance and other mechanical properties by creating compressive stresses in the hardened area. This is generally a result of volume expansion with the formation of martensite from the austenite phase (Roy 2001).

During the laser hardening process, a laser beam scans the surface of the material and heats very thin surface layer of material to reach the austenitization temperature (Kennedy *et al*. 2004, Ion 2006). Though the chemical composition of the melted layer does not change, the microstructure was refined and in small, localized areas of the base material is possibly metastable microstructure (Dezfoli *et al*.2017). With the effect of the high cooling rate, hard martensite phase formation occurs in the laser region, and thus surfaces with very high hardness and wear resistance can be obtained (Wang *et al*. 2020). Easy control of the hardening depth in laser surface treatment allows this technique to be used on small and geometrically complex parts (Tani *et al*. 2010, Tesker and Tesker 2014, Wang *et al*. 2020).

Hardness, hardening depth, heat-affected zone geometry, and metallurgical properties of the heat-treated zone are known as dependent variables. The properties of the steel surface and temperature depend on the power density and the traverse speed of the laser beam. Cabalin *et al*. (1999) and Li *et al*. (2001), have reported that pulse laser surface processing is controlled by several independent laser parameters namely, peak power, duty cycle, frequency and traverse speed. It is also reported that pulse energy level and interaction time determined the temperature profile and increased both width and depth of hardened surface (Kumar, 2006).

Pinkerton *et al*. (2003) reported that pulse laser exhibited lower surface roughness than sample processed using continuous wave mode. However, when high energy laser beam is used, controlling the surface roughness reported (Brabazon *et al*. 2008) to be a challenge despite obtaining perfect hardness. The effect of surface roughness has reported to be strongly dependent on the laser beam energy while low frequencies lead to producing highly localized pulse energy which result in roughened surface (Issa *et al*. 2008). However, high pulse energy can excessively abrade the surface of the material, especially when processed at a slow scan rate. The beam energy over the surface is controlled by varying laser irradiance, pulse repetition frequency and pulse duration. Some research (Qi *et al*. 2003, Kaldos *et al*. 2004, Kuar *et al*. 2006) has shown that pulse frequency has a significant effect on the laser machined surface roughness. Increased laser irradiances have been reported to result in increased surface roughness (Li *et al*. 2001). On the other hand, by increasing beam scanning speed and overlap, increased surface roughness reported to rake place in some situations (Jialang and Molian 2001, Batista *et al*. 2005). A lot of research has been performed in context of laser surface texturing for improving the tribological properties (lubrication, fretting coefficient, etc.) of surfaces (Du *et al*. 2005, Yi *et al*. 2008, Mirhosseini 2007, Voevodin *et al*. 2006, Klobcar 2008, Nothafzan *et al*. 2016), but none of them reported a clear correlation between performance indicators and influencing factors.



a) b)

Figure 1: Laser-treated surface zones on the test specimen roller used in the study (different texturing geometries); **a**) Planar surface, **b**) Cylindrical surface.

Despite the above-mentioned benefits of laser treatment, comprehensive studies which particularly focus on the effects of laser surface treatment parameters upon surface roughness and hardness of white cast iron are limited. The roller milling rolls generally subjected to abrasive wear and thermal cyclic loading. The function of the grinding rollers is to ensure that the product is taken between the rollers, thanks to their rough surfaces. However, highly abrasive grains and hard-seeded products such as coffee cause this roughness to disappear over time. For this reason, grinding rollers must be periodically dismantled and resurfaced. Understanding the effects of laser treatment on surface properties of industrial size roller mills is crucial to optimizing process parameters and exploiting the full potential of laser treatment. This study aims to investigate the effect of laser processing parameters (10, 30 and 50 W) on surface roughness and hardness of white cast iron roller mills used in grain milling industry. By means of design of experiments and response surface optimization it was sought to elucidate the underlying mechanisms governing surface modification and optimize laser processing parameters for enhanced surface properties (Figure **1.a** and **1.b**).

MATERIALS AND METHOD

The materials used in this study are white cast iron materials commonly used in roller mills produced in accordance with the ASTM-A532 standard. Schematic view of a grinding roller is shown in Figure **2**.

The laser head used in surface treatments is LMK-50-DT (LazerMik) (Figure **3.a**). Laser surface treatments were applied according to the experimental design parameters shown in Table **1**. The laser type is fiber-based, and the wavelength is 1064 nm. A beam diameter (spot size) of 40 μm (F160 mm F–Theta lens) is also used. The spacing parameter yields output in mm/s.

Surface roughness values (R_a, R_z) were measured (AFFRI 250 MRS) from different parts of the samples before and after the application of the laser process, and surface hardness was measured before and after the application (Figure **3.b**).

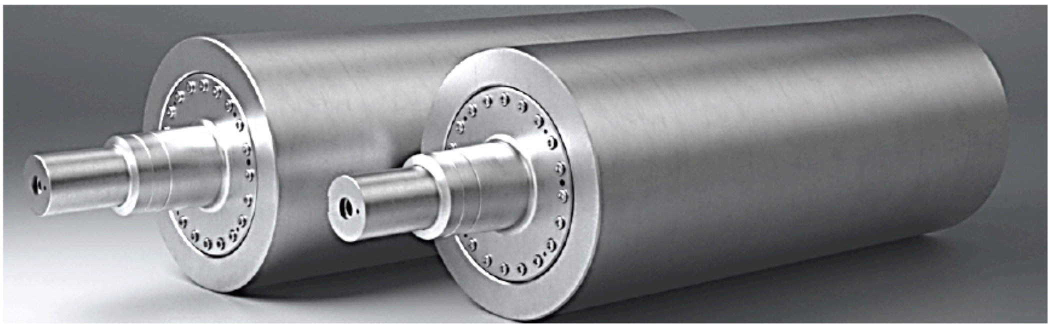
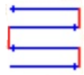


Figure 2: High performance rolls for mills.

a) b)

Figure 3*:* Test equipment detail view; **a**) Laser head and addition, **b**) Rockwell hardness tester.

Table 1: Experimental Parameters

Power (W)	Frequency (kHz)	Pattern Type	Spacing (mm/s)
10	20	Bidirectional 	100
30	20		150
50	20		200

Since the geometry and dimensions of the roller cylinders make testing difficult, the test samples are cylindrical samples with a diameter of 40x5 mm, which are formed by pouring the molten metal into a chill mold made of white material and cooling it (Figure **4**). Surface appearance of the specimens before and after laser treatment under different parameter sets.

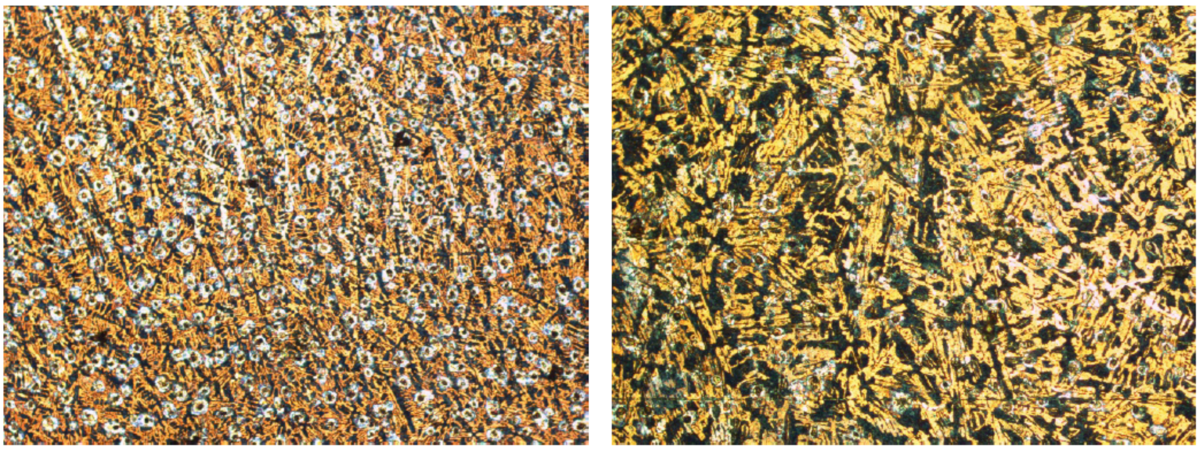
In addition, the samples before and after the process were etched for 30 seconds using an etchant at NITAL %2 concentration and the microstructures before and after the process were examined through an optical microscope. Figure **5** (**a** and **b**) shows the microstructure of white cast iron material. As seen in this figure, the microstructure of produced cast iron mainly consists of Fe_3C (cementite) and Pearlite. Some carbide particles are observed due to Chromium content.

To ensure the accuracy of the experimental results, each measurement was repeated at least 3 times. The statistical significance of the data was questioned by Chauvenet criterion and outlier results were removed from the analysis.

Whether there is a relationship between the laser process parameters and the output parameters, hardness and surface roughness, and the relative effects of the laser process parameters on the output parameters were examined using a regression study.

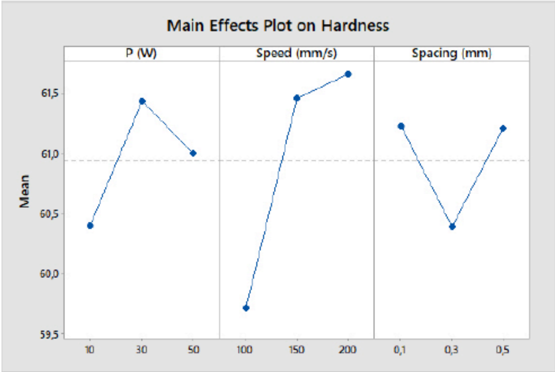
a) b)

Figure 4*:* Test specimens (Ø40×5 mm) produced from white cast iron and prepared for laser surface treatment process; **a**) Before, **b**) After.



a) b)

Figure 5: Microstructure of white cast iron; a) 100x, b) 200x.



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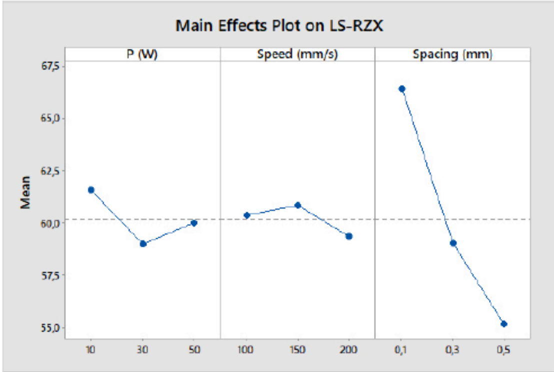

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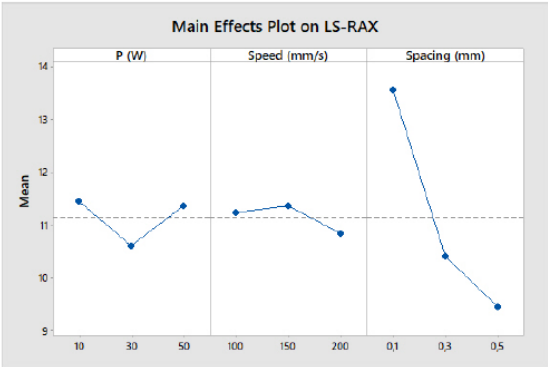


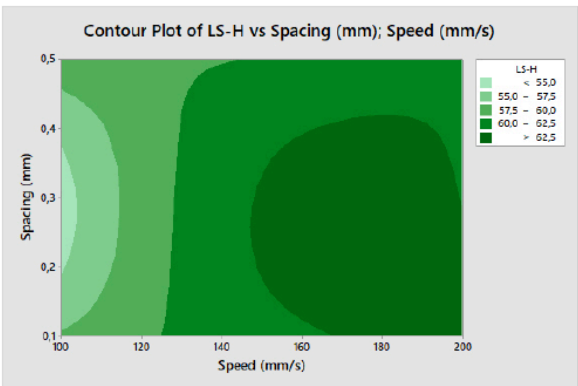
c)

Figure 6: Main effects plots after laser treatment; **a**) Hardness, **b**) Surface roughness (R_z) and **c**) Surface roughness (R_a).

RESULTS AND DISCUSSIONS

The data obtained was used using the Chauvenet criterion, and if there were any outliers in the data, these values were eliminated. Then, after the laser process, a variance analysis study was conducted between the efficiency and surface roughness R_a and R_z. However, statistical significance was not achieved based on the model used, focusing on a regression model rather than data analysis. Figure **6** shows the effect of laser processing parameters on hardness, R_a and R_x values. As seen in the figure, the highest hardness value is reached when the median value of power and the highest value of speed are selected for the power and range parameters. When looked at in terms of surface roughness, it is seen that the surface roughness values decrease as the spacing value increases.

As seen in Figure **7**–**9**, it was not possible to make a general evaluation of the effect of different test parameters on hardness and surface roughness. It has been reported in the studies in the literature that no general conclusion can be reached regarding the effect of laser process parameters on hardness and surface roughness (Du *et al*. 2005, Yi *et al*. 2008, Mirhosseini 2007, Voevodin *et al*. 2006).



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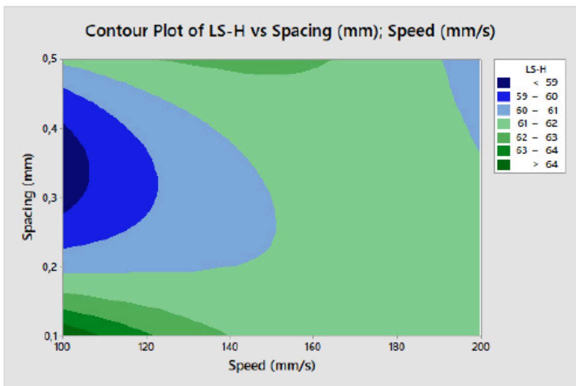

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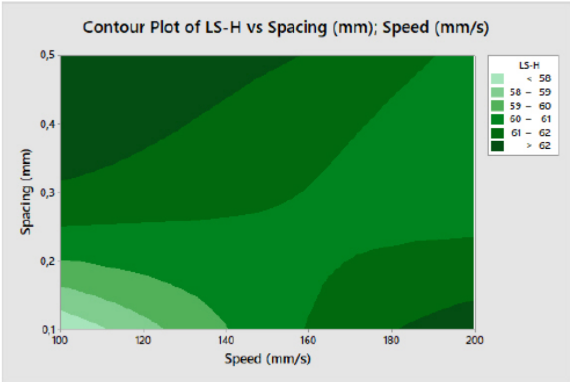

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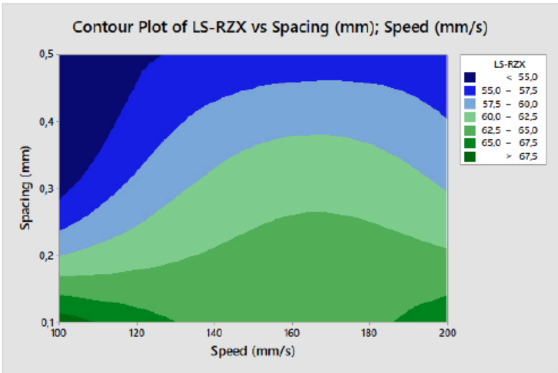
Figure 7: Contour plots for Hardness; **a**) 10W, **b**) 30W, **c**) 50W.



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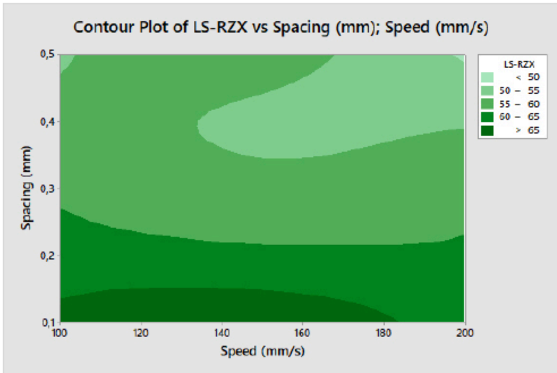

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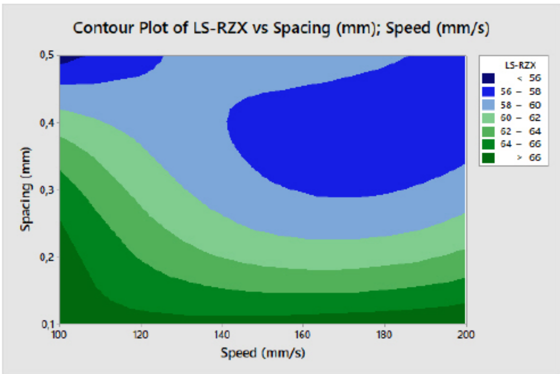
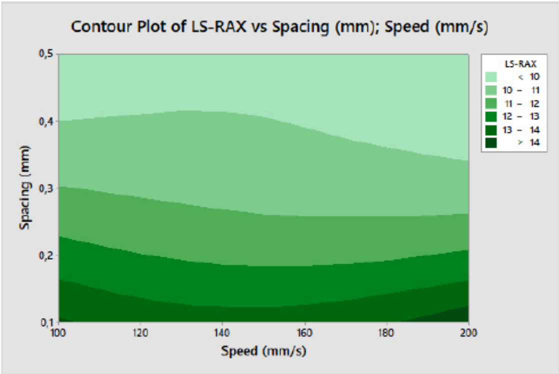


c)

Figure 8: Contour plots for Surface roughness (R_z) after laser treatment; **a**) 10W, **b**) 30W, **c**) 50W.

It was checked whether the hardness and surface roughness values statistically fit into a distribution type. To provide a clearer understanding of the influence of laser power on surface morphology, additional macrostructural examinations were performed on the samples treated at 10 W, 30 W and 50 W. Figure **10** shows the laser-marked regions produced on a single specimen, while Figures **11** (**a**–**c**) illustrate the corresponding macrostructural views at 50× magnification. At 10 W, the surface displays a relatively smooth topography with shallow melting traces and limited microstructural modification. The 30 W region exhibits a moderately rough texture with partial remelting and the formation of fine ripple-like patterns along the laser tracks. In contrast, the 50 W region reveals a clearly over-melted surface characterized by micro-craters and irregular resolidified zones. This transition from smooth to rough morphology confirms that the increase in laser energy input enhances localized melting and rapid solidification, leading to higher surface roughness values, as also reflected in the R_a and R_z data. These observations are consistent with the literature, indicating that excessive energy density may cause unstable melt flow and crater formation while simultaneously improving hardness through refined microstructures.



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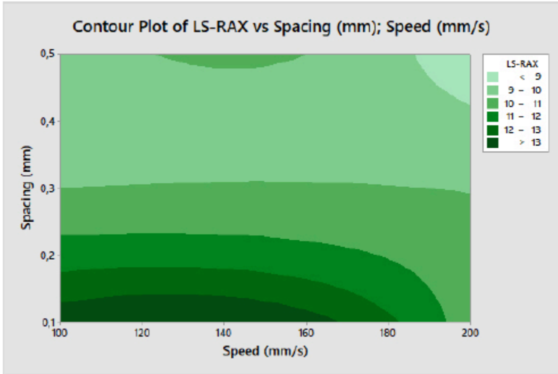

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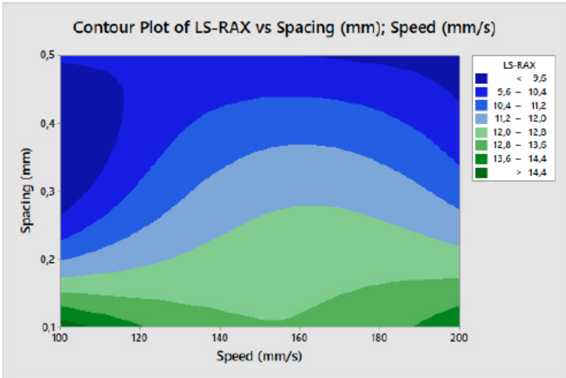

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Figure 9: Contour plots for Surface roughness (R_a) after laser treatment; a) 10W, b) 30W, c) 50W.

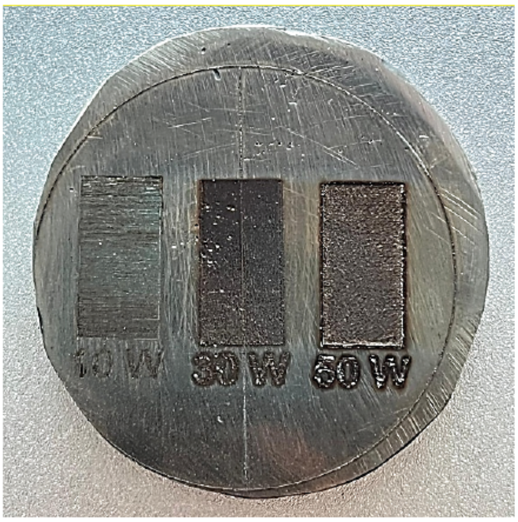

Figure 10*:* Laser-marked zones produced on the white cast-iron specimen at three different power levels (10 W, 30 W and 50 W).

In Figure **12**, the compliance of hardness and surface roughness values with Weibull and Normal distribution is examined. As seen in this figure, hardness values are compatible to normal distribution and surface roughness values in terms of R_z are compatible to Weibull distribution. It is also observed that surface roughness values in terms of R_a are compatible with both Weibull and Normal (Gaussian) distribution.

Regression is a statistical method used to model the relationship between a dependent variable and one or more independent variables, and the regression analysis used in the article was used to make predictions, determine cause-effect relationships, and understand how a system works. To examine whether there is a relationship between the experimental data obtained, a model was proposed, including quadratic and cross interactions, as shown below, and a regression study was conducted according to this model. The results obtained are presented in Table **2**. Here, letters A-K represent the coefficients and x, y, z represents laser power, speed and spacing respectively.

$$Response = A*x + B*y + C*z + D*x^2 + E*y^2 + F*z^2 + G*x*y + H*x*z + J*y*z + K$$

When Table **2** is examined, the correlation coefficients for both R_a and R_z, although not very satisfactory, were found to be 0.68 and 0.799, respectively. In terms of hardness, the correlation coefficient was obtained as 0.456. The R^2 value (0.456) obtained for the hardness value at the end of the experiments suggests that the independent variables in the regression model do not effectively explain the change in the dependent variable on a significant scale. This situation also highlights the need to focus in-depth

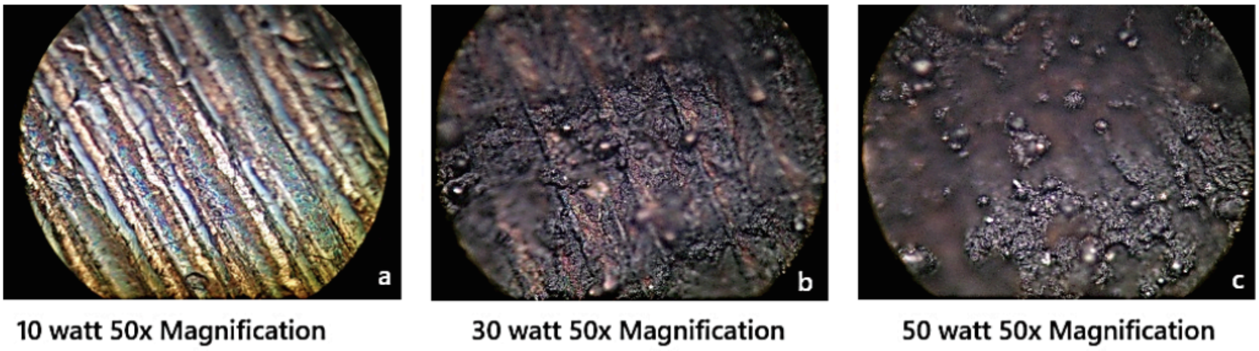

Figure 11: Macrostructural appearance of the laser-processed surfaces at 50× magnification; **a**) 10 W (smooth texture with shallow melting), **b**) 30 W (partially remelted region with ripple formations), **c**) 50 W (over-melted surface showing micro-craters and irregular solidification).

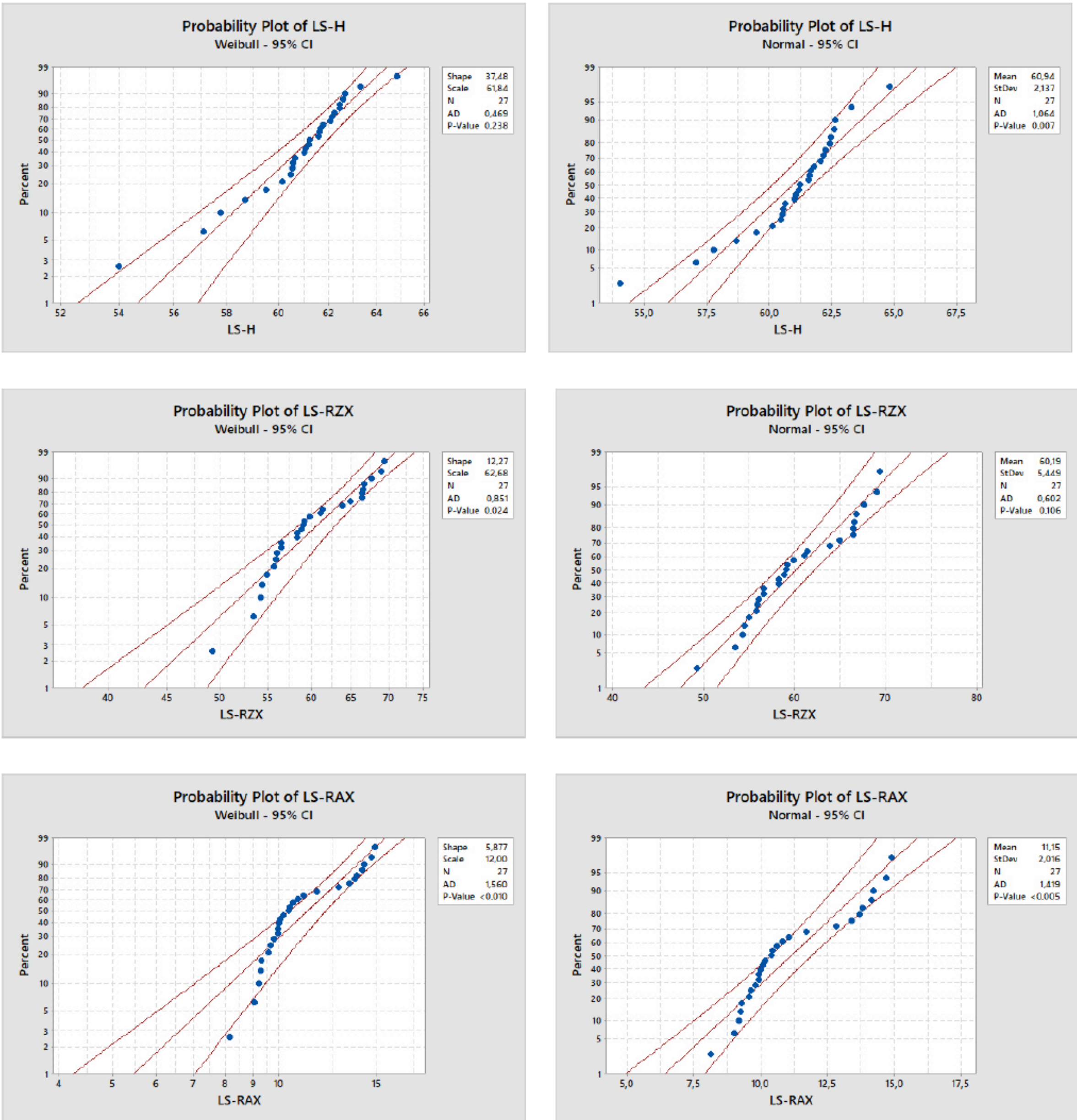

Figure 12: Weibull and Normal Probability plots for Hardness Surface roughness (R_z) and Surface roughness (R_a) after laser treatment.

on the parameters in the current study and may also be due to factors such as nonlinear relationships or inherent variability in the data that are not captured by the model.

Table 2: Regression Study

	Roughness (R_a)	Roughness (R_z)	Hardness (HRC)
A=	0,035166	-0,417460	0,263523
B=	0,196701	0,122319	0,166681
C=	-14,037290	-29,104255	-6,434560
D=	0,000927	0,004544	-0,001843
E=	-0,000580	-0,000551	-0,000308
F=	18,732179	-0,010608	20,737223
G=	-0,000505	0,000824	-0,001172
H=	-0,051116	-0,061374	0,126358
J=	-0,036129	0,021841	-0,065568
K=	0	66,983392	44,2299
R^2=	0,680	0,799	0,456

For the R_a model, one of the surface roughness models, it is seen that the C and F coefficients are higher than the other coefficients. For the R_a model, the most dominant coefficient is C. This indicates that the laser track spacing is quite effective for surface roughness. Similarly, in the model created for hardness values, it is seen that C and F coefficients are higher than other coefficients. Therefore, it was evaluated that the most effective parameter for hardness was track spacing.

When the effects of other parameters are evaluated among themselves, it is understood that the second most effective parameter for R_a and R_z is the speed of the laser head. For hardness, it was evaluated that laser power and head speed.

CONCLUSIONS

It this study, the effect of laser processing parameters upon surface roughness and hardness in grinding rollers made of white cast iron.

Because of general analysis study, it is concluded that no significant correlation is found between laser process parameters and output parameters as roughness and hardness. Since it has been reported in the literature that no general conclusion can be reached regarding the effect of laser process parameters on hardness and surface roughness, it is concluded that the obtained results are compatible with existing literature.

It is concluded that hardness and surface roughness values can be in accordance with Weibull and Normal (Gaussian) distribution.

According to regression study, it is concluded that spacing (in parallel with the comparisons made with the numerical values obtained in the formula) is the most effective parameter on both hardness and surface roughness. It is also concluded that the second most effective parameter for surface roughness is the speed of the laser head. As for hardness, it was evaluated that laser power and head speed have secondary importance.

At the values obtained with the difference in laser effect, a smooth surface texture with a shallow structure was achieved for 10 W, while at 30 W, ripples were observed in the remelted areas on a local scale. At 50 W, the presence of an over-melted surface showing irregular solidification on the surface was revealed by microcraters.

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CONFLICT OF INTEREST

Authors declare no conflicts of interest.

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