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ORIGINAL ARTICLE

Laser Surface Modification of Duplex Stainless Steel 2205 to Modify the Surface Roughness

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ABSTRACT – Laser surface modification is an emerging process that can produce texture on a work surface and effectively enhance surface topography while altering surface roughness. Laser surface modification is a sensitive process that depends on various laser processing parameters such as power, scanning speed, hatching distance. The significance of this work is to examine the influence of hatching distance on the surface characteristic of 2205 duplex stainless steel samples. The surface transformation and variation of the surface roughness properties of the materials were examined. The hatching distance was varied from 0.1 to 0.005 mm. Results indicate that, as the hatch spacing decreases, the overlap of laser track increases, thereby resulting in a decrease of surface roughness. Meanwhile, with the increase of hatch distance, the clear overlay tracks were transformed to irregular wavy surface. The best hatch distance parameter obtained was 100 µm that resulted in the highest roughness of 8.45 µm. Experimental results illustrate that, when the optimum hatch distance of 100 µm was adopted, the polished smooth surface of 2205 duplex stainless steel with initial average roughness value of 0.19 µm increased by 42 times of the polished surface roughness. A strong correlation between hatching distance and roughness was established in 2205 duplex stainless steel. High depth of the altered surface topography and increased roughness were linked to higher levels of hatching distance.

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INTRODUCTION

Duplex stainless steel (DSS) is commonly used for structural components for industries such as chemical, and oil and gas, owing to its excellent resistance to corrosion in environments containing chloride [1]. Besides, duplex stainless steel 2205 and other biphasic grades are commonly favoured products for piping systems, separators, scrubbers, pumps, filters, flow lines, and piping for corrosive oils and transportation. However, there are limitations of their usage in tribological or tribo corrosion environments that significantly are affected by the surface quality.

To date, advanced research was undertaken to improve the surface properties of the materials to better withstand high temperatures, wear, and friction by applying surface engineering. For instance, surface modification has gained greater interest to overcome these problems. Various studies have demonstrated that surface modification is the most efficient method for protecting the material surface from thermal fatigue by reducing the friction at the contact surface during processing [2]. According to Carvalho et al. [3] paper, the research mentioned that the surface modification changes in the corrosion properties induced by the treatment of outer-surface of stainless steel without modification of the bulk material. Thus, optimisation of this surface properties may improve the material behaviour. Meanwhile, another author [1] stated that laser surface modification is a new technique recently developed by many researchers to increase the surface roughness of the metal substrate without using a conventional technique. Finally, Zhang et al. [4] showed that surface modification also could be achieved to improve the super-hydrophobicity and corrosion resistance.

Recently, conventional surface treatment techniques such as flame hardening and carburising were replaced by modern methods using advanced thermal energy such as plasma, laser, ion, and electron. High-power lasers are rapidly recognised as tools for many uses, from cutting to welding and including techniques for surface modifications. A high-power laser is an effective surface treatment device since it can modify the surface composition and characteristics of the material with precise control, making them efficient and economical surface treatment tools [5]. The optimisation of surface properties can contribute to enhancing the material's behaviour. In this domain, the interest in laser processes is increasing rapidly with the current developments in surface treatment technology. Laser surface modification (LSM) has been commonly used to enhance resistance to wear and corrosion of mechanical components. LSM mainly derives its appeal in engineering applications from:

i. Leaving the bulk properties unaffected due to the creation of a small heat-affected zone and creating minor distortion.

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ii. Microstructure refining and homogenisation, leading to better mechanical properties, and higher corrosion resistance.
iii. The probability of introducing novel surface alloys which are unachievable by other methods due to the unbalanced nature of the process [6].

Through the surface engineering process, surface characteristic of metals, such as resistance to wear and hardness, can be achieved using LSM. Basically, LSM changes the characteristics of the materials' surface by introducing high thermal energy through the high energy of laser beam, while the conventional treatment process usually involves physical contact with the material surface. Thus, the LSM process is used as an alternative approach for the conventional heat treatment process to alter the surface of DSS to achieve the desire properties without impairing the other properties of the material. DSS 2205 is a steel-based alloy with a chemical composition of almost equal proportions of phases which are ferrite and austenite. Duplex stainless steels (DSS), in their thickest sections, can also achieve good weldability, and compared to austenitic steels, they are more resistant to stress corrosion cracking [7]. However, a very well-known problem for DSS is poor surface characteristics in tribo mechanical environments limiting its usage in tool and tribological applications. Thus, by applying LSM processing using a laser beam with high power energy, DSS can be surface-textured to make it suitable for various rough applications requiring surface modifications. This research is focused on the enhancement of surface properties and the role of various parameters in the LSM process by using fibre laser on DSS 2205.

METHODOLOGY

Material Preparation

In this research, 2205-Duplex stainless steel with the composition shown in Table 1, with a thickness of 2 mm, was used as the specimen in this work. The surface treatment was realised by pulsed wave (PW) fibre laser with maximum power and focal length of 30W and 50cm, respectively.

Table 1. Chemical composition of 2205 duplex stainless steel investigated for laser surface modification.

Element	Cr	Ni	Mo	Mn	Si	Cu	N	Nb	P	C	S	Fe
wt.%	22.37	5.74	3.20	1.52	0.40	0.17	0.17	0.05	0.02	0.02	0.001	66.58

The as-received sheet of metal of 2205-DSS was cut into a rectangular shape with the dimension 16×3×0.2 cm, as shown in Figure 1. The surface of the rectangular plate was then ground with silicon carbide (SiC) papers with a grit size of 300, 800, and 1500, and then cleaned with acetone until the mirror surface appearance achieved. LSM is conducted on the rectangular plate with five different hatching distances as shown in the black circles in Figure 1 to study the hatching distance parameter effect on the surface.

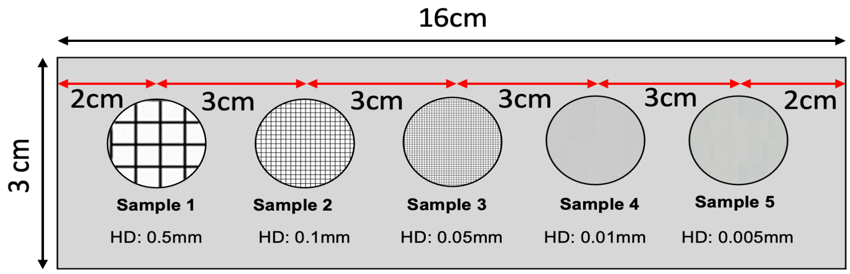


Figure 1. Schematic overview of 2205-DSS cut into the rectangular shape.

Laser Surface Modification Experimental Setup

Fibre laser marking apparatus was used to conduct the LSM process in this research, and the setup of the machine shown in Figure 2. The fibre laser has a 1064 nm wavelength, 300 kHz frequency with a precision of 0.001 mm. Both continuous and pulse waves can be performed using this apparatus. The maximum peak power for this apparatus is 20 W and 30 W for continuous wave and pulse wave, respectively. Using fibre optic and a collimator end, the source of the laser is moved to the laser head, and additional details are provided in Ref [8]. At the laser head, the focus lens is fixed with a protective mirror as a cover. The length from the laser focus spot to the focus lens is 50 cm. Arduino microcontroller is used on a custom machine with an attached laser head to control its movement. The movement is capable of covering three axes; x, y, and z-axis. The parameter for the shrouding gas, such as angle distance and flow rate, can be adjusted along with the requirements of the experiments. Based on recent research conducted by Papula et al. [9], which related to laser surface modification technique on the same material, DSS 2205. The suggested parameters are 850 mm/s scanning speed, 50 % of power and 0.1 mm of hatching distance [9], where these parameter has been chosen as a reference for present work. The parameters used are depicted in Table 3, where all of the parameters are kept constant for all five samples except for the hatch distance (HD), which varies between 0.5 mm and 0.005 mm. By choosing the hatch distance as the variable parameter, it has been possible to study the effect of the LSM on the surface characterisation of the polished surface of 2205-DSS.

Three different zones are formed on the surface of DSS due to the melting process, which are the unaffected base material, heat affected zone (HAZ), and melted zone (MZ). In LSM processing, a small region of the surface melted by the laser beam. The chemical composition within the melted layer does not change by the processing, but the microstructure was refined and in small localised areas of the base material is possibly metastable microstructure [10]. Through this procedure, a fine homogenous structure is obtained due to the rapid cooling rates where the base material or unaffected zone act as a heat sink.

Table 2. Parameter used in this study to enhance the surface of 2205- duplex stainless steel.

Sample	Hatch distance (mm)	Laser power (%)	Scan speed (mm/s)	Pulse width (Ns)	Laser frequency (kHz)	Loop count
1	0.5	80	450	20	10	2
2	0.1	80	450	20	10	2
3	0.05	80	450	20	10	2
4	0.01	80	450	20	10	2
5	0.005	80	450	20	10	2

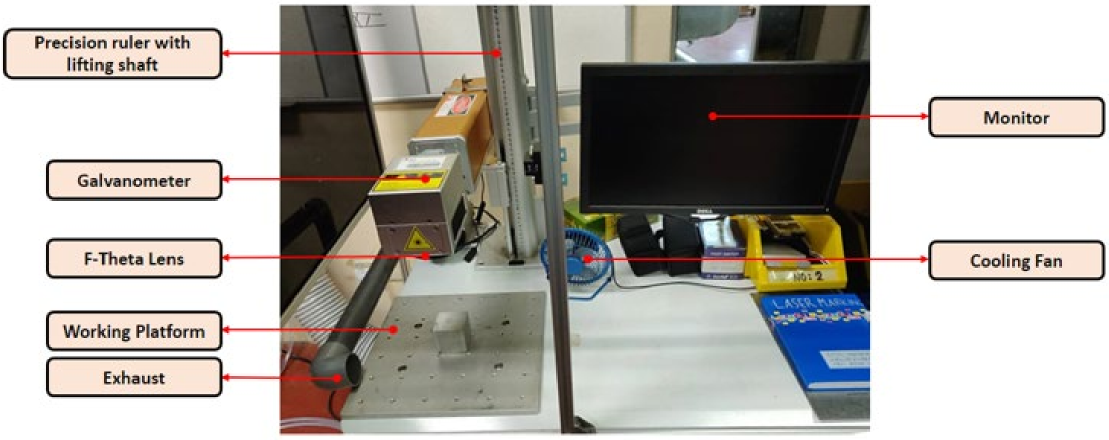


Figure 1. Laser marking machine apparatus for laser surface modification.

Surface Characterisation

The LEXT OLS5000 laser confocal scanning microscope was used for 3D measuring and analyses through non-contact and non-destructive imagery. It can simultaneously allow for both 3D measurements and deep focus field observation. It has no sample size or content limitations, and it makes observations under normal environmental conditions possible. The apparent reproduction of an object or optical image is achieved by a mirror or a lens system through reflected, refracted or diffracted light waves. In determining the surface properties as the objective, the optical and height image from a 3D laser microscope were recorded on the LSM sample to further study the effect of hatching distance towards the DSS-2205 substrate. After carrying out the LSM processing, the mechanical properties of the specimen were studied by measuring surface roughness on the LSM sample of DSS. Line roughness and surface roughness were measured on the sample to study the effect of LSM processing.

Surface Roughness

Surface roughness or normally known as roughness, is one of the measurable properties of surface textured surfaces. It is measured from its ideal form by the deviations in the direction of the normal vector of a real surface. If those deviations show a large value, the surface was considered rough; if small, the surface was smooth. The units used to measure roughness is in micron or micrometre (µm). Surface roughness assessment is essential to most structural applications that experience friction, contact deformation, heat and electrical current conduction, contact tightness, and positional precision. For many decades, theoretical investigations and experimental experiments on surface roughness were conducted due to its importance. The roughness can be evaluated either in two-dimensional (2D) or three-dimensional (3D) forms.

To study DSS sample 2205 LSM surface, roughness value was measured using the OLS5000 laser confocal microscope conforming to ISO/TC213 and ISO25178-compliant surface roughness measurement standard, which precisely measures surface profile, depth information and surface roughness at the submicron level. The quantitative roughness value is observed based on 2D line roughness and 3D surface profile. The machine can record the following four parameters average line roughness (Ra), the mean depth of line roughness (Rz), arithmetical mean height (Sa), and maximum height (Sz).

RESULTS AND DISCUSSION

Surface Morphology Characterisation

Optical images of the LSM surface are shown in Figure 3. On the 2205-DSS plate, five samples of LSM with different hatching distances are conducted on the same size of the circle's shape with a diameter of 2 cm, starting from the highest hatching distance of 0.5 mm down to 0.005 mm. The pattern produces by the hatching can be observed from the ablation of the laser with both horizontal and vertical hatches. From Figure 3, the result of the modified surface can be observed by looking at the 2D and 3D images of those samples. It can be observed that the change of the hatch distance itself has a considerable impact on the surface topography. The effects of laser hatching also can be observed on the surface profile illustrated in Figure 5. According to Foster et al. [11], more valley and hill types were created on the surface by increasing the hatch distance, which affected the surface roughness. For a surface with a hatch distance between 0.5 and 0.05 mm, the sinusoidal pattern can still be observed on the surface, while the surface with a hatch distance of 0.01 and 0.005 mm is completely diminished with inconsistent shapes of peaks and valleys.

Based on the sample overview, it is observed that as the hatching distance decreases, the colour of the hatched surface darkens. This observation was also documented by Ma et al. [12] on stainless steel, who demonstrated that applying small hatch distances resulted in an unreflective dark colour while increasing the hatch distance resulted in a more shiny surface [12]. One of the factors for this contrast is that when the distance of hatching becomes smaller, the heat given on the surface becomes higher because smaller hatch distances increase the number of hatching lines. Thus, a longer time is taken to complete the hatching in the circle, which results in high temperature absorption. The change in colour also occurs because the surface is almost incinerated due to the overlapping of the hatching lines that leads to a higher amount of heat overlaid on the approximately the same line that occurs as a consequence of the small hatch distance, as can be observed in Figure 3 (d) and Figure 3 (e). This finding can be corroborated with a similar report recorded by Dong et al. [13], wherein the rate of overlap increased by decreasing the hatch distance.

Figure 2. Overview of 3D, 2D of sample optical image from laser scanning on each LSM sample with different hatching distance from 0.5 to 0.005.

At relatively low hatch distances, Qiu et al. [14] reported that a relatively high manufacturing temperature was achieved, resulting in excessive fusion on the surface. The 2D image of the sample with hatch distances of 0.01 and 0.005 mm; the two lowest distances of all five samples. The image shows that the pattern of the hatching on the surface results in an irregular and insignificant pattern of the surface due to the overlapping process. This is supported by Brown et al. [15], who illustrated that decreasing the hatch distance could overburn the laser track due to an increase in overlap where multiple passes of laser ablation occurred. Figure 3 compares the two lowest hatch distances where the sample with HD of 0.005 mm shows deeper valleys than 0.01 mm. The overlaying process occurred on the melt zone, where 0.005 mm is higher since the first and second hatching distance is smaller in 0.005 mm than the sample with HD of 0.01 mm. The heat and mass transfer in the molten pool has a major impact on the surface roughness and geometry profiles [16]. Table 2 shows the optimal parameters of LSM based on a previous study. The optimum hatch spacing stated by Papula et al. [9] to be 0.1 mm, thus the inconsistent topography of the surfaces with the hatch distance of 0.01 and 0.005 mm, can be related since those two distances are far from the optimum value where it is much smaller than the optimum value of 0.1 mm. The effect of LSM with different hatching distances on the surface roughness of the LSM sample has been studied in detail. A 3D laser scanning is carried out across the treated surface as shown in Figure 4 and Figure 5, where 2D, 3D image and the profile measurement of the depth of the valley of the hatched samples are displayed for each HD.

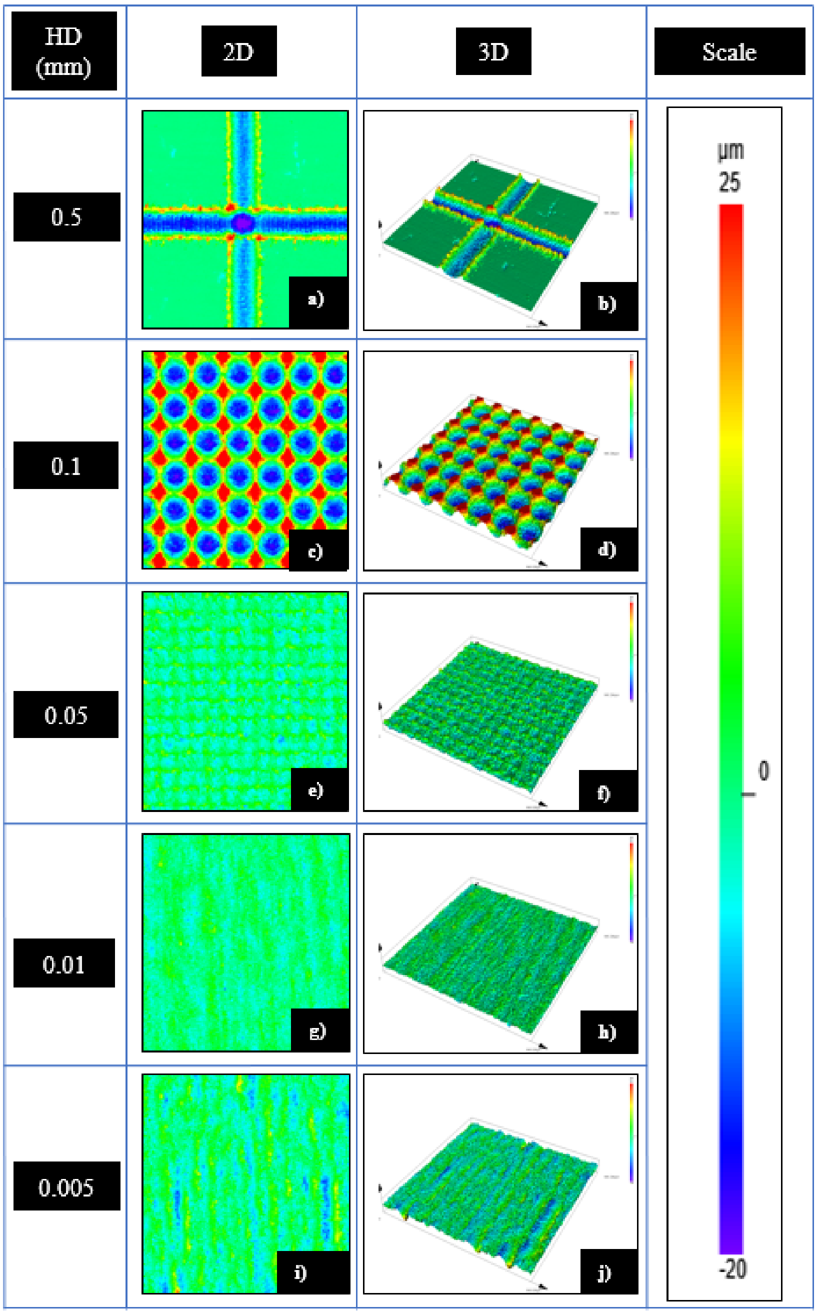


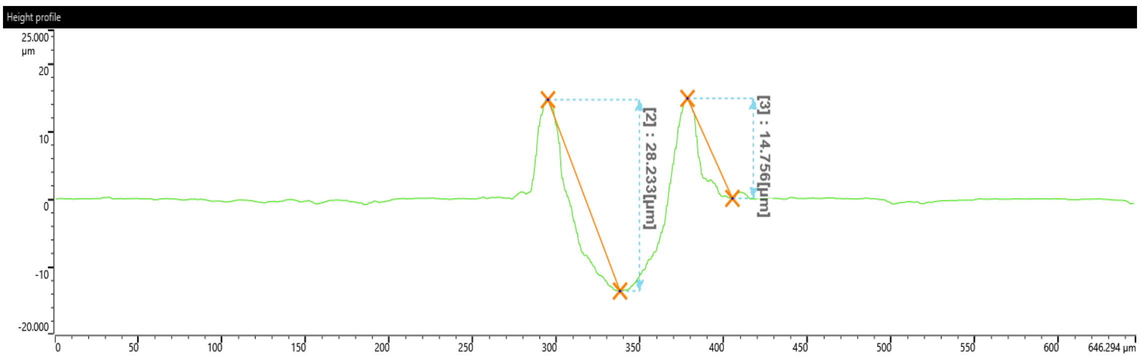
Figure 3. 2D overview of sample height image from laser scanning on each LSM sample with different hatching distance from 0.5 to 0.005 mm.

It is shown in Figure 4 that varying the HD gives a significant effect on the surface topography. The 3D scan shows a consistent surface for HDs between 0.5 and 0.05 mm but varying the HD from 0.01 to 0.005 mm gave irregular surface topography with light and dark blue shaded areas which are randomly distributed. For samples with HD of 0.1 mm in Figure 5(b), the surface shows the most constant distribution of peaks and valleys; the highest depth value from peak to the valley is 28.053 µm. At the high HD range of 0.5-0.05 mm, both vertical and horizontal hatching lines can be observed based on the 2D and 3D images in Figure 4(a), 4(c) and 4(e). Reducing the HD to the range of 0.01-0.005 mm, affected the topography of the surface which is more likely only to show the trend of vertical hatching lines, Figure 4(g) and 4(i). The initial design of the texture should result in a square pattern on the surface due to the horizontal and vertical hatchings, as can be observed in Figure 4(a), 4(c), and 4(e). The topography of the LSM surface is influenced by decreasing the hatching distance due to the overlap rate and temperature distribution on the LSM surface of the sample. The effect of the hatch distance on the topography can be related to a previous study by Qiu et al. [14], which showed that the melt flow became increasingly unstable, misaligned and creating irregular-shaped due to the overlapped on the scan track. Dong et al. [13] mentioned that decreasing the range of the hatch distance results in higher absorption of thermal energy on the material surface, thus reducing surface roughness since it is correlated with overlap intensity and heat accumulation of the sample.

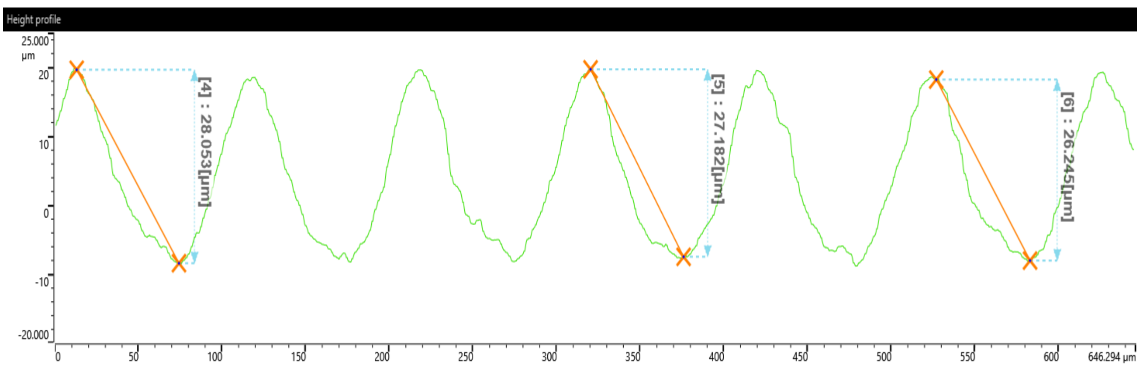
For the highest HD among the examined samples, 0.5 mm, only one hatching line (vertical and horizontal) is observed. Figure 4 (a and b) and Figure 5(a), because the distance of one hatch to another is too far, 0.5 mm. Since the evaluation length for the profile measurement and roughness measurement is only 0.65 mm, a sample with an HD of 0.5 mm is neglected when comparing the roughness of the treated surface. This is to avoid invalid data since the roughness value is calculated based on areal roughness, where the whole area of a surface is calculated to achieve the area roughness value.

Profile Depth Analysis

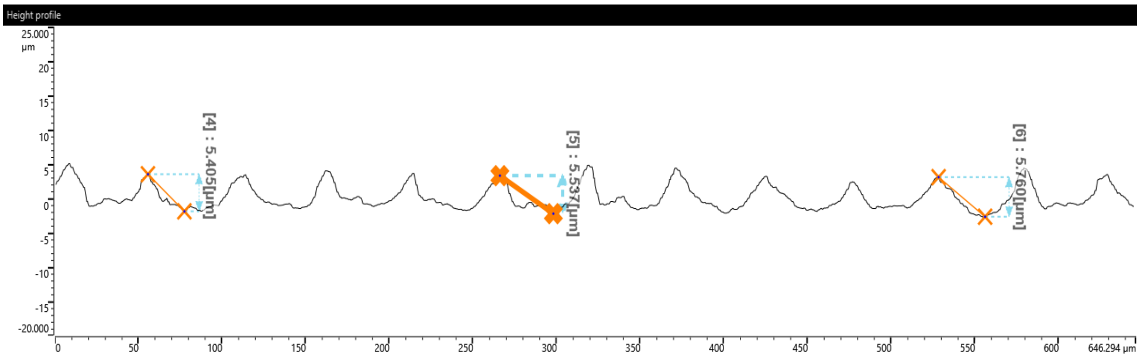
By neglecting the 0.5 mm HD, it can be understood that the depth of the valley from the peak decreases as the HD decreases until the HD reaches 0.01 mm before a sudden increase is attained when the HD decreases from 0.01 to 0.005 mm. The surface roughness is directly proportional to the depth of the surface profile, as can be observed in Figure 5(a) to 5(d). The height of the peak from the valley illustrated for samples 1-4 shows a continuous decrease as the hatch distance decreases, while sample 5 in Figure 5(e) shows an increment. A recent study by Sadali et al. [17] performed sintering laser melting (SLM) with varying the hatching distance and showed that the topography and surface roughness were affected by changing the distance of the hatching line. A maximum depth of 28 mm was observed for HD 0.5 and 0.1 mm, signifying that a smaller hatching distance caused a greater penetration in laser material removal. However, a further increase in HD led to a significant reduction, reaching a minimum of 5 times and a maximum of 18 times laser depth. This signifies that the height of the surface peak and valley could be controlled in micrometers scale with hatching distance.



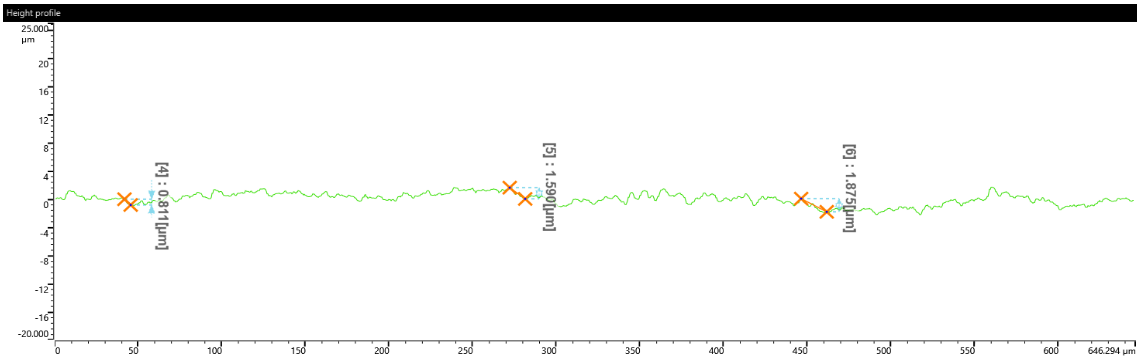
(a) HD = 0.5 mm



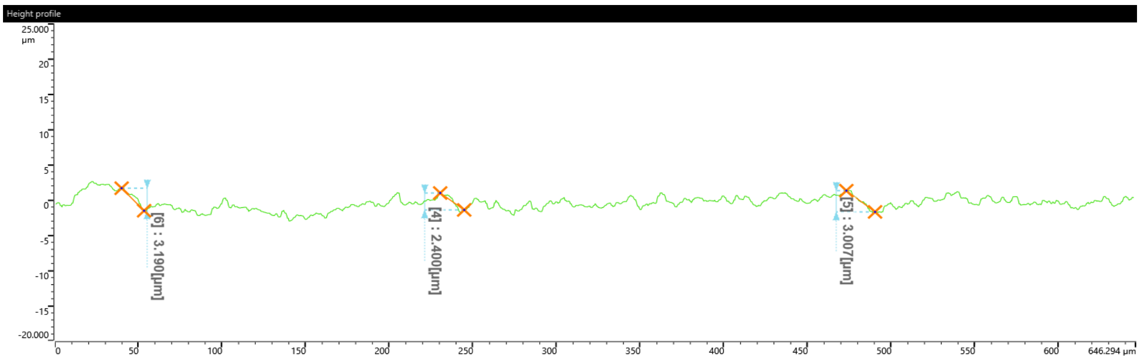
(b) HD = 0.1 mm



(c) HD = 0.05 mm



(d) HD = 0.01 mm



(e) HD = 0.005 mm

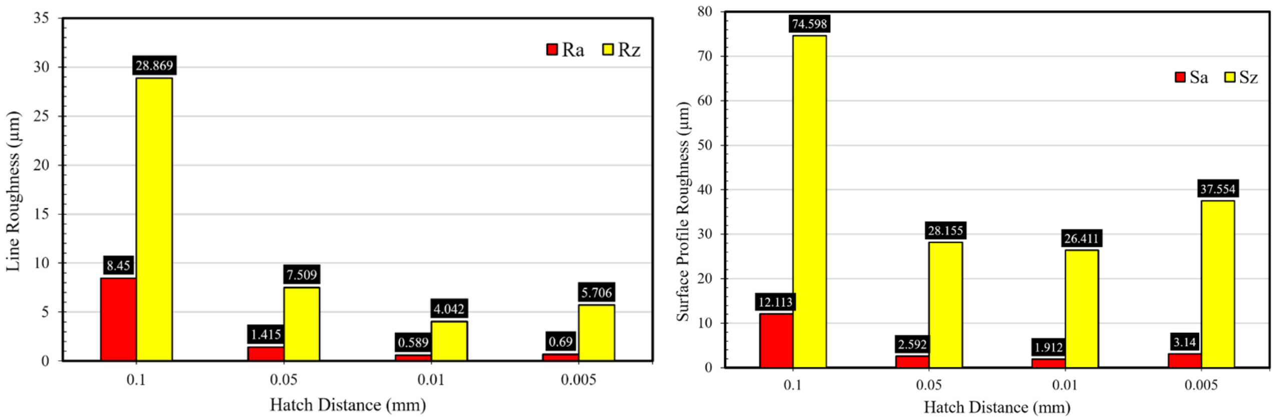
Figure 4. Profile measurement for the textured surface of different hatch distances.

Surface Roughness

Four surface roughness parameters (Ra, Rz, Sa, and Sz) were measured by 3D Laser Measuring Microscope for surfaces under different hatching distances, and the surface roughness for each hatch distance is recorded as shown in Figure 6(a) and 6(b). By referring to Rz and Sz values on line and surface profiles, Figure 6(a) and 6(b) minimum roughness can be achieved with a hatch distance of 0.01 mm, while to obtain the highest roughness, a hatch distance of 0.1 mm is preferred. Applying the hatching using laser surface modification shows that all the parameters used in this experiment give a significant increase of the surface roughness compared to the as-polished Ra value of the material surface, which is 0.195 µm.

Based on the Ra value depicted in Figure 6(a), applying a hatching distance of 0.1 mm can approximately increase the initial roughness by 42 times its initial value before LSM, to 8.45 µm. By decreasing the hatch distance from 0.1 to 0.005 mm, the profile roughness decreases by 80.23% and the area roughness by 49.66%. Thus, by decreasing the hatch distance, the surface roughness decreases. This is in agreement with Maamoun et al. [18], who reported that the decrease in surface roughness is due to the increasing overlap occurring when the hatch distance is smaller.

This trend also agrees with Foster et al. [11] where they stated that it is expected to achieve a smoother surface finish when more melt pool passes per layer occurred because a closer hatch distance is applied [11]. Here, it can be proposed that the optimal distance for the polished surface of duplex stainless steel is 0.1 mm and with laser parameter 80% of 2 kW laser power, 450 mm/s of scanning speed, laser frequency of 10 Hz and pulse width of 20 µm, which gives Ra value of 8.45 µm.



(a) (b)

Figure 5. (a) Line roughness and (b) surface profile roughness for the sample with hatch distance of 0.1, 0.05, 0.01, and 0.005 mm.

CONCLUSION

Laser surface modification of duplex stainless steel (DSS-2205) substrates was carried out. Altering the surface of the as-received material of DSS-2205 using the laser surface modification approach with fibre laser marking apparatus, the surface properties of the material surface were enhanced. Based on the results of the modification process, it can be concluded that:

i. The roughness of the substrate material could be altered by the laser surface modification technique.
ii. The effect of the hatching distance as a processing parameter is significant on surface roughness parameters such as Ra, Rz, Sa and Sz.
iii. The topography of the modified surface shows an inconsistent pattern when the hatch distance used is below 0.05 mm as the distance between lines is too large to produce a significant effect.
iv. The hatching distance significantly affects the profile depth signifying a maximum height between peak and valley to about 28 µm and a minimum to about 0.81 µm.
v. By applying the hatching distance of 0.1 mm, the roughness (Ra) of the polished surface can be increased from 0.197 to 8.45 µm for the laser textured sample.

More comprehensive advanced surface characterisation may be performed to study the transformation mechanism of the microstructure during laser surface modification. These methods of characterisation may be conducted using nano-indentation, electron microscopy transmission, and electrochemical impedance spectroscopy testing. For future works, the level of the hatching distance could be optimised, and additional parameters can be analysed. Laser surface modification of engineering alloys are now finding great applications in hardening [19] and brazing technology [20], and it would be wise to see their effect on other applications as well.

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