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Laser Micromachining of 304 Stainless Steel

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Abstract

Laser micromachining recently used for surface modification of engineering components aiming to enhance their properties to prolong their lifetime in various industrial applications. This study reports the laser micromachining experimental results of 304 stainless steel surface using a nanosecond laser to fabricate micro dimple pattern with various inner shapes. The inner shape of micro dimples modified from V–letter to a partially rectangular shape with the increase both width and depth were successfully applied based on the laser beam defocusing distance and pulse to pulse overlap concept. The results showed the laser processing parameters have the capability to precisely control the shape and dimensions of the micro dimples. The obtained results in this study might help to understand the effects of processing parameters on the morphology of the inner shape of fabricated micro texturing patterns aiming to extend the using of 304 stainless steel in new engineering applications.

Keywords: Laser Micromachining, Laser Texturing, Laser Fluence, 304 Stainless Steel, Tribological

Introduction

Fabrication of functional micro structuring pattern on engineering materials surfaces such as stainless steel, tool steel and titanium received great interest in last two decades aiming to improve the material properties such as tribological, wettability and increasing the lifetime of the engineering components under severe working condition [1-6]. Conventional machining such as micro electrical discharge and micro-milling were used to fabricate micro-texturing surfaces. However, they have certain limitations such as difficulty in controlling dimensional accuracy beside the machining tools shape [4]. Alternatively, laser beam as a non-conventional machining tool has been used in various industrial applications such as cutting, welding and surface treatment [7-17] and recently for micromachining where the need for precise control of surface topography and texturing has been a great demand [1-6]. In this regards, laser micromachining has been a subject of interest especially for the fabrication of functionally surfaces due to its sophisticated characteristics such as flexibility, ease of use and precise control of the fabricated pattern [4, 5, 18]. In this technique, a focused pulsed laser beam operated at high frequency irradiated the specimens surface and forming a series of uniform and regulated pattern with controlled dimensions. The use of a laser beam for surface texturing is known for enhancing the joint bond strength and increase both roughness and surface area of specimen for the tribological applications [1-6, 18]. The shape and size of the created structures such as micro dimple, hemispherical, elliptical, triangular, rectangular and square play an important role in governing the tribological, wetting and other desired surface properties of the substrates [2-5]. Ahmed et. al. [2], investigated the effect of different micro textures shapes such as parallel, perpendicular, and square patterns on machining performance and process efficiency of cutting tools. Ahmed et. al., showed that the square textured pattern provides higher efficiency compared to other shapes. Wang et. al. [3], fabricated ordered hierarchical structures using picosecond laser on the 304 stainless steel. Wang showed that the shape of the fabricated hierarchical structures has great influence on the wetting properties of stainless steel. Singh et. al. [5], showed the fabrication of micro texture (micro pillars and micro dimples) geometry has noticeable influence on the wettability and the tribological properties of various materials. Demir et. al.[18], generated different surface structures by varying the processing parameters such as laser fluence, spot size and number of pulse using nanosecond pulse fiber laser for adhesion, tribological and biomedical applications. Simões et. al. [19], investigated the influence of laser fluence, pulse overlapping, number of scans and the surface finishing on the efficacy of laser induced periodic surface structures generation in 304 stainless steel surfaces using a nanosecond laser. Simões showed fine surface roughness is needed to increase the efficacy of the texturing process. In addition, the desired texturing quality can be obtained by appropriate control of other processing parameters. Li et. al. [20], investigated the influence of laser fluence and a pulse number of 400 in air on the surface topography of 304 L stainless steel surfaces using micro second laser texturing. Li showed the topographies of the fabricated surfaces changed from bump to crater through five phases corresponding to changes in laser fluence. Reviewing the published results showed the importance of micro texturing shape but the morphology of the inner shape of the created micro texturing pattern have not been highlighted. Accordingly, the objective of this work is to characterize the morphology of the inner shape of the fabricated micro texturing pattern on 304 stainless steel surfaces where V-letter micro dimples were fabricated through adapting the laser fluence and pulse number to precisely control the dimension of the fabricated micro dimples. In addition, the micro dimples inner shape was modified from V-letter to partially rectangle shape using the laser beam defocusing distance and pulse to pulse overlap concept. The micro dimples dimension, shape and morphology are to be characterized as a function of the focus position, laser fluence and pulse numbers. The aim of the study is to investigate of the focus positions and defocused of laser fluence, and the pulse number overlap on the micro dimples depth.

Experimental Procedures

The laser micromachining process were performed using a nanosecond pulsed laser A Doubled Nd: YAG Laser system (Ultra CFR Big Sky Laser) with a Q-switch is used. The FWHM of generate pulses with 8ns pulse duration and 10Hz pulse repetition. The maximum pulse energy 230mJ with a wavelength at 532 nm is applied. To protect the specimens from oxidation, argon gas was used as shielding gas during micromachining process. For scanning the laser beam, a galvanometric scanner with an F- theta focusing lens controlled by a PC was used. Polished 304 stainless steel with chemical composition given in Table 1, was used as specimens. Prior to micromachining process, the specimens were conventionally cleaned using ethanol. The diameter and depth of the micro dimples were measured with an optical microscope. The morphological features of treated specimens were investigated using field emission scanning electron microscope (FESEM).

Table 1. Chemical Composition of 304 Stainless Steel

C	Si	Mn	P	S	Cr	Ni	Mo	Al	Fe
0.042	0.415	1.170	0.027	0.000	18.710	8.180	0.086	0.004	Bal.

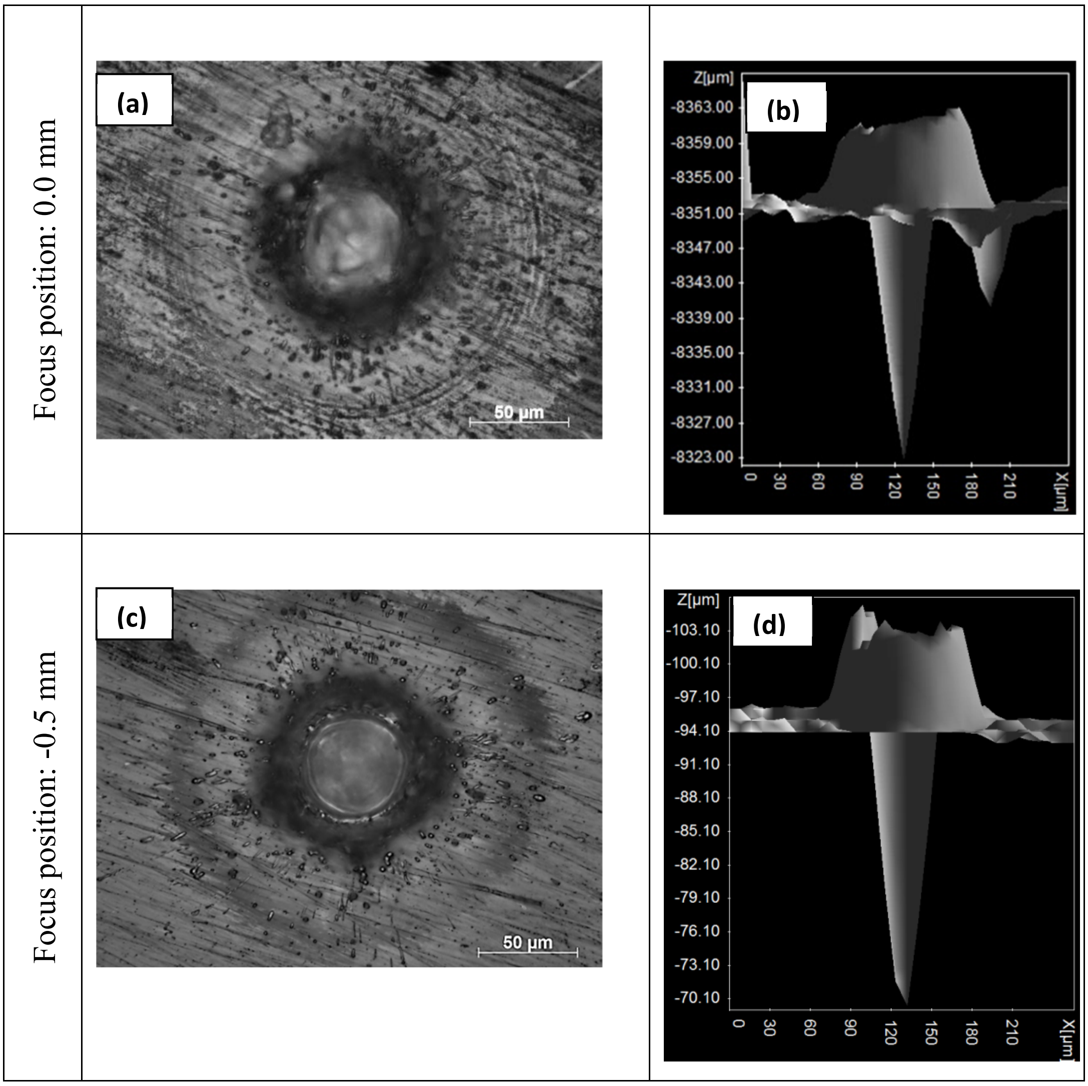

Figure 1. OM images of micro dimples inner diameter and corresponding 3D depth profile at different focus position

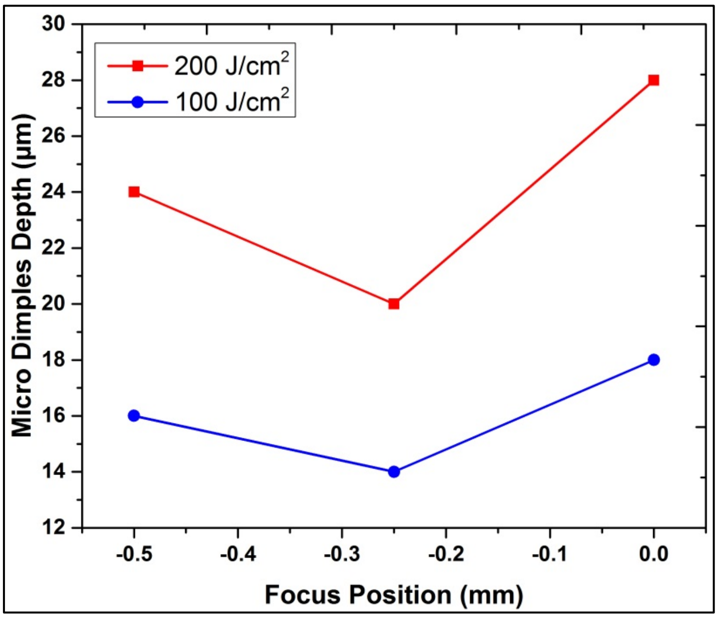

Figure 2. Effect of focus position on the micro dimples depth

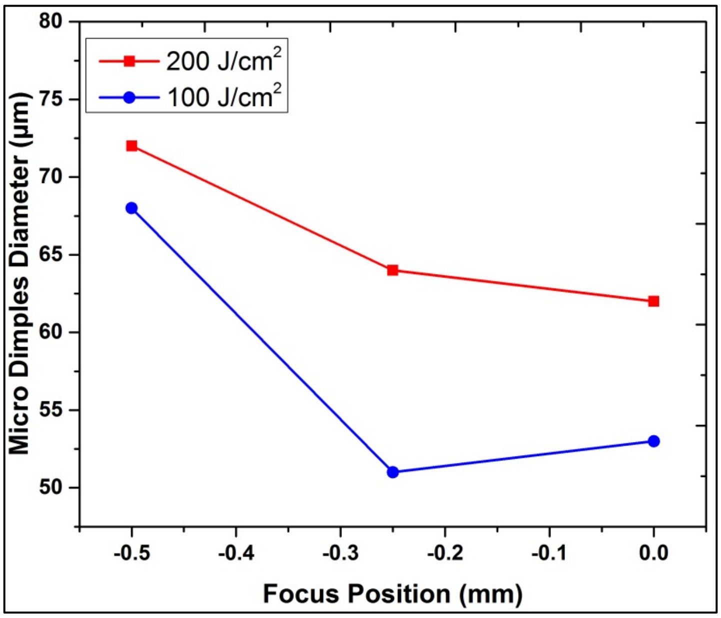

Figure 3. Effect of focus position on the micro dimples inner diameter

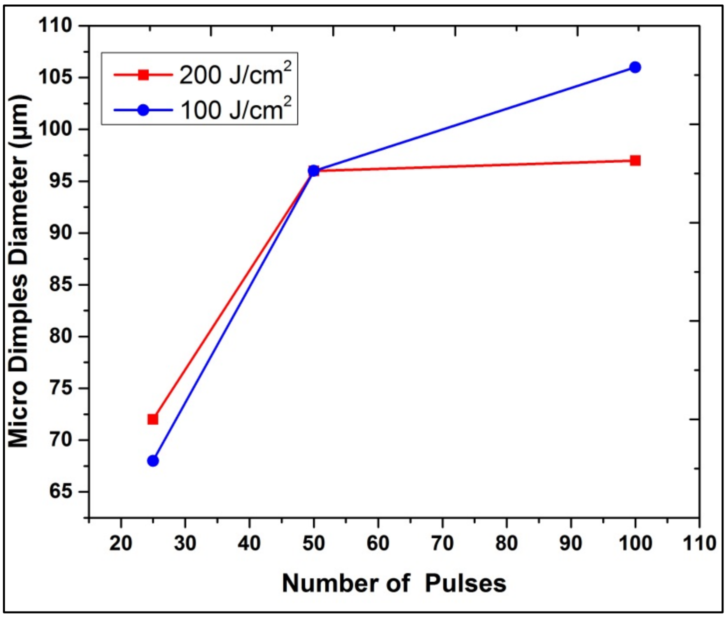

Figure 4. Effect of number of pulses on the micro dimples diameter

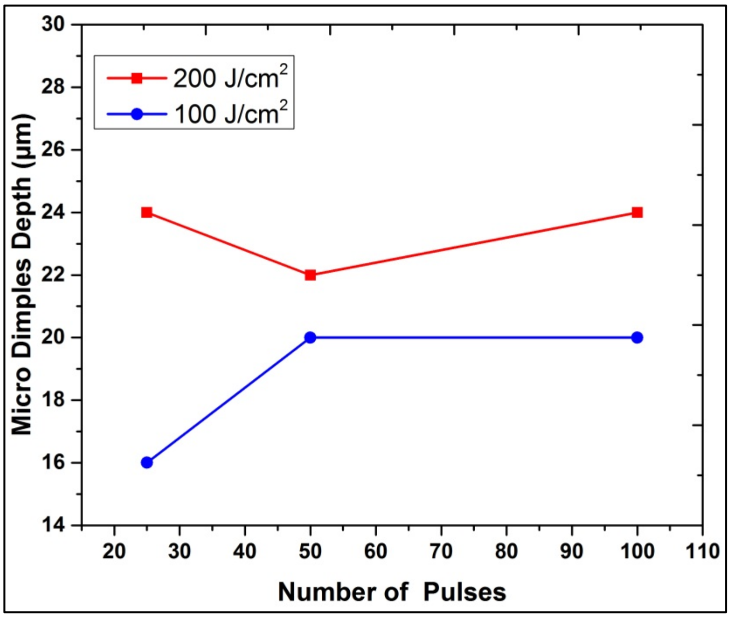

Figure 5. Effect of number of pulses on the micro dimples depth

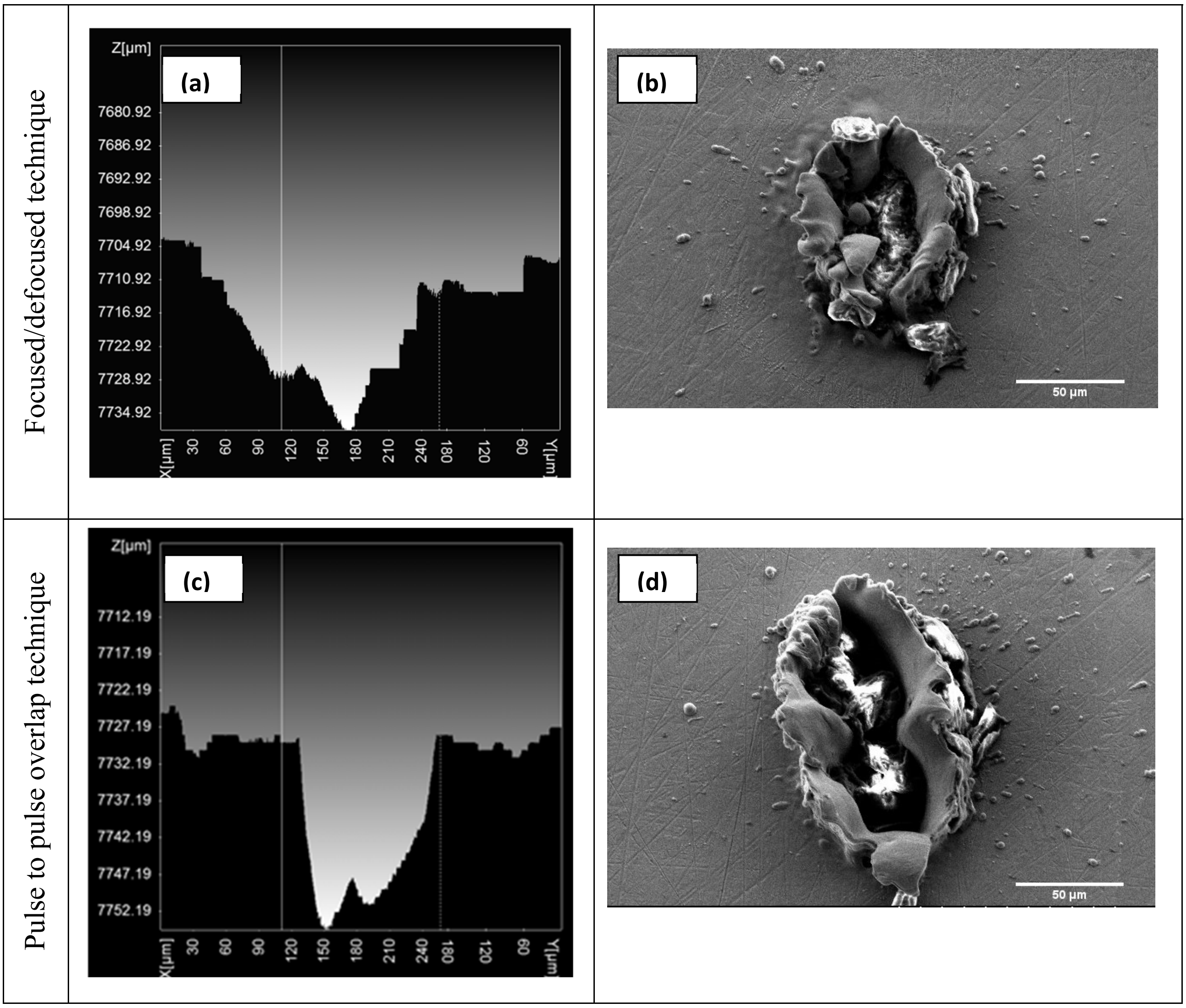

Figure 6. Focused/defocused technique, pulse to pulse overlap technique

Results and discussion

The term focus position is representing the position of the laser beam spot where 0.0 mm representing the laser beam spot on the specimen surface. While, (+ / - mm) indicating that the laser beam spot position can be located above/below the specimen surface. The position of laser beam spot must be maintained during the micromachining process to avoid any change in the dimensional accuracy [4]. Normally, minimum focused beam spot size was found at 0.0mm focus position, and then spot size was increased with either positive or negative focus position. Positioning of the focused beam above the specimen surface was not favored in this study as the laser beam spread over wide area and diminished the effect of laser fluence, resulting in wider dimples with shadow depth. To investigate the effect of changing focus position on the micro dimples dimension, a series of experiments were made using 25 pulses per position to obtain noticeable change in micro dimples diameter and depth. The experiments conducted at three narrow different positions (0.0, -0.25, -0.5 mm) using laser fluence 100 and 200 J/cm^2 to keep the effect of laser fluence as high as possible. As the laser beam positioned below the specimens surface, the spot size increased and subsequently laser fluence reduced. Figure 1 shows three-dimensional (3D) depth profile images and corresponding two-dimensional (2D) of micro dimples at different focus position for comparison. The micro dimples showed V-letter inner shape attributed to Gaussian laser beam as it is known that, the micro dimples inner shape greatly depends on the laser power distribution i.e Gaussian or top hat [21]. Moreover, large heat affected zone was observed at focus position 0.0mm due to localized heat at beam spot was much higher compared to other defocused positions. Similar observations were reported in [4, 18]. Figs. 2 and 3 showed the change in inner diameter and depth of micro dimples with focus position. Normally, the focused laser beam on the specimen surface provides greater influence than other positions of defocused laser beam where the maximum laser influence reached at spot center which explain the noticeable increase in dimples depth at 0.0 mm position as its clear in Figure 1(b) and Figure2. Alternatively, the inner micro dimples diameter increased with increasing defocusing distance due to increase the beam spot size that spread over large area. The changing of laser fluence from 100 to 200 J/cm^2 shows same behavior but with increasing the values of micro dimples diameters and depth at 200 J/cm^2 where large amount of the incident laser beam absorbed by specimen surface and exhausted through material thickness. Furthermore, the high laser fluence is higher interaction time that resulted in ablation of large amount of materials. The increase of micro dimples depth with increasing laser fluence is in good agreement with reported results in [1, 20]. The maximum depth of the created micro dimples at focus position 0.0 mm where higher than the reported values by Li et. Al. [20], who used long pulse duration rather than nanosecond pulse duration that used in this study. Moreover, with the machine specification the maximum diameter and depth of the fabricated micro dimples were 72 µm and 24 µm respectively at -0.5 mm defocusing distance using 200 J/cm^2. A series of experiments were made to investigate the effect of number of pulses on the micro dimples diameter and depth. The number of pulses increased from 25 pulse to 50 and 100 pulse on the same position at -0.5 mm defocusing distance. Figure 4. shows a linear increase in micro dimples diameters due to heat dissipation from the laser spot area to the surrounding area. While, the micro dimples depth slightly increased with changing the number of pulses as it shown in Figure 5, indicating that the laser beam energy is completely absorbed and exhausted through metal thickness. Though the increase of a number of pulses shows to increase the diameter and depth of the micro dimples, the increasing of laser fluence from 100 J/cm^2 to 200 J/cm^2 makes the change of the number of pulses is more significant. Thus, the laser fluence is more dominated parameters that influence the micro dimples dimensions while the number of pulses is less dominated and associated with laser fluence for controlling micro dimples diameters. Therefore, it is possible to control the micro dimples dimensions by precise control of laser fluence and number of pulses. The fabricated micro dimples increased the contact surface area, which may improve the tribological properties of engineering components as it reported in [1, 22]. Moreover, it may provide mechanical interlocks for improving bond strength of heterogeneous layers[18]. Despite the fabricated micro dimples have a V-letter shape is favored for injection molding applications [4] and adhesive bond strength [18], it is may not preferable for some other applications. Therefore, two different techniques were used to modify the inner shape of micro dimples and increase both micro dimple diameter and depth with respect to machine specifications. The 2D profile of the micro dimples fabricated by using both techniques and corresponding morphologies are shown in Figure 6. The first technique called defocused multi shots where, laser beam spot adjusted at 0.0 mm position on the specimen surface to get dipper depth then defocused below specimen surface at -0.5 mm to wider the micro dimples diameter and smoothing the inner wall. The 100 pulse per position was used for each position to increase micro dimples dimension. The results showed remarkable increase in dimples depth and diameter up to 30 µm and over 100 µm respectively as it shown in Figure 6 (a). The second technique called pulse to pulse overlap multi shots shown in Figure 6 (c) where, laser spot focused below the specimen surface then 100 pulses were used to create micro dimples. The laser beam then shifted 50 µm from the micro dimples center where additional 100 pulse were used to overlap the created dimples. Thus, the micro dimple width increased while the depth remains constant. The results showed noticeable increase in dimple width more than 100 µm. Both techniques showed parallel side dimples wall indicating that the micro dimples inner shape changed from V-letter shape to partially rectangle shape, which could be useful for applications that required rectangle shape. The focused/defocused technique morphology shown in Figure 6(b) while, the overlap technique morphology is shown in Figure 6(d), the consecutive pulses tend to homogenize the inner wall of the micro dimples. Both techniques successfully alter the dimensions and the inner shape of micro dimples with the limited machine specifications without using any external part or expensive machine modification. This cheap solution may be used with any machine in the market, leading to extend the use of 304 stainless steel in various engineering applications.

Conclusions

The use of laser micromachining for the fabrication of surface texturing on a 304 stainless steel surface is proposed in this paper. The influence of focus position, laser fluence and pulse number on the micro dimples dimensions and shape were extensively investigated. The following conclusions can be drawn based on the results of the experiments:

1. The fabricated micro dimples have a V-letter inner shape due to Gaussian beam profile.
2. The laser fluence is the governing parameter that influences the micro dimples dimensions while the number of pulses has less influence.
3. The laser fluence associated with number of pulses is needed for controlling micro dimples dimensions precisely.
4. The maximum diameter and depth of the fabricated micro dimples were 72 μm and 28 μm respectively at -0.5 mm defocusing distance using 200 J/cm^2.
5. The focused/defocused technique and pulse to pulse overlap technique successfully alter the dimensions and the inner shape of micro dimples from V-letter to partially rectangle shape.
6. The focused/defocused technique mainly increases the depth of the micro dimple while the pulse to pulse overlap technique mainly increases the width of the micro dimples.
7. The micro dimples depth and width increased to 30 μm and over 100 μm respectively using both techniques.
8. The changing in inner shape and dimensions of the fabricated micro dimples might extent the use of 304 stainless steel in new engineering applications.

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