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FUTURE ENGINEERING

# A Study on the Influence of Laser Surface Texturing Parameters on the Dimensional Accuracy of the Textured Designs

The research involves an experimental investigation into the laser surface texturing (LST) of stainless steel 316L parts to explore the correlation between the laser process parameters and the dimensional accuracy of the textured designs. A full factorial experimental design was used to analyse the impact of the input parameters via main effects plot and analysis of variance (ANOVA) test. The results indicated that laser track distance along the traverse scanning direction had the most significant effects on all the output responses, i.e. width and depth of the textured grooves and width of the riblet (unmachined region). Laser intensity also had significant effect on the riblet width and groove depth, while scanning velocity did not exhibit any statistically significant influence on any of the responses. The deviations in the riblet and groove widths from the nominal CAD design were the least when using a track distance of 10 µm, whereas the deviations in the groove depth was minimum for a track distance of 100 µm.

*Keywords:*
*Laser surface texturing, microtextures, full factorial experiment, stainless steel.*

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A.Y. Escudero-Ornelas, A. Valera-Medina, S. Bigot, and D. Bhaduri, 'A Study on the Influence of Laser Surface Texturing Parameters on the Dimensional Accuracy of the Textured Designs', *Cardiff University School of Engineering Research Conference 2024*, Cardiff, UK, 2024, pp. 57-61.

**doi.org/10.18573/conf3.n**

## INTRODUCTION

Topological modification, such as surface texturing, is frequently employed to enhance specific properties and performance characteristics of surfaces [1]. In the energy sector, microtextures have demonstrated their effectiveness in reducing energy consumption and improving the tribological properties of various components, including turbines and swirl burners [1,2]. Each component has a certain characteristic that surface texturing aims to enhance. To achieve this goal, these topological modifications can be inspired by biomimetic designs. Some biomimetic designs such as the lotus, scallop, sharkskin, and diamond have already proved to enhance certain characteristics, such as wettability, surface drag, anti-corrosion etc. However, the dimensional parameters of each design can vary, leaving ample opportunity to optimise these parameters.

To test the performance of a textured design, a simulation is typically performed to predict the fluid properties of the texture for a particular application, to reduce the cost of the experimental validation. Once the texture design is successfully optimised it is possible to manufacture these designs on real objects. Nevertheless, the produced textures often display deviations in the dimension from the nominal values used in the simulation. This leads to deviation in the experimental results from the simulated values [3]. Consequently, as a preliminary step to enable the manufacturing process closely adhering to the intended CAD design, this research aims to identify the key process parameters for the fabrication process. Several studies have explored different texture manufacturing technologies, such as micro electro-discharge machining (μ-EDM) and abrasive-based jet machining (ABJM) [4], together with identifying some design and processing challenges. Laser surface texturing (LST) is an alternative manufacturing technology that is clean, automated, flexible and does not involve any dielectric fluid or abrasive slurry [5]. In LST, a laser beam is focused on the surface to remove material by melting and vaporisation. However, this often results in the deviation of texture dimensions from the nominal values. Thus, the aim of the research is to investigate the capability of LST to accurately produce the targeted dimensions from a CAD texture design, together with analysing the surface roughness of the produced textured surfaces [6]. The ultimate is to ensure that the resulting textures closely resemble those designed for the simulation. To achieve this, the LST parameters were evaluated to determine their effects on the texture dimension and roughness, using a full factorial experimental design [7]. The influence of laser intensity, scanning velocity and laser track distance on the texture dimensions was assessed while maintaining the laser pulse frequency and focal distance constant.

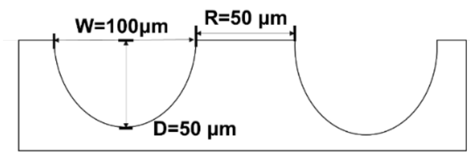


Fig. 1. The dimensional parameters of the Groove texture: Width (W), Depth (D) and Riblet (R).

## MATERIALS AND METHODS

*Workpiece material and texture design*
Stainless steel 316L square workpiece samples, measuring 35 × 35 × 2 mm$^3$ were used. Channel texture design was selected for this study, the nominal dimensions of a single channel as seen on the cross-section is in Fig 1. The three simulated and measured texture dimensions were the width and depth of the channel, and the width of the riblet.

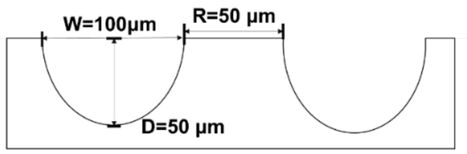


Fig. 1. The dimensional parameters of the Groove texture: Width (W), Depth (D) and Riblet (R).

*Machine and equipment*
Laser texturing was carried out on a Lasertec DMG-40 nanosecond fibre laser machine, with 0.25 mJ laser energy and 80 kHz frequency. The surface topography measurements on the textures were carried out using a 3D optical profilometer Sensofar SMART, with 10X magnification. Representative textured topographies are shown in Fig. 2. The dimensional parameters (groove depth, groove width and riblet width) were measured at five different locations on each specimen, as shown in Fig. 3. Three measurements were taken at each location. The average dimensions and the deviations from the nominal values were recorded.

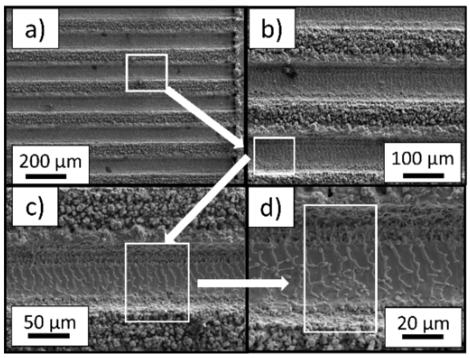


Fig. 2. SEM images of Groove texture at different magnifications.

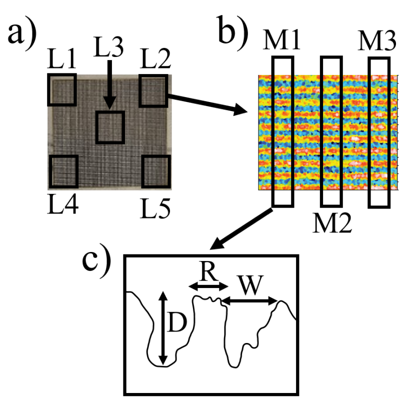


Fig. 3. (a) The five locations on each specimen, (b) three measured areas at each location, and (c) dimensional parameters measured within each area.

*Experimental array*

Experiments were carried out using a full factorial design involving three factors at three levels that resulted in 27 trials, allowing for a comprehensive exploration of the main effects and interactions among these factors.

Table 1 lists the three input parameters, viz. laser intensity (I), scanning velocity (v) and laser track distance (T), together with their respective levels.

| Input parameters | Units | Levels | | |
|---|---|---|---|---|
| | | 1 | 2 | 3 |
| Laser intensity (I) | % | 60 | 80 | 100 |
| Scanning velocity (v) | mm/s | 600 | 800 | 1000 |
| Laser track distance (T) | µm | 10 | 50 | 100 |

Table 1. Factors and their levels.

## RESULTS AND DISCUSSION

The Analysis of Variance (ANOVA) results corresponding to the mean riblet width, mean groove width and mean groove depth, together with the deviations in these dimensions from the nominal values are presented in Table 2. The main effect plots for the aforementioned responses are shown in Fig 4. It is revealed that laser track distance (T) had the most significant effect ($p<0.05$) on all the response variables with the PCRs varying from ~68-83%.

Laser intensity (I) also had statistically significant influence ($p<0.05$) on the mean riblet width and mean groove depth with PCRs of ~5% and 18%, respectively. In contrast, laser scanning velocity (v) did not exhibit significant effects on any of the response variables, with p-values greater than 0.05 and relatively low PCRs (~0.3-5%), suggesting that its impact was minimal compared to that of T and I.

The impact of the input factors on the dimensional deviations of the response variables from their nominal CAD values was also analysed. Laser track distance again showed the maximum influence on the dimensional deviations of all three output responses.

**(a) Mean riblet width**

| Source | DF | SS | MS | P-value | PCR% |
|---|---|---|---|---|---|
| I | 2 | 331.87 | 165.94 | 0.045 | 5.09* |
| v | 2 | 19.85 | 9.93 | 0.762 | 0.30 |
| T | 2 | 5448.43 | 2724.21 | 0.000 | 83.49* |
| Error | 8 | 282.50 | 35.31 | | 4.33 |
| Total | 26 | 6525.61 | | | 100 |

**(b) Mean groove width**

| Source | DF | SS | MS | P-value | PCR% |
|---|---|---|---|---|---|
| I | 2 | 99.48 | 49.74 | 0.563 | 1.99 |
| v | 2 | 254.70 | 127.35 | 0.264 | 5.10 |
| T | 2 | 3404.66 | 1702.33 | 0.001 | 68.19* |
| Error | 8 | 644.02 | 80.50 | | 12.90 |
| Total | 26 | 4993.22 | | | 100 |

**(c) Mean groove depth**

| Source | DF | SS | MS | P-value | PCR % |
|---|---|---|---|---|---|
| I | 2 | 1609.2 | 804.59 | 0.001 | 18.09* |
| v | 2 | 179.3 | 89.65 | 0.188 | 2.02 |
| T | 2 | 6230.7 | 3115.37 | 0.000 | 70.06* |
| Error | 8 | 345.8 | 43.23 | | 3.89 |
| Total | 26 | 8894.0 | | | 100 |

**(d) Deviation riblet width**

| Source | DF | SS | MS | P-value | PCR% |
|---|---|---|---|---|---|
| I | 3 | 43.290 | 43.290 | 0.252 | 7.86 |
| v | 2 | 8.363 | 8.363 | 0.736 | 1.52 |
| T | 2 | 183.038 | 2724.21 | 0.018 | 33.23* |
| Error | 8 | 105.142 | 35.31 | | 19.08 |
| Total | 26 | 550.980 | | | |

**(f) Deviation groove width**

| Source | DF | SS | MS | P-value | PCR % |
|---|---|---|---|---|---|
| I | 2 | 96.36 | 48.18 | 0.363 | 8.05 |
| v | 2 | 25.41 | 12.71 | 0.746 | 2.12 |
| T | 2 | 331.51 | 165.76 | 0.063 | 27.69 |
| Error | 8 | 333.93 | 41.74 | | 27.89 |
| Total | 26 | 1197.07 | | | |

**(g) Deviation groove depth**

| Source | DF | SS | MS | P-value | PCR % |
|---|---|---|---|---|---|
| I | 2 | 314.36 | 157.181 | 0.020 | 37.42* |
| v | 2 | 30.05 | 15.025 | 0.553 | 3.58 |
| T | 2 | 172.50 | 86.251 | 0.074 | 20.53 |
| Error | 8 | 188.45 | 23.556 | | 22.43 |
| Total | 26 | 840.04 | | | |

Table 2. ANOVA analysis on the mean (a) riblet width, (b) groove width, (c) groove depth and (d), (e), (f) their corresponding dimensional deviations.

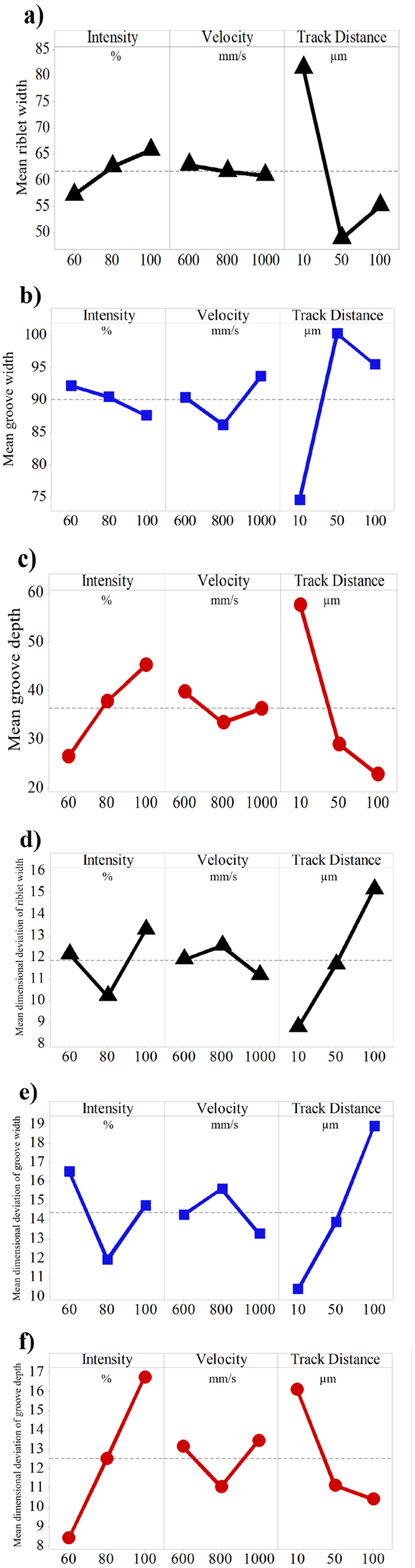


Fig. 4. Main effect plots for mean (a) riblet width, (b) groove width, (c) groove depth and (d), (e), (f) their corresponding dimensional deviations.

The ANOVA analysis on the dimensional deviations shows that laser intensity (I) had the most significant effect on the deviation of groove depth, with a PCR of 37.42% and a p-value of 0.020, which is less than 0.05, indicating statistical significance. Laser scanning velocity (v) did not exhibit significant effects on any of the dimensional deviations, with p-values greater than 0.05 and relatively low PCRs (ranging from 1.52% to 3.58%), suggesting that its impact was minimal compared to that of T and I. The error terms in the ANOVA tables account for a considerable portion of the total variability in the dimensional deviations (ranging from 19.08% to 27.89%).

Regarding the two-way interactions, the overall interaction effect (I × v, I × T, v × T) was not statistically significant for any of the riblet dimensions (riblet width, groove width, and groove depth), with p-values of 0.491, 0.787, and 0.506, respectively. The PCRs for the two-way interactions were also relatively low, ranging from 5.95% to 11.82%, indicating that the combined effects of any two factors did not considerably influence the response variables beyond their individual main effects. Among the two-way interactions, the interaction between intensity and track distance (I × T) had the highest PCR for both riblet width (4.06%) and groove width (7.61%), while the interaction between velocity and track distance (v × T) had the highest PCR for groove depth (2.97%). However, these interactions were still not statistically significant, with p-values greater than 0.05. The low PCRs and high p-values for all the two-way interactions suggest that the input factors can be optimised independently.

## CONCLUSIONS

The present study investigated the capability of LST to accurately reproduce proposed dimensions from nominal CAD designs on 316 stainless steel surfaces. The aim was to ensure that the resulting texture closely resembled those designed for the simulation. The ANOVA results revealed that laser track distance had the most significant effect on all the response variables. The two-way interactions were not statistically significant, suggesting that the combined effects of any two factors did not significantly influence the response variables beyond their individual main effects.

These findings further suggest that the laser track distance is the most critical parameter in accurately reproducing the proposed dimensions from the CAD design using LST. By carefully controlling the track distance, the resulting texture can be optimised to closely resemble the designed simulation. Laser intensity also plays an important role for certain response variables and should be considered in the process optimisation. To further improve the dimensional accuracy of the laser textured geometries future studies could focus on testing a wider range of the track distance and laser intensity parameters, as well as investigating the effects of other factors, such as material properties (thermal conductivity, reflectivity, diffusivity), and prior surface preparation techniques, such as removal of surface contaminants.

***Acknowledgments***
*The research is supported by The Mexican National Council on Science and Technology (CONAHCYT) PhD scholarship.*

***Conflicts of Interest***
*The authors declare no conflict of interest.*

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E. Spezi and M. Bray (eds.) 2024. *Proceedings of the Cardiff University School of Engineering Research Conference 2024.* Cardiff: Cardiff University Press.
doi.org/10.18573/conf3

*Cardiff University School of Engineering Research Conference 2024* was held from 12 to 14 June 2024 at Cardiff University.

The work presented in these proceedings has been peer reviewed and approved by the conference organisers and associated scientific committee to ensure high academic standards have been met.

First published 2024

Cardiff University Press
Cardiff University, Trevithick Library
First Floor, Trevithick Building, Newport Road
Cardiff CF24 3AA

cardiffuniversitypress.org

Editorial design and layout by
Academic Visual Communication

ISBN: 978-1-9116-5351-6 (PDF)

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