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Research Article

Optimization of fibre laser parameters for micro-texturing in piston ring manufacturing

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ABSTRACT

Surface texturing with laser is a common method to enhance tribology of interacting surfaces, and, nevertheless, there are serious difficulties with controlling a perfect size of texture. This paper examines how fiber laser process parameters influence the depth of the texture, roughness, and diameter and how Taguchi methodology can be used to optimize this process. The test materials were commercial cast iron piston rings which had a surface roughness of 0.482 um, hardness of 410 HV, and a Youngs modulus of 250 Gpa. Surface texturing was performed on a Marko Laser fiber laser machine with power of 20 W, wavelength of 1062 nm, frequency of 200 KHz and a speed of 140 mm/s. We have used Taguchi method in conjunction with multi-objective optimization with the aid of the gray relational grade (GRG) rank method where an L9 orthogonal array was used to assess the influence of laser power, frequency, and scanning speed on the texture dimensions. A confocal microscope was used to determine surface topography. Findings have shown that laser power has the strongest effect on dimple attributes with 58.14 percent variance in diameter because of it, after which laser frequency (31.49 percent) and scan speed (0.35 percent) follow. The best set of parameters used gave an ideal dimple size and this was; scan speed of 140 mm/s, 25 KHz frequency, and laser power of 16 W. The originality of the study at hand is that, it uses a combination of Taguchi analysis and gray relational grade (GRG) rank to optimize the laser parameters including power, frequency, scan speed with dimple characteristics of cast iron piston rings. This method does not only enable one to have a clear picture on the influence of these parameters on the dimple sizes and the surface roughness but also helps to create more efficient and durable piston rings by using efficient laser texturing.

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INTRODUCTION

Surface texturing enhances the performance of moving mechanical parts due to their high load capacity, lesser wear and less friction. Scientists are making attempts to identify the optimal texture sizes under various circumstances. One can make these textures in a number of ways, such as using photochemical etching, abrasive jet machining, embossing, burnishing, and laser surface texturing. The most used is laser surface texturing that is capable of producing very finer textures. Yet, it is hard to make very small textures, particularly required in such applications as ring-liner systems. The textures are dependent on the laser settings such as power, scanning speed, frequency, and pulses. It is complex to find the appropriate environments. This research intends to come up with the influence of these laser settings on the texture size to simplify the process. Laser texture fabrication is a process that requires laser accuracy and the ability to create fine features on the surface, which is needed in most cases in industries. To this end, femtosecond (fs) and nanosecond (ns) pulse lasers are often employed, since they are very precise when creating textures. But in comparison with other fiber laser machines that run in the millisecond (ms) band, these systems are often prohibitively costly as a result of their advanced technology. Fiber lasers can be less accurate and less high quality of texture but still remain a rather cost-efficient solution that can address most of the industrial challenges where cost is a decisive factor.

Surface texturing with the help of laser is mainly aimed at the improvement of tribological properties of cast iron piston rings. This is done through the formation of accurate dimple designs on the face, which may contribute to better lubrication retention, and lessening friction, and wear hence making the complete functioning and life cycle of the piston rings in the mechanical systems more functional. The accuracy of texture dimensions is of great significance to tribological uses since surface texture influences directly the friction, wear resistance, retention of lubricants, and bearing capacity of load. The existence of uniform dimples are micro-reservoirs of lubricants that guarantee maximum lubrication, less friction, and uniform wear, which contribute to component longevity and better performance. The unreliability due to inconsistency of texture dimensions may result in uneven lubrication, localized wear, and load distribution. In the case of cast iron piston rings, tight texturing enhances the retention of oil, sealing, and minimization of friction loss as well as engine efficiency and is recommended in the quest to increase the service life and efficiency of vehicle engines. The key challenges in achieving precise dimensions in laser surface texturing include:

Laser Parameters Control

Laser power, frequency, scan speed and-pulse duration need to be accurately regulated to achieve uniform dimple size(diameter, depth, and roughness of the surface). Minor differences may lead to a mismatch of textures, which influences tribological performance [1].

Material Properties

Various materials respond differently to laser energy as in the case of cast iron. Their thermal characteristics (including melting point, thermal conduction and reflectivity) may affect the intensity with which the material may absorb laser energy and the precision with which texture may be controlled [2].

Heat Affected Zone (HAZ)

Laser surface texturing can induce localized heating, which may result in microstructural changes, residual stresses, or thermal deformation around the textured region. This may impact on the accuracy of the dimple formation adverse [3].

Debris and Surface Contamination

When performing the laser process, the molten material can harden differently resulting in debris or flaws that impact the consistency of the textured surface. These residues might need to be removed by post-processing[4].

Laser Spot Size and Focus

It is important to ensure that laser spot size and focus is constant in order to produce accurate dimples. Deviation in focus and alignment used in the process may result into variation in the dimensions of texture [1].

Surface Reflection and Absorption

Lasers are reflected by the surface and hence surfaces with a high amount of reflectivity cause the inefficiency of the process and erratic dimensions. Pre-treatments or surface coating can be required to alleviate this problem [5].

Reproducibility

It may be difficult to obtain the same and repeatable result using different samples because controlling all the factors at the same time can be difficult particularly in mass production settings.

To overcome those obstacles, careful optimization of laser parameters, strict control of the processes, and even post-processing procedures are necessary to achieve the required level of the surface texture. Laser processing has been experiencing remarkable progressions in an effort to enhance different technologies of laser and their uses. Recent investigations have discussed various issues of laser performance such as distribution of beam energy, optimization of parameters, and improvement in processing of materials. Moradi et al. [2] examined the consequences of energy distribution of laser beams on the surface transformation hardening by using Ndlasers and diode. Their research has showed that distribution of energy has a significant impact on the hardening process, which has an impact on the property of resulting material. This literature makes it possible to establish the parameters of laser, which may be customized to obtain the desired hardness characteristics in treated materials. The paper by Karamimoghadam et al. [1] gave an overview of the developments in the area of laser surface transformation hardening of automotive metals. They have pointed out recent advances in technology that sought to enhance the life span and reliability of automobile parts by laser hardening. Their review explains that more research is necessary to streamline and perfect laser hardening processes and apply them to improved automotive interests. Mehrabi et al. [6] examined the use of direct laser metal deposition in the production of functionally graded materials. Their paper used experimental and response surface techniques to optimize additive manufacturing processes, and demonstrated that laser techniques can be successfully used to form complex graded structures with improved performance properties. Moradi et al. [7] discussed the processes of enhancing CO2 laser cutting on polycarbonate materials with a lot of focus on better cutting efficiency and quality. As evidenced in their study, process optimization had the potential of greatly improving the output of laser cutting in manufacturing process especially when dealing with plastic material. Baranowski et al. [8] have worked out and optimized a new process in laser-sintering to additively manufacture parts of carbon fiber reinforced polymer. Their experimental study aimed at the optimization of the process parameters that could yield high-quality continuous fiber-reinforced components to demonstrate the improvement of the laser-based manufacturing technologies. Ding et al. [4] used generalized regression neural networks and genetic algorithms to optimize the fiber laser cutting. Their method enabled a multi-objective optimization, cutting quality and efficiency. The paper is relevant to the research of the enhancement of laser cutting processes using highly developed optimization methods. The pump of a Tm-doped fiber laser was a compact design that Yao et al. [9] employed in environmental gas sensing. They were working on maximizing the design of laser to improve sensor operation, portending the ability of fiber lasers to monitor the environment. In a study conducted by Shehryar Khan et al. [10], the impacts of laser beam defocusing on welding process of automotive press- hardened steels were investigated. Their numerical and experimental confirmation gave them an insight into how to optimize the laser welding parameters to enhance the quality and productivity of the welds. Pan et al. [11] maximized the optical fiber laser linewidth with a self-injection technique of light. The study of their research led to the stability and performance of fiber lasers in thermal of the challenges to do with linewidth and operation of laser. Khozeymeh et al. [12] analyzed the applicability of the dysprosium-doped yellow fiber lasers in ophthalmology. They oriented their research to maximization of laser parameters to address a medical necessity, which brings the importance of fiber lasers to the medical practice. The in situ measurement of the temperature of fiber core laser by Lou et al. [13] was designed with consideration of the optical frequency domain reflectometry (OFDR). This development has made it possible to have a better temperature control of the high-power fiber lasers and this has enhanced overall performance. The approach taken by Lapre et al. [14] was to use genetic algorithms in optimizing the operation of noise-like pulse fiber lasers operating on broadband. Their work proved the usefulness of optimization methods in improving the work of laser and the working distance. Gopinath et al. [15] used Technique of Order of Preference by similarity to ideal solution (TOPSIS) to maximise the fibre laser microcutting parameters on duplex steel**.** Chen et al. [16] studied dissipative solitons in Er-doped fiber lasers by optimizing the tasks using machine-learning, using Gaussian processes. Their work shed light on how to optimize laser functioning with the help of the best machine-learning methods. Vora et al. [17] experimentally studied and Pareto optimized the processes of fiber laser cutting of Ti6AL4V. Their research was aimed at enhancing cutting quality and efficiency of titanium alloys, which prove useful in the practice of optimizing laser. In the study by Najjar et al. [18], neural networks and chimp optimization were utilized in forecasting the quality of the kerf when cutting basalt fiber-reinforced composites using lasers. Their output helped in the development of predictive models on enhancement of laser cutting in composite materials. Wu et al. [19] optimised the parameters of the fiber laser welding to achieve the trade-off between energy use and bead geometry. Their work helped to enhance efficiency and performance in welding with the emphasis of the multi-objective optimization. Zeng et al. [20] balanced stimulated Raman scattering (SRS) and thermal-mechanical instability (TMI) effects in direct diode-pumped high-power fiber lasers by optimizing them. Their study was to improve the work of lasers, which are high-power. Han et al. [21] studied the production, optimization, and use of ultrashort pulses of a few seconds in mode-locked fiber lasers. They worked on high precision of laser processing with ultrashort pulse. Kokhanovskiy et al. [22] used the mode-locked fiber laser inverse design based on the particle swarm optimization. Their efforts led to optimization methods in designing lasers and this has helped enhance the performance and efficiency of lasers. Yassin and Hojjati [23] conducted a review of the thermoplastic matrix composite processing in terms of automated fiber placement and tape laying. Their overview shows the developments in composite fabrication process, and the role played by automation in promoting the efficiency of the process and the characteristics of the materials. The review of artificial intelligence-based mode-locked fiber lasers was given in detail by Ma and Yu [24]. Their paper examined the possibility of optimizing the work of lasers using AI methods, with attention to the progress in mode-locking processes and their use in other applications in high-precision areas. Wu et al. [25] examined the intelligent soliton generation of breathing in ultra fast fiber lasers. Their study showed the possibilities of employing the advanced control algorithms to improve the stability and performance of soliton generation, which is the part of the high performance ultrafast lasers development. Motard et al. [26] optimized the work of a monolithic Tm3+, Ho3+-codoped fiber laser through the control of the fiber gain and the reflected wavelength. They demonstrated that optimization of these parameters would be capable of improving the efficiency and output properties of fiber lasers. Kumar Mishra et al. [27] reviewed several laser beam drilling methods of fiber-reinforced composite that have compared Nd and CO 2 lasers. Their overview of the most common types of lasers in terms of their use in drilling composite materials showed the advantages and disadvantages of each type, which can be used to comprehend the most successful techniques in various cases. Mathew et al. [28] discovered how machine learning can be used to align the laser beams automatically using the Raspberry Pi auto-aligner. Their work reflected how machine learning could be used to automate the process of laser system alignment, making laser systems more precise and efficient. Kuprikov et al. [22] used the deep reinforcement learning to self tune the laser sources of dissipative solitons. Their study proposed a new method of optimizing the performance of lasers based on self-learning algorithms, which increases the stability and the performance of laser systems. Chengal Reddy et al. [29] used the grey relational analysis to optimize the laser drilling process on the AISI 303 material. Their research was aimed at the process parameter optimization to increase the efficiency and quality of drilling proving the usefulness of optimization techniques in the manufacturing process. The optimization of the production of polarization squeezed light in nonlinear optical fibers with femtosecond pulses was performed by Andrianov et al. [30]. Their efforts helped in the development of nonlinear optics, as they enhanced the methods of light generation so that they can perform better. Czelusniak and Amorim [31] used a selective laser sintering of carbon fiber-reinforced PA12 by using Gaussian process modeling, and stochastic optimization. Their experiment was based on optimization of process variables to enhance the quality and consistency of the 3D-printed parts.

The latest developments in laser machining have also played a significant role in the development of accurate surface texturing to be used in other engineering activities. Among such developments, the article by Chandan and Sahoo [32] is quite resourceful in the applications of low-power nanosecond lasers in scalable machining of surface on Ti-6Al-4V alloy, which is used broadly in aerospace and biomedical applications.

However, in spite of the tremendous improvement in the mode of laser processing and optimization procedures, the gap in total insight and optimization of laser parameter in specific purposes is still extremely significant, especially in the context of cast iron piston rings. Current research has mostly concentrated either on general laser processing information or on an individual material type, thus there is a gap in the optimization strategies applied to cast iron components, which play a significant role in most industrial applications. The present study fills this gap by concentrating on optimization of the machine settings of laser texturing of surfaces on cast iron piston rings, which is a major part of an automotive engine.

The originality of the current study is that it uses Taguchi analysis and gray relational grade (GRG) rank as the only means of optimization of laser parameters including power, frequency and scan speed in dimple characteristics of cast iron piston rings. Such a method is not only able to give a clear insight into how these parameters influence the nature of dimples and surface roughness but also leads to more efficient and robust piston rings that are formed by laser flints.

The advantage of this study is that it was focused on the optimization of laser texturing of the cast iron piston ring surface by applying a complex of new methodologies and detailed analysis. This study is not only a huge gap in the existing literature, but it also provides the means of improvement in the work of the piston rings and their service life using laser texturing that establishes a new standard of the same application in the industry. Finally, the use of ns and fs pulse lasers in metal texture fabrication is more precise, at the expense of cost-effectiveness so that the application is not very common in industries. Although fiber lasers are less precise, they offer a feasible economic option to many applications, which is sustained by the current research to optimize the parameters of fiber lasers to improve the texture quality and material properties in diverse metals and uses.

MATERIALS AND METHODS

The effects of laser processing parameters on texture characteristics were also evaluated through the composite method of assessment consisting of experimental and analytical methods. A fiber laser machine was employed to systematically change laser power, frequency and scan speed. Employing optical microscope and profilometer was employed to scan the texture characteristics like dimple diameter, depth and surface roughness. Taguchi designed experiments and gray relational grade (GRG) analysis were utilized to establish the optimal parameter settings while analysis of variance (ANOVA) was applied to find out the significance level of each parameter on the texture properties. This general approach allowed us to effectively determine how the parameters of the laser influence the surface texture. Figure 1 shows the Methodology of this Research work.

This was then followed by the integration of some response variables, such as dimple diameter, depth and surface roughness, into a single performance index using the gray relational grade (GRG) technique. This helped facilitate the analysis for the overall quality of the parameter settings. Also, the Analysis of Variance (ANOVA) was performed to ascertain significance of every parameter towards the characteristics of texture and thus the best parameters of the processes of lasers that would provide the most desired outcome in terms of quality of the surface texture. Other traditional methods are response surface methodology (RSM) and genetic algorithms (GA) that are used in laser processing optimization. Although RSM is useful in the development of predictive models and parameter interaction, it needs more experiments to achieve reliable outcomes. Likewise, GA is good at global optimization that is computationally expensive and challenging to execute. Unlike that, our selected Taguchi-GRG method offers a more effective and realistic solution to multi-objective optimization that has a few experimental runs. The Taguchi method with its orthogonal array design reduces the amount of experimental effort necessary, whilst retaining accuracy and the Gray Relational Grade method has been found to offer a good way of transforming multiple responses into one optimization problem. This hybrid method is quite beneficial in the industrial sectors where the resources are limited, and speed is of the essence. Our work, concerned with cast iron piston rings, is the first attempt to apply this technique properly to obtain accurate surface texturing, which provides major gains in tribological performance.

Details of Specimen and Texturing

Some of the materials that were used in this study were commercially obtained piston rings made of cast iron. These piston ring segments were wire-cut electric discharge machining (EDM) to extract them out of the entire assembly to make them suitable samples to be used in laser texturing. Table 1 gives specifications of the test specimens in detail and the test specimens in this case are the cast iron piston rings that are to be texturized. The specimens have a roughness of the surface of 0.482 um, a Youngs modulus of 250Gpa and a hardness of 410 HV. The topography of the specimens following laser texturing was determined using a confocal microscope. The averaging values of the measurements of three different locations on each specimen were used to create depth of the textured areas and to determine the average diameter.

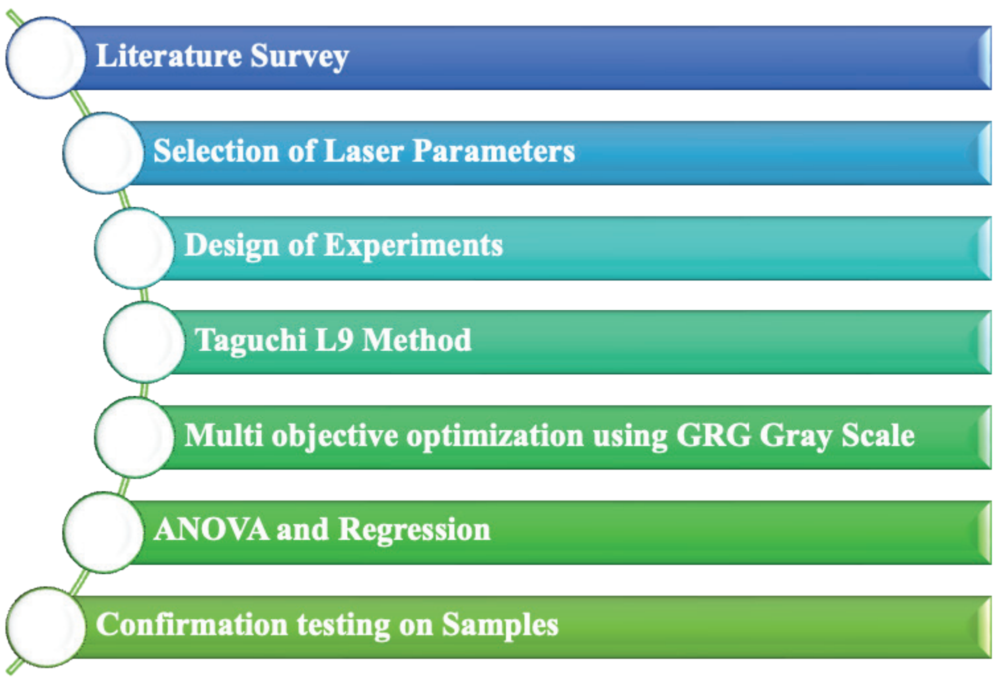


Figure 1. Methodology for Research work.

Table 1. Laser textured specimen details

Material	Chemical structure (%)	Hardness (HV)	Roughness of surface Ra (µm)
Piston Ring (Commercial) Samples	C-3.61, P-0.085, Mn-0.80, S-0.043, Si-2.80 and Fe- Remaining	410	0.482

Cast iron piston ring specimens are subjected to surface texturing using a fiber laser system with a maximum power of 20W, a maximum frequency of 500 KHz, and an operating wavelength of 1064 nm. In this study, a fiber laser was used for surface texturing. Below are the key specifications of the fiber laser machine employed in the experiments:

1. **Laser Type**: Fiber Laser
2. **Laser Wavelength**: 1064 nm
3. **Maximum Power Output**: 20W
4. **Pulse Frequency Range**: 10–50 kHz
5. **Scan Speed**: 100–300 mm/sec
6. **Beam Quality (M^2 factor)**: ≤ 1.3
7. **Spot Size**: Approximately 30–50 μm (depending on focusing lens)
8. **Pulse Duration**: Adjustable within the nanosecond range (ns)

These specifications were adjusted during the experiments to optimize the dimple dimensions (diameter, depth, and surface roughness) on the cast iron piston rings. The fiber laser was selected for its high precision, control, and ability to produce consistent surface textures. Figure 2-a depicts the schematic diagram of the fiber based laser system, While Figure 2b depicts the actual laser apparatus,

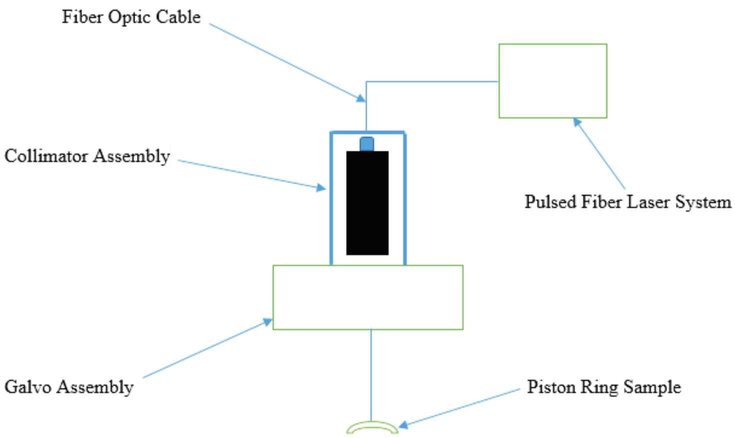


Figure. 2a Schematic of Fiber based laser system

Figure. 2b Actual laser apparatus.

The distance between the bottom of the galvo and the textured specimen is dependent on the focal length of the lens that has been absorbed into the galvo assembly. Table 2 presents the various input laser parameters that were altered when using a serial connection that was connected to a computer system. These parameters are frequency, scanning rate and power of laser. In order to determine the effect of every parameter on the texture dimensions of the piston ring material, the difference in values was broadly explored. The calibration and validation of the confocal microscopy has various major steps to be followed to ensure a good surface measurement. Reference standards with known step heights are used to perform vertical (Z-axis) calibration, whereas precision grids are in turn used to perform lateral (X and Y axes) calibration. Measures such as roughness are verified by using certified reference materials (CRMs) whose surface features are known. The resolution of the system is tested to sub-micron standards and its repeatability checked by scanning the system multiple times. Moreover, the data analysis algorithms in the software are verified to be accurate, and the surrounding conditions such as temperature and humidity are kept at the same level. The steps are used to obtain accurate and repeatable outcomes in measurements of surface topography and roughness.

Experimental Plan

Design of experiments (DOE) is a method which is systematically applied to plan, execute and analyze experiments in order to gain knowledge about the impact of different factors on a process or an outcome. Through a planned manipulation of the input factors, DOE assists in determining the factors that have a substantial effect on the outcomes and the interaction between these factors. This method permits effective experimentation of the test environment, as well as optimizing the processes in order to generate the desired results.

The Taguchi Method is a certain kind of DOE that is dedicated to the quality and performance improvement by minimizing variation and responsiveness to external factors. This technique was developed by a doctor by the name Genichi Taguchi to design experiments with a reduced number of runs, thus, a reduced amount of time and resources are saved. The Taguchi approach focuses on strong design by identifying favorable settings which maximize deviations at target values thereby improving process reliability and performance. The optimal parameters of laser processing to texturing the cast iron piston ring segments were determined with the help of Taguchi Method that considers three factors in an L9 orthogonal array and three levels [11-13]. This experimental design helped in evaluating the control factors, which were laser power, frequency and speed of scanning. According to a thorough review of literature, the ranges chosen in these factors are 8W-16W of laser power, 15 kHz-25 kHz of laser frequency, and 80mm/s-180mm/s of laser scanning speed [11-13]. Table 2 shows the particular components and their level used in the experiment.

Table 2. Variables and their intensities

Factors	Units	Levels		
		1	**2**	**3**
Laser power	Watt	8	12	16
Laser frequency	KHz	15	20	25
Laser scanning speed	mm/sec	80	140	180

Table 3. L_9 orthogonal experimental array with level details

Experiment no.	Laser power (Watt)	Frequency in (KHz)	Speed of the scanning (mm/sec)
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	2
5	2	2	3
6	2	3	1
7	3	1	3
8	3	2	1
9	3	3	2

The L9 experimental plan's specific levels for each of the nine experimental trials are outlined in Table 3, which is based on the factors and corresponding levels listed in Table 2. After conducting the laser texturing process according to this plan, the outcomes for each of the nine trials were evaluated in terms of texture diameter, texture depth, and texture roughness of the surface. The average values of these parameters were then calculated across all the textures created on the piston ring surface [7].

The Taguchi method can be used to reduce the need for numerous experiments while also saving money on them. The experiment's results were used to determine the (S/N) Signal to Noise ratio, which measures the quality features and makes it possible to comprehend how the results deviate from or approach the acquired results. The diameter of dimple, depth of dimple, and dimple roughness of the surface were the output parameters that were acquired from the designed experimentation. The ideal quality characteristics criteria for each of these output metrics are taken into consideration as they are covered below [15–17].

As dimple diameter increases it leads to increase in storage of lubrication for enhancing tribological applications and therefore "larger the better" optimum condition is considered in this case [2] shown by Equation 1.

$$\text{S/N ratio= -10}\log_{10}(1/n \textstyle\sum_{i=1}^{n}(\frac{1}{y2})) \qquad (1)$$

Reducing dimple depth contributes to minimizing friction and wear on components, making the "smaller the better" criterion optimal in this context [2], as indicated by Equation 2. Moreover, optimizing dimple roughness of the surface, characterized by small peaks and valleys that serve as reservoirs for lubricating oils even under starvation conditions, enhances tribological performance. Hence, achieving a "smaller the better" condition for dimple roughness of the surface is crucial [1], also illustrated by Equation 2.

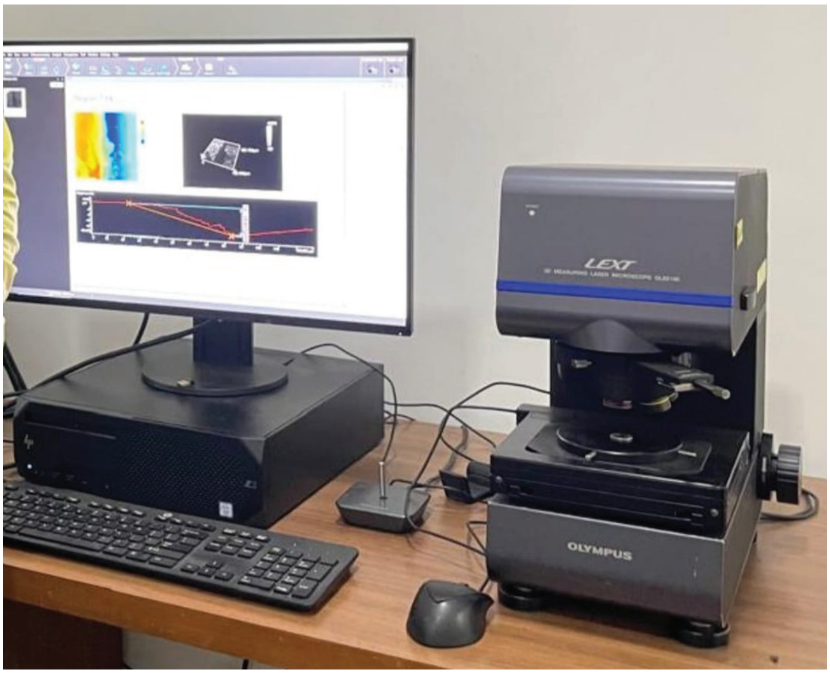
$$\text{S/N ratio= -10}\log_{10}(1/n \textstyle\sum_{i=1}^{n} y2) \qquad (2)$$

where y denotes the unique response of the experimental data and n the number of replications.

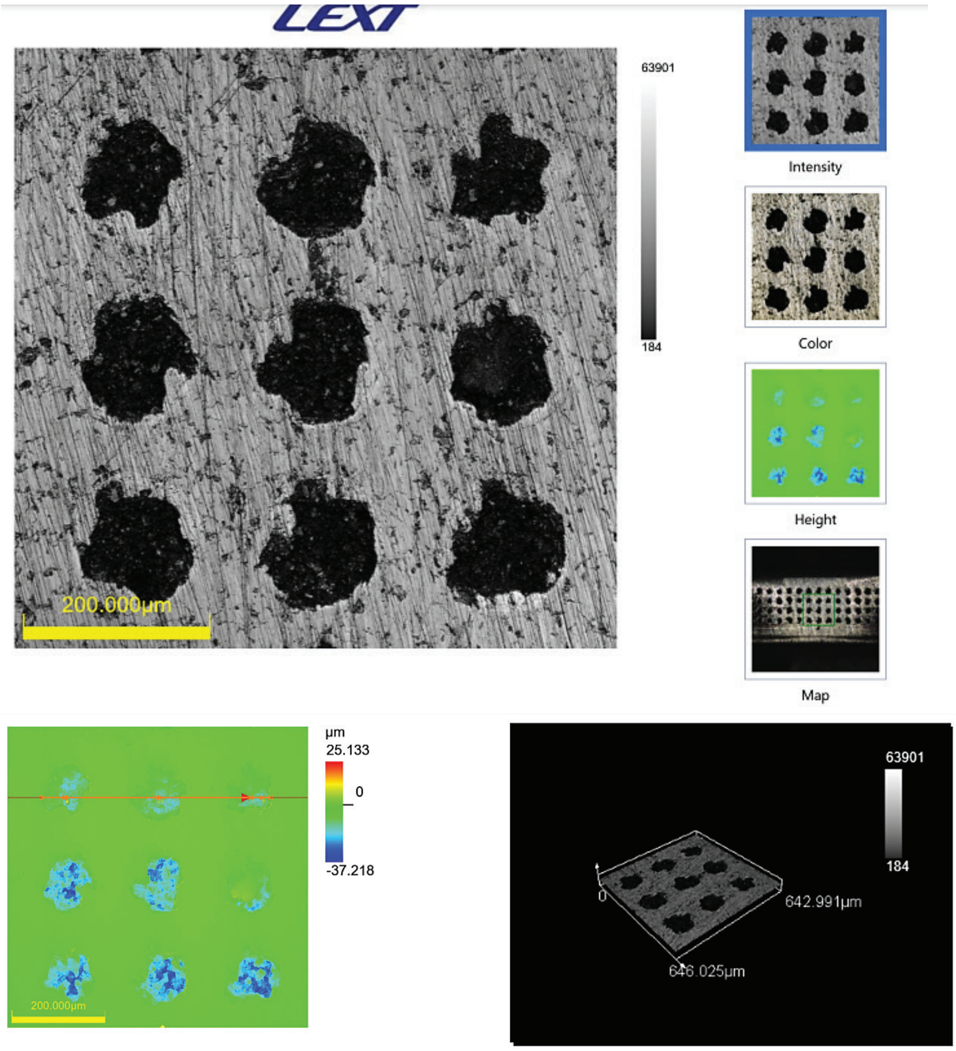
Characterization of the Specimen

An Olympus LEXT5000 confocal microscope was used to analyze the specimens of cast iron piston rings that have gone through laser texturing. The Olympus LEXT 3D OLS5000 is a 0.5 nm resolution high resolution confocal microscope and 3D profiler which has a 54x-17280x magnification and a 16-5120 micron field of view. With a reflection-type confocal laser, it can provide precise, non-contact surface profiling wherein it is suitable to analyze delicate surfaces without faulting them, as opposed to using a depth profiler. This microscope was used to measure the diameter, depth, and roughness of the dimples on the textured surfaces. The confocal microscope set up is illustrated in figure 3(a). We used confocal microscope to examine the topography of the surface of laser-textured cast iron piston rings in our study and this is essential to understand the efficiency of the laser processing parameters. Nevertheless, the original documentation of the topographical review was not detailed enough, which is why we decided to make our results more comprehensible. Confocal microscope was used to image the textured surfaces in 2D and 3D mode that enabled us to comprehensively examine the surface morphology including dimensional features of the dimple that were created by laser. We have created 3D images and this allowed us to visualize the spatial distribution and geometry of the textures, which are important in assessing their effect on the tribological performance of the piston rings. Also, we performed 2D roughness measurements, which quantifies surface properties and the parameters were Ra(average roughness), Rz (average maximum height of profile), and Rq(root mean square roughness). These measurements were important quantitative measurements of the surface finish, which allowed us to work out the correlations between roughness and possible performance under operational conditions. We made the collection of data representative by examining multiple scans on various parts of the surface, and this definition of the data collected any variability in the texture produced by the laser processing parameters. Such a combination of 2D and 3D analysis provided us with an overview of the surface properties and gave credence to the role of the laser processing parameters in our experiments. This elaboration allows us to enhance the methodological soundness of our research, as it helps us to make our work a good contribution to the existing body of knowledge and make the further study of the laser processing applications to different materials possible. Figures 3(b) to 3(d) present confocal microscope images of the piston ring sample textured under controlled conditions, in which the ranges for laser power, frequency, and scan speed were 8 W to 16 W, 15 KHz to 25 KHz, and 80 mm/s to 180 mm/s, respectively.

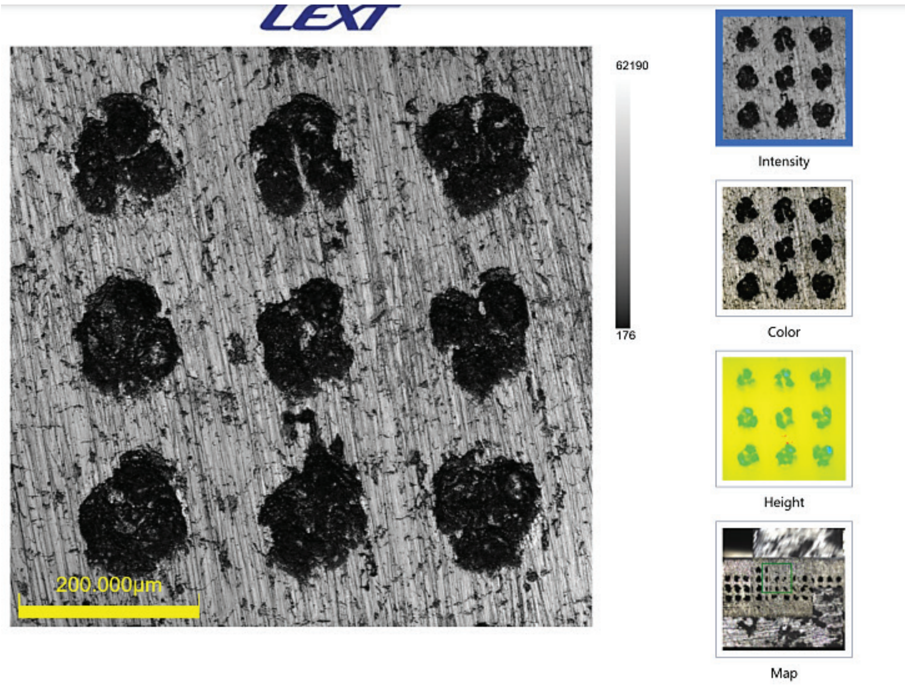
Detailed dimensional data for the specimen textured using these laser processing parameters are provided in Figures 4 to 7, sample readings of dimple diameter and depth for experimental trials 1, 4, and 8 as detailed in Table 3 of the Orthogonal array. The dimple roughness of the surface, averaged over a specific length of the experimental sample, was also measured using the confocal microscope.

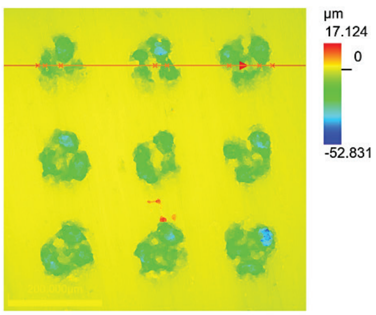


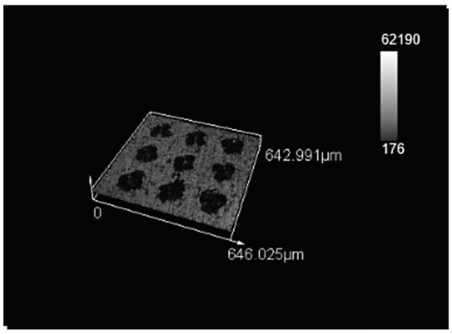
a)



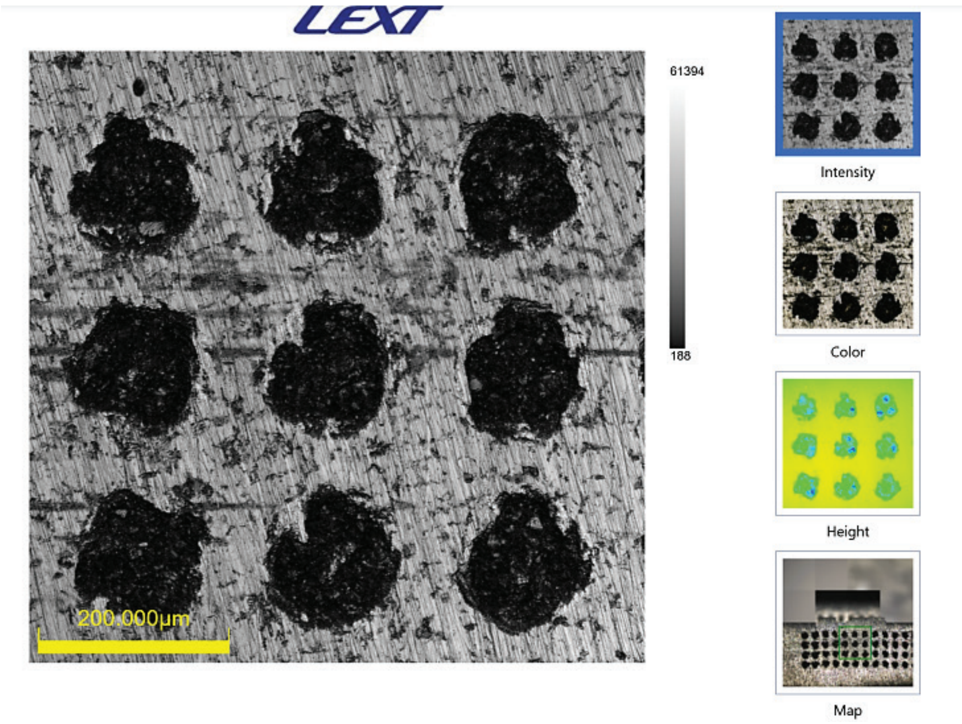
b) 8W, 15 KHz, 80 mm/sec

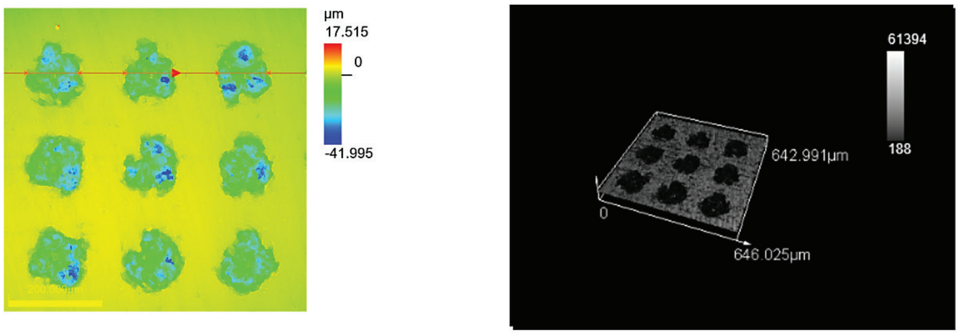






c) 12W, 15 KHz, 80 mm/sec





d) 16W, 20 KHz, 140 mm/sec

Figure 3. Laser Textured cast iron piston ring sample images for different laser process parameters.

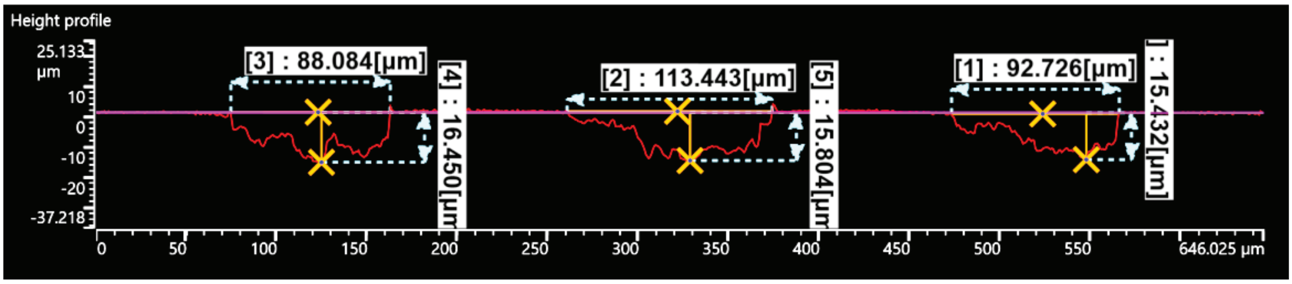


Figure 4. Dimple diameter and depth for textured sample with laser parameters 8W, 15 KHz, 80 mm/sec.

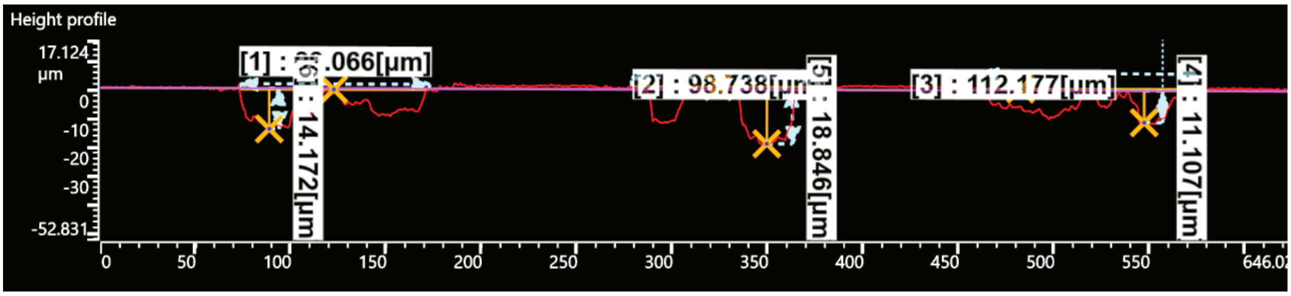


Figure 5. Dimple diameter and depth for textured sample with laser parameters 12W, 15 KHz, 140 mm/sec.

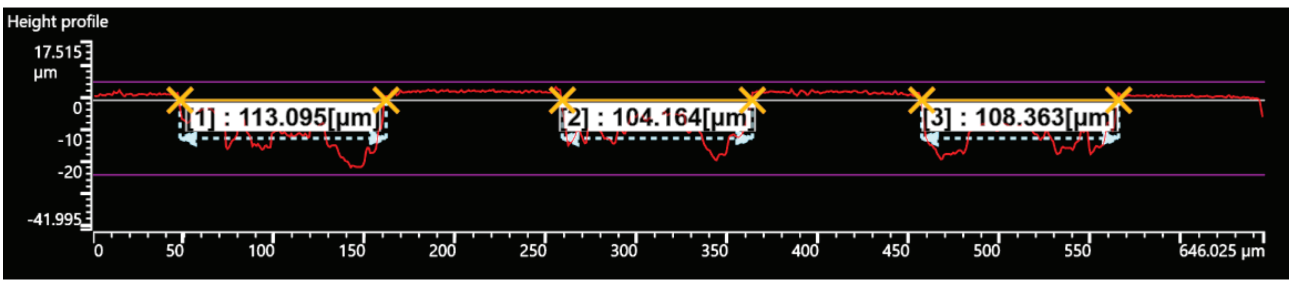


Figure 6. Dimple diameter for textured sample with laser parameters 16W, 20 KHz, 80 mm/sec.

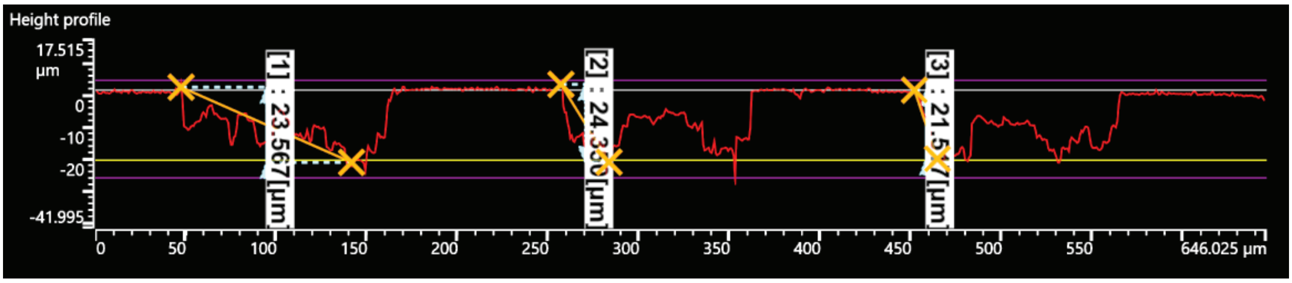


Figure 7. Dimple depth for textured sample with laser parameters 16W, 20 KHz, 80 mm/sec.

RESULTS AND DISCUSSION

Statistical analysis of the experimental data was conducted using Minitab 17. The study aimed to evaluate how laser processing parameters—specifically laser power, frequency, and scanning speed—affect the dimensions of the textured features (specifically the diameter of the dimples, their depth, and the surface roughness) created on the surface of cast iron piston rings. Table 4 provides a consolidated overview of the input parameters used in the 9 experimental runs and the corresponding output responses measured for each run.

The experiment design described in the table explores the relationship between the parameters of the laser processing and the cast iron piston ring dimple properties. The experiment involves three parameters viz. laser power, frequency and scanning speed and each parameter was varied in various experimental runs to observe their effect on the diameter of dimples, depth of the dimples and surface roughness.

Experimental Design Analysis

Laser power

As observed in the data, increased laser power between 8W and 16W is likely to give increased dimple diameter and depth. Indicatively, at power 16W, the dimple diameter and depth increase with the value being 116.782 um and 25.429 um, respectively, as compared to low powers. This is a pattern that indicates the greater power of the laser is involved in deeper and larger dimples.

Frequency

Frequencies that are high are likely to correspond with the more diameters and depth of dimple. Indicatively, the diameter and depth of the dimple at the 25 KHz frequency would be significantly elevated as is the case with the experimental runs 3, 5 and 6. However the effect of frequency with respect to roughness is not so definitive which implies that the frequency affects the diameter and depth but the effect on the roughness of the surface may be secondary or more complex.

Scanning speed

Scanning speed influences dimple sizes ambivalently. Indicatively, as the speed of scanning is slowed (e.g. at 140 mm/sec to 80 mm/sec), so does the depth and diameter of dimples. On the other hand, an increase in the scanning speed seems to reduce the dimple diameter and depth at the expense of increasing roughness. As an example, with

Table 4. Experimental input and output responses with L_9 Orthogonal Array

Expt. No.	Parameters (Input)			Responses (Output)		
	Laser power in watt	Frequency in KHz	Speed of the scanning in mm/sec	Dimple diameter in µm	Dimple depth in µm	Dimple Roughness of the surface in µm
1	8	15	80	98.084	15.895	2.451
2	8	20	140	102.993	16.555	2.525
3	8	25	180	104.03	17.344	2.765
4	12	15	140	102.993	14.708	3.545
5	12	20	180	104.03	17.344	3.434
6	12	25	80	107.507	21.901	4.23
7	16	15	180	107.13	23.069	4.3
8	16	20	80	108.541	23.144	4.23
9	16	25	140	116.782	25.429	4.442

a scanning speed of 80 mm/sec, deeper and larger dimples are created than with high speeds.

The experimental design has been effective in demonstrating the relationship between laser power, frequency and scanning speed with the achievement of intended dimple characteristics. Increasing laser power and frequency are more likely to encourage dimple diameter and depth rather than scanning speed whose measure varies irregularly. Knowledge of these types of behaviors helps in optimizing laser texturing conditions so as to achieve desired dimple profiles which may be essential in improving the performance of cast iron piston rings.

The response and parameters used in this study were informed by the aim of producing as many cast iron piston rings dimples as possible with perfection of the sharp dimples. The justification behind the following is as follows:

a. Parameters

Laser power

Justification: Laser power is an important parameter in laser processing because it directly influences the amount of energy that is applied on the material. Increase in the laser power usually augments the energy level of the laser beam which may cause bigger weldings and bigger dimples. This parameter was selected because it was to test the effect of that parameter on the dimensions of dimples so that the best power settings to apply to get the intended texture properties can be determined.

Frequency

Reasons: The frequency of the laser pulses determines the number of pulses to be applied on a unit time and this determines how the material reacts to the laser. Increased frequencies are able to put more thermal energy into the system, affecting dimple formation. The frequency aspect of the study would enable an evaluation of the degree of change in the rate of energy application on texture aspects.

Scanning speed

Justification Scanning speed determines the speed at which the laser moves across the surface and therefore the amount of energy deposited in each area. Faster scanning rate would mean low exposure time and less energy deposition, which may result in thinner and as well as shallow dimples. It is a parameter that was chosen to examine its effect on the formation of the desired dimple profile and surface finish.

b. Responses

Dimple diameter

Justification: Dimple diameter: This is a significant response as the dimension directly affects the functionality of the texture. Dimple diameter control is required in applications where there is a requirement to have a particular pattern of texture to make the substance more lubricated or less friction. This response can be measured and explicitly controlled in terms of texture profile.

Dimple depth

Rationale: Dimple depth has an impact on the behavior of the surface e.g.: can it retain lubricants or influence wear patterns. The dimension of the depth is essential to determine that the dimples are of the right size as well as possess the right depth to perform their purposes.

Dimple roughness

Justification: The general quality of the textured surface and its performance depend on the surface roughness. It determines friction, wear and retention ability of lubricants. Roughness measurement is done to verify that the surface finish is of acceptable quality concerning its intended application.

The parameters and responses adopted are in line with what the optimization of laser texturing entailed, in order to achieve some dimple characteristics. As the laser power, frequency and scanning speed are varied as well as the dimple diameter, depth and roughness are measured, the research ensures that a holistic examination is done as regards to how the contribution of these factors change to the final texture with the ultimate aim being to greatly customize the surface properties to improve its performance in the industrial processing.The selection to employ merely 9 samples in the project was based on the use of the Taguchi method experimental design, namely the L9 orthogonal array. Here is why this selection was done and why additional samples were not added:

The Taguchi approach aims at enhancing quality and performance with a small amount of experimentation through the utilization of orthogonal arrays. For this research, 3-level design was chosen for every one of the 3 variables (laser energy, frequency, and scanning velocity). For a full-factorial design with 3 variables and 3 levels, there would have been 3^3 = 27 experimental runs, which would involve a lot more time, resources, and expense.

But the L9 array of Taguchi method lets the same 3 factors and 3 levels be investigated with just 9 trials, reducing the number of tests by orders of magnitude while still allowing all factor interaction to be well represented. This reduces the process of experimentation to a more efficient scale without losing the scope for determining the best set of parameters.

More than 9 experiments would necessitate more time and cost in terms of resources. Laser texturing and measuring dimple size (diameter, depth, roughness) after that are complicated processes and equipment. The use of 9 experiments only minimizes the experimental load but not without valuable input into understanding how the input parameters influence the responses.

Practical constraints

Including more samples or trials would have increased the complexity of the study. Practical constraints such as equipment availability, project deadlines, and resource limitations may also have played a role in limiting the number of samples.

Effect of Control Factors

The signal-to-noise (S/N) ratio response tables for the textured features of cast iron piston ring segments, specifically for dimple diameter, depth, and surface roughness, are shown in Tables 5 through 7. As explained in Tables 5-7 [10–13], these tables use delta or rank values to assess how control factors affect these dimensions. The results presented in Tables 5-7 indicate that the most significant factor influencing dimple diameter, depth, and surface roughness is laser power. Laser scan speed has the least bearing on these dimensions, whereas laser frequency comes in second. This analysis highlights that the size of the dimples formed on the piston ring surfaces is primarily determined by the laser power.

Figure 8, 9, and 10 illustrate the optimal laser processing parameters identified for creating textures on commercial piston ring segments composed of cast iron, summarized in Table 8. The results indicate that to achieve a precise dimple diameter in the circular textures on the ring samples, laser power should be set to 16 W, laser frequency to 25 KHz, and laser scan speed to 140 mm/sec. For achieving the desired dimple depth on the cast iron piston rings, the optimal parameters are 8 W of laser power, 15 KHz of laser frequency, and a laser scan speed of 140 mm/sec. Similarly, to attain the targeted dimple roughness of the surface on the studied cast iron piston ring sample, the recommended settings include 8 W of laser power, 20 KHz of laser frequency, and a laser scan speed of 140 mm/sec.

Figure 3-5 shows that while laser scanning speed has a distinct impact on each of these output variables, dimple diameter, depth and roughness of the surface all rise as laser power and frequency increase. Overall dimple roughness of the surface decreases with the increase in laser scanning speed.

ANOVA and Regression Analysis

ANOVA, a statistical technique grounded in the least squares method, is frequently employed to evaluate the effects of experimental parameters like laser power, frequency, and scan speed.

Table 5. S/N response table for dimple diameter

Level	Laser power in watt	Frequency in KHz	Speed of the scanning in mm/sec
1	40.14	40.23	40.39
2	40.41	40.44	40.62
3	40.89	40.77	40.43
Delta	0.74	0.54	0.23
Rank	1	2	3

Table 6. S/N response table for dimple depth

Level	Laser power in watt	Frequency in KHz	Speed of the scanning in mm/sec
1	-24.40	-24.88	-26.04
2	-24.98	-25.48	-25.28
3	-27.55	-26.57	-25.61
Delta	3.16	1.69	0.76
Rank	1	2	3

Table 7. S/N Response table for dimple roughness of the surface

Level	Laser power in watt	Frequency in KHz	Speed of the scanning in mm/sec
1	-8.222	-10.483	-10.947
2	-11.412	-10.429	-10.663
3	-12.716	-11.437	-10.740
Delta	4.494	1.008	0.284
Rank	1	2	3

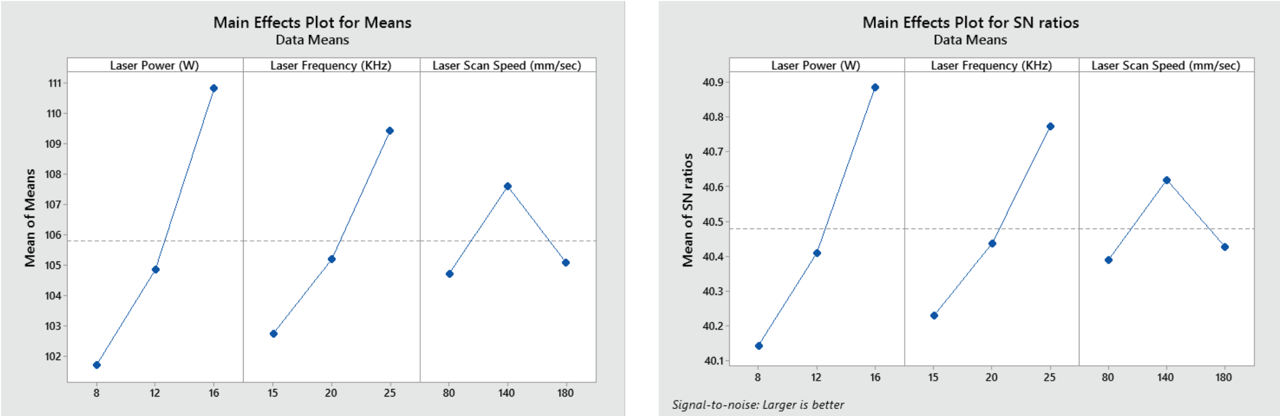


Figure 8. Plot of the main effects for the dimple diameter means and S/N ratios.

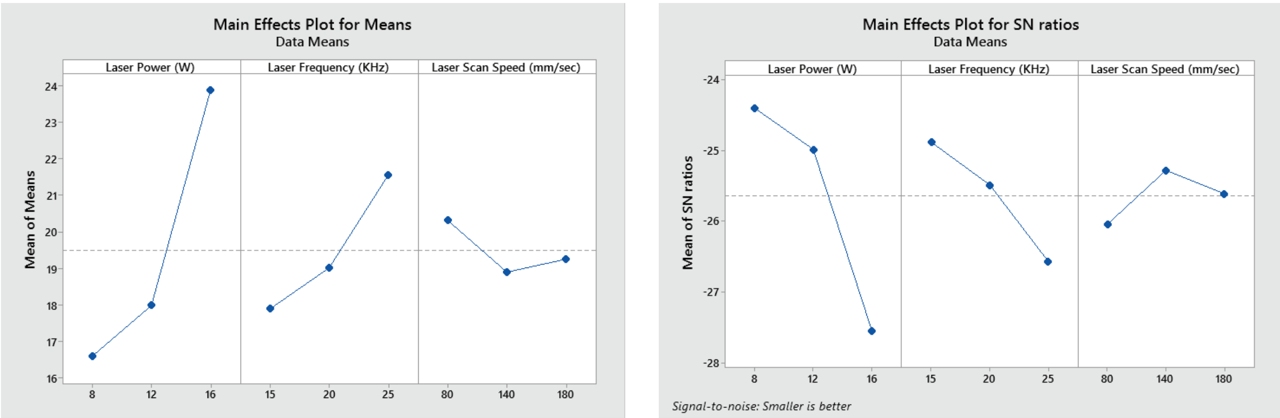


Figure 9. Plot of main effects for dimple depth means and S/N ratios.

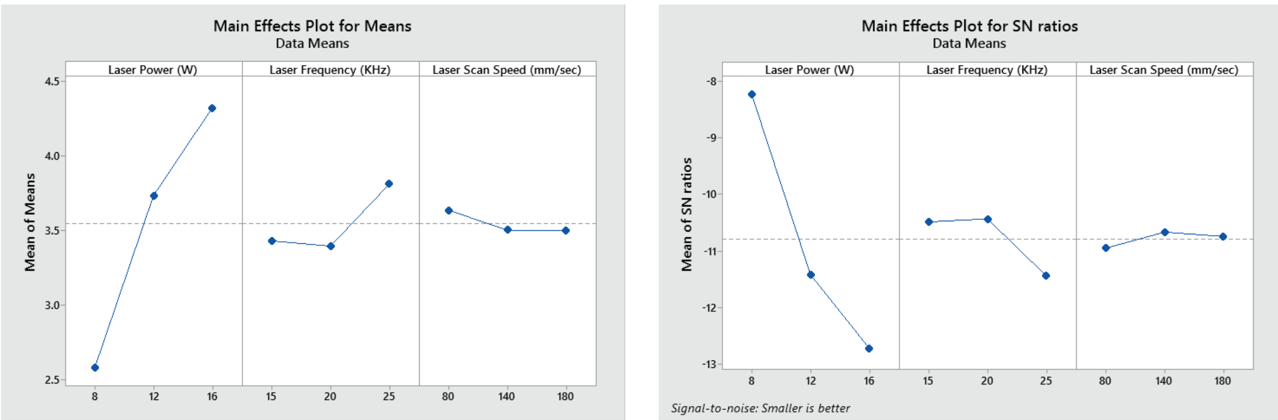


Figure 10. Principal effect plots for the surface dimple roughness's means and S/N ratios.

Table 8. Optimum laser processing parameter

Parameters	Laser power in watt	Frequency in kHz	Speed of the scanning in mm/sec
Dimple diameter	16	25	140
Dimple Depth	8	15	140
Dimple roughness of the surface	8	20	140

Tables 9, 10, and 11 present the ANOVA results for these factors, respectively. Each table includes the percentage contribution of these parameters to the measured responses, along with their significance levels indicated by p-values, where values below 0.05 are considered significant [10]. Table 9 reveals that laser power and laser frequency contributed significantly to the dimple diameter, with percentages of 58.14% and 31.49%, respectively. In contrast, laser scan speed had a minimal effect, contributing only 0.35%. For dimple depth, Table 10 shows that laser power had the highest influence at 65.82%, followed by laser frequency at 16.69%, and laser scan speed at 1.702%. Similarly, Table 11 indicates that laser power had a substantial impact on dimple roughness of the surface, contributing 88.19%. Laser frequency contributed 4.19%, while laser scan speed had the smallest influence at 0.60%. By examining these results, significant factors affecting the output dimensions can be identified based on their respective contributions and p-values.

Regression analysis serves as a tool to establish relationships between observed outcomes and controlled variables in experimental settings. In analyzing the current dataset, linear regression equations were utilized to link measured parameters—specifically dimple diameter, dimple depth, and dimple roughness of the surface—to controlled variables: laser power, laser frequency, and laser scan speed. Below is the regression equations derived from this statistical analysis for these measurable factors. The regression equation for dimple diameter in terms of the input control factors is presented below, where the coefficient of determination (R^2) assesses the goodness of fit of the model. An R^2 value closer to 1 indicates a better fit of the model [10]. The calculated R^2 of 89.94% suggests that the developed model explains approximately 89.94% of the total variance in the dimple diameter. This leaves less than 11% of the variance unexplained by the model. The adjusted R^2 value of 83.91% also supports the model's good fit.

Dimple Diameter (μm) =77.77 + 1.139 Laser Power (W) + 0.670 Laser Frequency (KHz) + 0.0070 Laser Scan Speed (mm/sec)

Similarly, the regression equation for the output parameter dimple depth, considering the input control parameters, is provided below. The coefficient of determination (R^2) for this model is 84.22%, indicating that approximately 84.22% of the total variance in dimple depth is explained by the developed model. This suggests that less than 16% of the variance remains unexplained. The adjusted R^2 value of 74.75% also indicates good agreement and robustness of the model.

Dimple Depth (μm) =2.78 + 0.910 Laser Power (W) + 0.367 Laser Frequency (KHz) - 0.0116 Laser Scan Speed (mm/sec)

Furthermore, here is the regression equation for the output parameter dimple roughness of the surface concerning the input control parameters. The coefficient of determination (R^2) for this model is 93.00%, signifying

Table 9. ANOVA table for dimple diameter

Source	DF (Degrees of Freedom)	Adj_SS (Adjusted Sum of Squares)	Adj_MS (Adjusted Mean Square)	F-Value	p	% Contribution
Laser power (Watt)	1	124.634	124.634	28.91	0.003	58.142
Laser frequency (KHz)	1	67.415	67.415	15.64	0.011	31.449
Laser scan speed (mm/sec)	1	0.752	0.752	0.17	0.693	0.350
Error	5	21.558	4.312			10.056
Total	8	214.360				

Note: S=2.07644 R^2=89.94%, R^2adj=83.91%, R^2pred=70.07%

Table 10. ANOVA table (dimple depth)

Source	DF (Degrees of Freedom)	Adj_SS (Adjusted Sum of Squares)	Adj_MS (Adjusted Mean Square)	F-Value	P-Value	% Contribution
Laser Power (Watt)	1	79.556	79.556	20.85	0.006	65.823
Laser Frequency (KHz)	1	20.174	20.174	5.29	0.070	16.691
Laser Scan Speed (mm/sec)	1	2.058	2.058	0.54	0.496	1.702
Error	5	19.074	3.815			15.781
Total	8	120.862				

Note: S=1.95316, R^2=84.22%, R^2adj=74.75%, R^2pred=44.14%

Table 11. ANOVA table (dimple roughness of the surface)

Source	DF (Degrees of Freedom)	Adj_SS (Adjusted Sum of Squares)	Adj_MS (Adjusted Mean Square)	F-Value	P-Value	% Contribution
Laser Power (Wall)	1	4.56056	4.56056	63.00	0.001	88.194
Laser Frequency (KHz)	1	0.21698	0.21698	3.00	0.144	4.196
Laser Scan Speed (mm/sec)	1	0.03151	0.03151	0.44	0.539	0.609
Error	5	0.36195	0.07239			6.999
Total	8	5.17101				

Note: S=0.26905,R^2=93.00%, R^2adj=88.80%, R^2pred=75.64%

that the constructed model explains approximately 93.00% of the overall variation in dimple roughness. This implies that about 7% of the variation remains unexplained by the model. The adjusted R^2 value of 88.80% also indicates strong agreement and reliability of the model.

Dimple Roughness of the surface (µm) =0.363 + 0.2180 Laser Power (W) + 0.0380 Laser Frequency (KHz) - 0.00144 Laser Scan Speed (mm/sec)

Figure 11 shows the all interaction plots obtained from ANOVA analysis which supports the results.

Figure 12 shows the pair plots of all parameters with other.

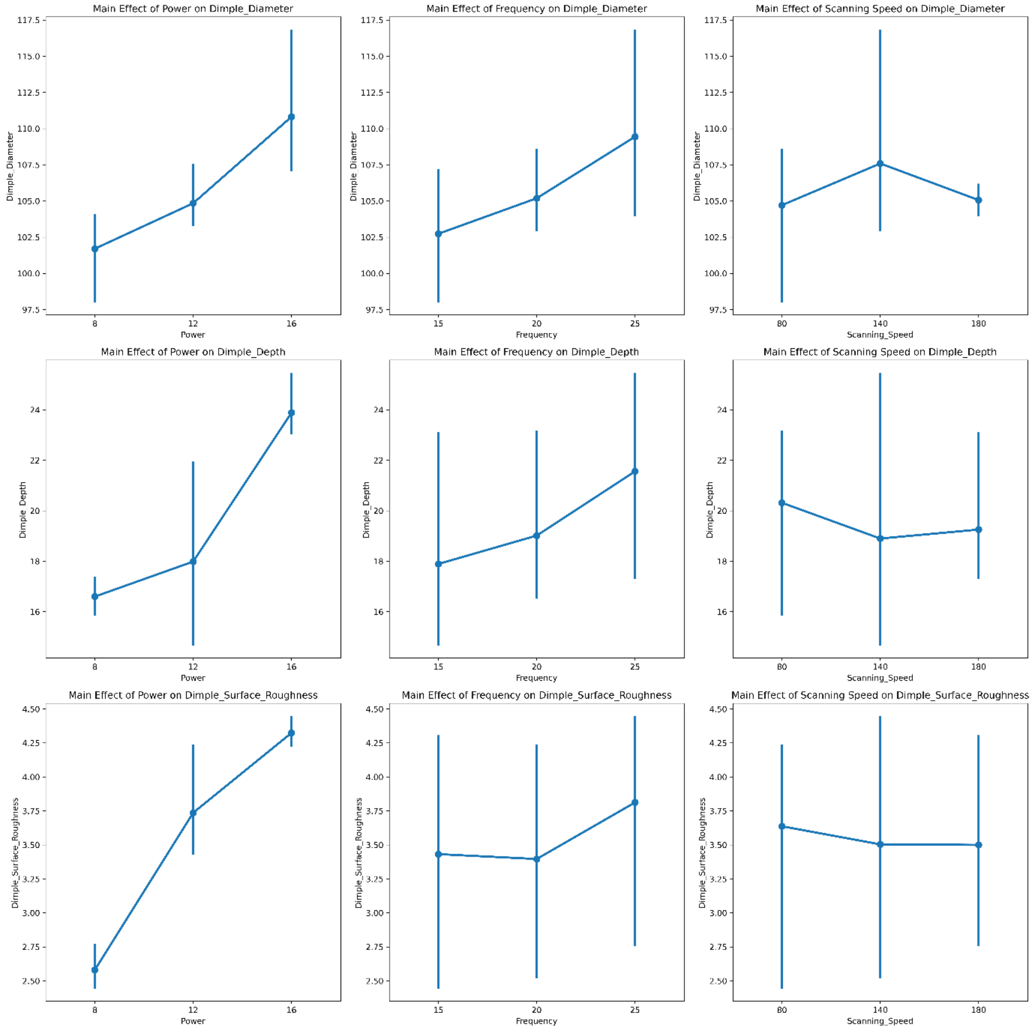
The interaction plots of the ANOVA (Fig. 11) indicate the effect of different parameters of the laser processing such as laser power, frequency and scan speed on the texture properties, such as dimple diameter, depth and roughness. The plots reveal that the largest effect on the size of dimples in a laser light is through the laser power, and the relationship between laser power and both laser frequency and scan speed gives interactions between dimples and laser power, and the relationship between dimples and laser frequency respectively. In the case of laser power variations, dimple diameter variations are mostly affected, although there are complex interactions between frequency and scan speed that affect the overall texture. These results are being supported by the pair plots (Fig. 12) which are the visual display of the relationships between the parameters in pairs. They show the effect of laser power, frequency and scan speed variation on a texture feature and illustrate such trends as increasing sizes of dimples as power and frequency increase. Those plots also imply that scan speed is compounded, it would tend to reduce the roughness of the surface, but with the various levels of power and frequencies.

The combination of these two numbers confirms that laser power is the most notable variable that can influence the size of dimples based on the contribution to the variance in the attributes of texture. ANOVA and pair plots provide a rough depiction of the combined effect of all the parameters and their interactions in creating the final texture to be able to finely-tune the process of laser texturing. The last step of the Taguchi analysis is the confirmation experiments for verifying the experimental data with the calculated outcomes obtained from regression analysis [15-17]. Table 12 shows the results of the confirmation studies that examine dimple diameter, dimple depth, and dimple roughness of the surface through regression equations to predict values based on the experimental data obtained. The verification experiments were performed under the optimal parameters found using Taguchi analysis: 16 W, 25 KHz, and 140 mm/sec for dimple diameter; 8 W, 15 KHz, and 140 mm/sec for dimple depth; and 8 W, 20 KHz, and 140 mm/sec for surface dimple roughness.

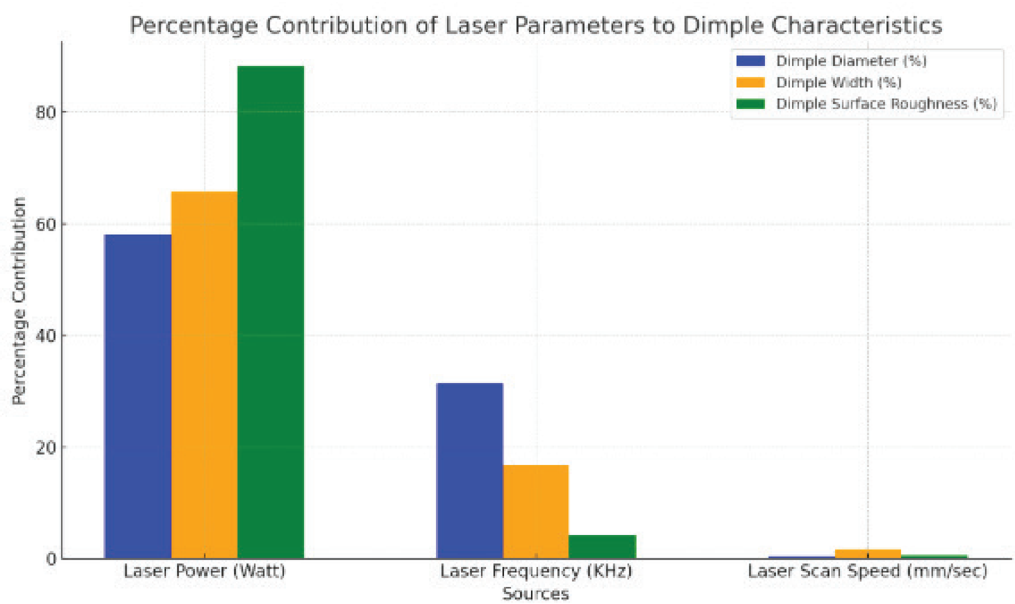
The outcome from the optimization of the laser surface texturing on cast iron piston rings, with regression equations analyzed, has a high degree of accuracy in the experiment and predicted values for dimple diameter, depth, and surface roughness. For the diameter of the dimple, with the optimum values of 16W, 25 KHz, and 140 mm/sec, the experimental value of 98.08 µm is almost the same as the calculated value of 98.57 µm, with an error of just 0.5%. This small error points to the accuracy of the regression equation to estimate the dimple diameter from the provided laser parameters. The depth of the dimple, with best parameters of 8W, 15 KHz, and 140 mm/sec, has an experimental result of 15.89 µm versus the predicted value of 16.24 µm, for a very small error of 2.2%. Although the deviation remains within acceptable limits, this implies that dimple depth might be less tolerant to variations in material properties or laser-material interaction during processing, which might cause the slight difference.

In the case of dimple surface roughness, the optimal values of 8W, 20 KHz, and 140 mm/sec gave an experimental result of 2.19 µm, whereas the calculated result was 2.24 µm, causing an error of 2.28%.

Surface roughness generally depends on smaller aspects of laser-material interaction and thus becomes prone to minute changes in experimental conditions. However, the low error rate shows that the regression model performs well in terms of predicting surface roughness with high accuracy.



A)



B)

Fig. 11A), Percentage Contribution of Laser parameters, B)ANOVA Interaction Plots of all parameters.

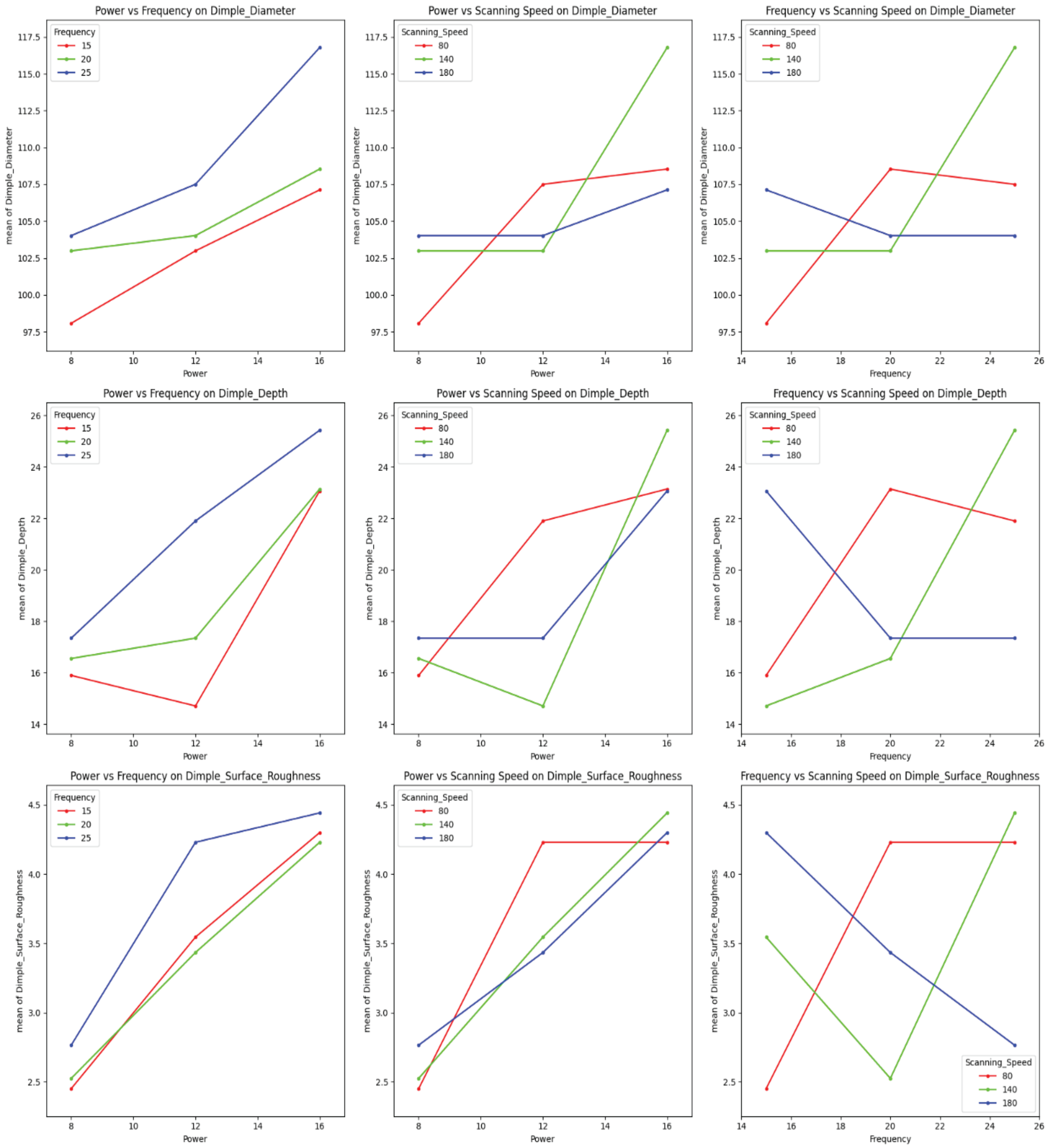


Figure 12. Pair plots of all parameters with each other.

Table 12. Confirmation Experiments for output responses

Responses	Optimum parameters	Experimental results	Predicted results by regression equations	Error (%)
Dimple diameter	16W, 25KHz and 140 mm/sec	98.08	98.57	0.5%
Dimple depth	8W, 15 KHz and 140 mm/sec	15.89	16.24	2.2%
Dimple roughness of the surface	8W, 20 KHz and 140mm/sec	2.19	2.24	2.28%

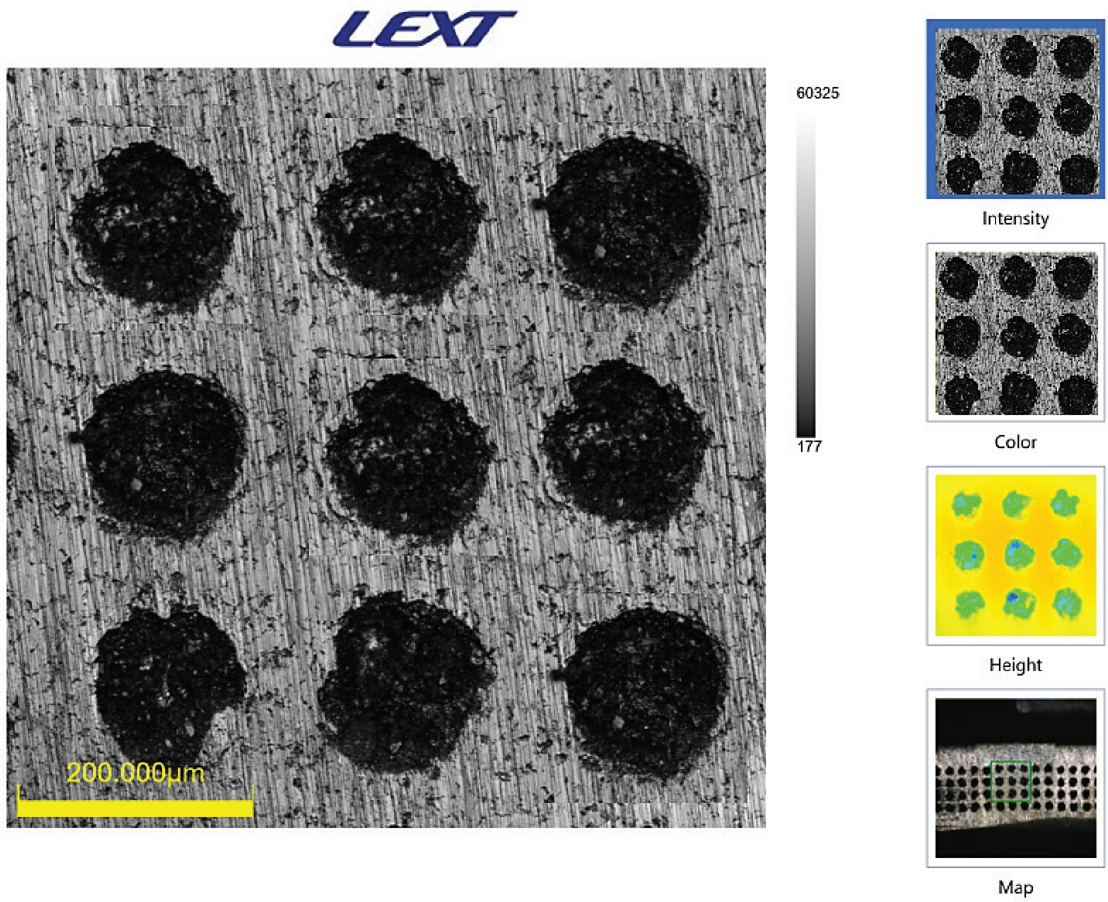


Figure 13. Laser textured cast iron piston ring sample images for 16W, 25 KHz and 140 mm/sec.

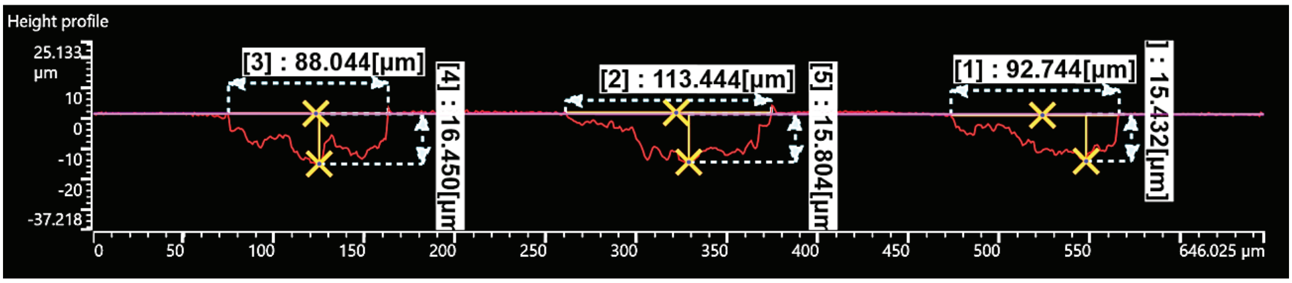


Figure 14. Dimple diameter and depth for textured sample with laser parameters 16W, 25 KHz and 140 mm/sec.

In addition to the quantitative analysis, Fig. 13 showcases the laser-textured cast iron piston ring sample images for the optimum parameters of 16W, 25KHz, and 140 mm/sec. The figure clearly illustrates the circular dimples, which are formed with high precision and accurate dimensions. The optimal parameters used ensure that the dimples are uniform, highlighting the effectiveness of the laser settings in achieving the desired texture.

Furthermore, Fig. 14 presents the dimple diameter and depth for the textured sample, using the same laser parameters (16W, 25 KHz, and 140 mm/sec). The figure confirms that these parameters result in consistent and well-defined dimple features, validating the accuracy of the regression model in predicting the dimple characteristics. Both figures support the conclusion that the optimized parameters produce high-quality surface texturing, with minimal error between experimental and predicted results.

Multi-objective Optimization Using the Gray Relational Grade (GRG) Rank Method

To perform multi-objective optimization using the Gray Relational Grade (GRG) rank method, we need to follow several steps:

1. **Normalization of data**: Normalize the data for each criterion to ensure that they are on a comparable scale.
2. **Calculation of gray relational coefficients (GRC)**: Determine the GRC for each experiment based on the normalized data.
3. **Calculation of gray relational grade (GRG)**: Compute the GRG by averaging the GRCs for each experiment.
4. **Ranking**: Rank the experiments based on the GRG.

Normalization of Data

The normalization of data can be done using the following formulas:

- For beneficial criteria (higher values are better):

$$Xi= \frac{Xi-Xmin}{Xmax-Xmin} \tag{3}$$

For non-beneficial criteria (lower values are better):

$$Xi= \frac{Xmin-Xi}{Xmin-Xmax} \tag{4}$$

Let's start by normalizing the data. For the given dataset, we will assume the following:

- Beneficial criteria: Dimple Diameter, Dimple Depth.
- Non-beneficial criteria: Dimple Roughness.

Calculation of Gray Relational Coefficients (GRC)

The GRC is calculated using the normalized data:

$$GRC= \frac{\Delta min+\xi\Delta max}{\Delta i+\xi\Delta max} \tag{5}$$

where Δi is the absolute difference between the reference sequence and the comparative sequence, Δmin and Δmax are the minimum and maximum values of Δi and ξ is the distinguishing coefficient (usually set to 0.5).

Calculation of Gray Relational Grade (GRG)

The GRG is the average of the GRCs for each experiment:

$$GRG=\frac{1}{n}\sum_{i=1}^{n} GRG_i \tag{6}$$

where n is the number of criteria.

Ranking

Rank the experiments based on the GRG.

The multi-objective optimization performed by the use of the Gray Relational Grade (GRG) process gives the overall ranking of the experiments in terms of the performance criteria of dimple diameter, dimple depth, and dimple roughness. The experiment with the highest GRG of 0.77777878, 16 watts of laser power, 25 KHz frequency and 140 mm/sec speed was ranked first in Experiment 9. The maximum dimple diameter (116.782 um) and the maximum dimple depth (25.429 um) were obtained in this experiment and the roughness was relatively high (4.442 um). Experiment 2 was second with a GRG of 0.570483 with the use of laser power of 8watts, frequency of 20 KHz and a speed of 140mm/sec which gave an average dimple size and minimum roughness of all the experiments. Experiment 1 has a GRG of 0.56441 close behind in third place, and with a laser power of 8 watts a frequency of 15 KHz and a speed of 80 mm/sec. The other experiments recorded different results with Experiment 4 recording the lowest GRG of 0.404606 and was positioned in position 9. The power of the laser used in this experiment was 12 watts, the frequency was 15 KHz, and the speed was 140 mm/sec, which yielded a moderate size of dimples but a comparatively high level of roughness. The rankings have shown that the greater the laser power and frequency combinations especially at moderate speed that the greater the overall performance in terms of the desired dimple characteristics.

Table 13. Results of Multi-objective optimization using the gray relational grade (GRG) rank method

Expt. No.	Laser power (Watt)	Frequency (KHz)	Speed (mm/sec)	Dimple diameter (µm)	Dimple depth (µm)	Dimple roughness (µm)	GRG	Rank
9	16	25	140	116.782	25.429	4.442	0.777778	1
2	8	20	140	102.993	16.555	2.525	0.570483	2
1	8	15	80	98.084	15.895	2.451	0.56441	3
8	16	20	80	108.541	23.144	4.23	0.530477	4
3	8	25	180	104.03	17.344	2.765	0.527303	5
7	16	15	180	107.13	23.069	4.3	0.512107	6
6	12	25	80	107.507	21.901	4.23	0.487958	7
5	12	20	180	104.03	17.344	3.434	0.441618	8
4	12	15	140	102.993	14.708	3.545	0.404606	9

Figure 15 shows the Experiment ranking by GRG method

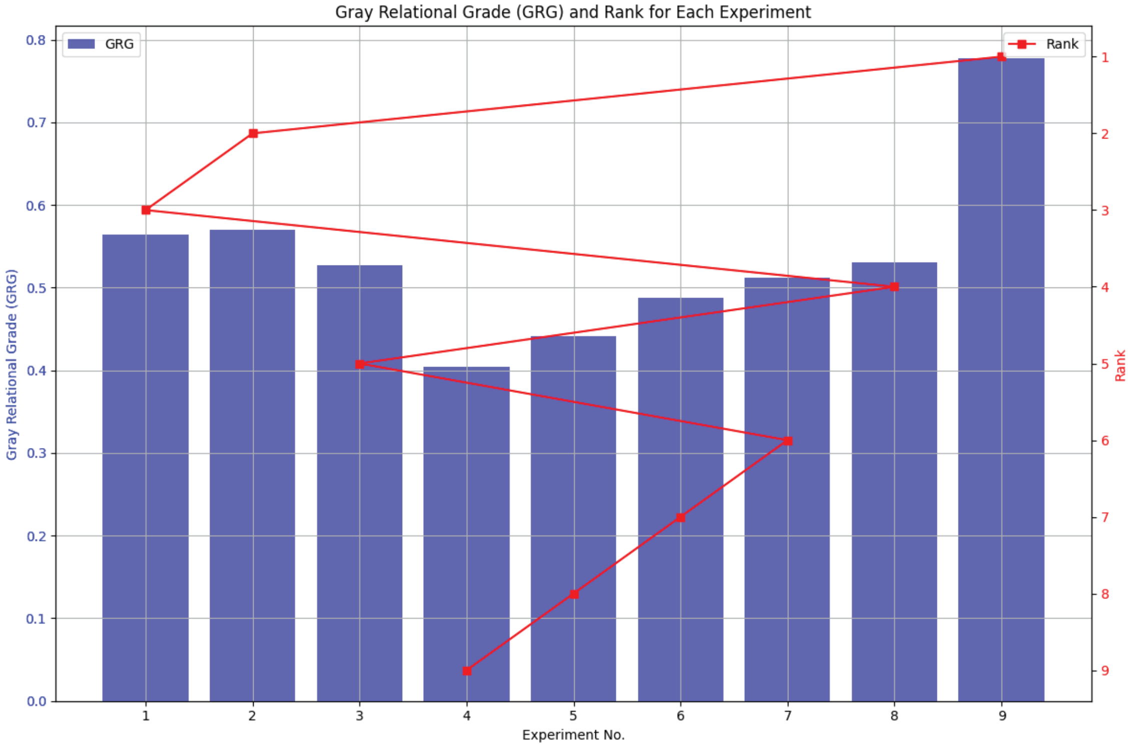


Figure 15. Experiment ranking by GRG method.

The results of the present research have the potential to be used in other materials other than cast iron. Here's how:

General rules of laser texturing

Laser surface texturing principles including laser power, frequency and scan speed optimization are very general to different materials. Parameters can be optimized in a way to adapt the study to other substrates by modifying the parameters to the material characteristics.

Material-specific adjustments

Although the experiment used cast iron, the process can be applied to other materials in that one should perform comparable experiments to find out the best laser parameters in the material. As an example, laser power or frequency may have to be varied to obtain the required dimple sizes and quality of the surface using different materials.

Test and validation

In an attempt to generalize the findings on other materials, one must conduct more tests and validation. This entails modification of the experimental apparatus to reflect the physical and thermal characteristics of the new material including thermal conductivity, melting point and absorption properties.

Scaling and transferability

Taguchi analysis and gray relational grade (GRG) are the optimization methods employed in the given study that can be applied to various materials. The systematic variation of the parameters and investigation of their influence on the characteristics of texture could be applied and modified to new materials.

Material-specific research

In order to be able to use it in practice, the material-specific research should be continued to know how the material reacts to the laser processing. The study would aid in narrowing down the parameters and seeing to it that the texturing of the surface is attaining the targeted results.

The laser surface texturing can be optimized and has a number of unlimited applications at the industrial level:

Improved tribological performance

Piston Rings in Internal combustion engines: Rough surfaces on the piston rings can have a huge impact on wear resistance and friction levels in the engine, which result in reduced fuel consumption, emissions, and engine life. Direct metal-to-metal contact can be reduced by laser surface texturing of piston rings and this increases their resistance to high pressures and temperatures. This application would have some advantages to the automotive industry, whereby it would enhance efficiency of the engines and minimize frequent maintenance.

Enhanced bonding and coating

Coatings in Automotive and Aerospace Components: Laser-textured piston rings or other engine parts can work to enhance coating adhesion of other types of anti-corrosion or wear-resistance coating. These textured surfaces have superior mechanical interlocking of the coating to enhance their functionality and durability. This technique may be useful in the aerospace sector where parts have to be robust, such as high-speed friction and thermal loads, such that they are more likely to last longer, e.g., turbine blades and cylinder line.

Biomedical implants

Surface Texturing of medical devices: The principles of laser surface texturing that you are researching can be applied in biomedical implants, i.e., orthopedic joint replacement surgery or dental implantation. It is possible to develop micro or nano-scale textures on the surfaces of implants, which improves the mechanical connection of the implant with the bone, facilitating a faster and more successful process of osseointegration. This method has been especially beneficial in the medical sector where successful patient recovery and long-term success is reliant on the functionality of the implant.

Precision Engineering

High-precision components in electronics

Electronic and optical components Electronic and optical components can be made with textured surfaces at high precision, where the quality of the surface can make or break performance. The precision engineering of textured surfaces in precision optical lens design, semiconductor devices, or a micro-electromechanical system (MEMS) can be optimised in terms of functional performance, such as light reflection, flow control, and heat dissipation.

Functional surface design

Heat exchangers and fluid handling: In any industry where surface texture of parts such as heat exchanger fins or fluid handling systems is optimized this can improve heat dissipation or fluid friction. An example would be the texturing of the heat exchanger plate surfaces to improve thermal performance of the system by providing more area to the heat transfer resulting to more efficient cooling and use less energy to run the industrial processes.

Overall, the study offers a good methodology to texturize the surface of lasers, but its extension onto other materials needs to be experimented upon with a greater number of changes in parameters to suit the specific characteristics of materials.

To be able to compare trials and results, we undertook a comparative study with the available studies that have investigated such methodologies of laser surface texturing.

1. Wang et al. concentrated on the efficiency performance of axial piston motor with laser-textured valve plates. Their results suggested a 2.8-6.1 per cent all-around enhancement of efficiency in the presence of micro-dimples, with special focus on the impact of such a change on the fluid dynamics at pressure pulsations. Although our research focuses on cast iron piston rings, we find ourselves in agreement with Wang et al. in terms of the positive effects of micro-dimple scale in enhancing the mechanical performance, as laser texturing is capable of being a process of universal benefit to an array of applications [33].
2. In their study on the impact of lasers processing parameters on the texture dimensions in cast iron piston rings, Patil et al. met the target dimensions of 100 um in diameter, 20 um in depth, and 3 um in surface roughness in the target samples. Their findings showed that laser power and frequency played a significant role in determining texture characteristics, although our research agrees with this result by finding the best parameters of 116.782 um dimple diameter, 25.429 um depth, and 4.442 um roughness. The differences of the best results could be related to the differences in the experiment settings, and the parameter tuning in the special material use could be crucial [34].
3. Regarding the methodology, our study, as well as the research mentioned, had used the Taguchi method of optimizing the parameters of laser processing. This pattern of consistency justifies the usefulness of the Taguchi design to enhance the result of surface texturing of various materials and applications[7]. Moreover, our use of the Gray Relational Grade (GRG) technique gave us a useful ranking mechanism that helped us to make our analysis effective than conventional methods [35].
4. Our results also show that the laser power was the most impactful variable in all responses, and ANOVA analysis proves this argument. This observation is similar to the findings made by Patil et al. in the context of the importance of the laser parameters, and the idea that laser processing plays a critical role in the attainment of desirable surface properties.
5. The optimization of high-power fiber laser cutting was done by Lopez et al. [36] in the case of nuclear decommissioning. Their paper has discussed the efficiency and safety of the processes when using a high-power laser. Turkkan et al. [37] applied the multi-objective optimization of fiber laser cutting of stainless steel plates using Taguchi-based grey relational analysis. They enhanced the quality of cutting through optimization of several process parameters. Azaman et al. [38] did a test on the feasibility of harvesting oil palm with a pulse fiber laser system with the help of various lenses. Their study showed that there is a possibility of using the laser technology in the agricultural industry, which is harvesting. In the study, Kasman, S., Buyuker, B., and Ozan, S. (2023) are interested in machining of Ti-6Al-4V alloy through fiber laser technology and the impacts of various process parameters on the surface roughness. Their results show that, surface roughness tends to increase with a higher laser power, whereas surface quality with higher cutting speeds tends to be good. Optimal focal

position adjustment is also essential in getting required surface finishes. This paper contributes to the knowledge of laser machining parameters and can be effectively utilized in the optimization of surface quality to be applied in high performance. The contribution of the work is the development of laser machining technologies of Ti-6Al-4V alloys [39].

The comparative analysis highlights the applicability of using laser texturing of the surface as a material performance enhancement method. The observed differences and similarities between our results and those provided in the literature literature themselves indicate the need to conduct more research and optimization according to particular materials and applications [4]. The combination of the results of these investigations highlights the potential of laser texturing as a kind of transformation in many industrial applications, including auto-parts or even in a highly accurate engineering setting [11].

CONCLUSION

This research was able to examine the influence of the laser processing parameters in this case, power, frequency, and scan rate of the laser on the accuracy of texturing surfaces on cast iron piston rings. Optimal parameter combinations were determined using the Taguchi design method and multi-objective optimization based on gray relational grade (GRG) ranking to obtain the desired dimple dimensions, i.e. diameter, depth and surface roughness. Of the parameters, laser power was determined to have the most dramatic effect on the resultant dimple dimensions with frequency and scan speed also playing a role in the overall quality of the texture.

The results of the analysis demonstrated that the general tendency in the increases in laser power and frequency was larger dimple dimensions, whereas scan speed demonstrated a less general relationship with surface roughness. The ANOVA study offered a significant numerical measure of the significance of each parameter to the texture attributes, which can be useful in enhancing laser processing methods. Such conclusions demonstrate the usefulness of the selected techniques to attain accurate and reproducible surface textures, which play a significant role in promoting the tribological behavior of piston rings and other mechanical parts.

Although the research was done on cast iron, the methodologies are applicable to most materials to extrapolate the research to an industry setting. Future research such as the extended range of laser parameters, the combination of more sophisticated surface characterization methods, and the study of the long-term behavior under real-life conditions are also anticipated based on the research. In addition, laser texturing may be used together with other surface treatments to further increase the material characteristics and functionality.

Summarily, the findings of this research give a detailed methodology of maximizing the parameters of laser surface texturing, which have many implications in industry where high accuracy in surface features is necessary. This study will enhance the current research on the enhancement of advanced manufacturing processes to satisfy the requirements of the modern engineering applications by increasing the durability and efficiency of the elements, like piston rings.

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AUTHORSHIP CONTRIBUTIONS

AP: conceptualization, investigation, PB: resources, Methodology, investigation, visualization writing original and revised draft, US: revised draft, PK: supervision and project administration, VW: investigation, visualization writing original and revised draft. All authors have read and approved the manuscript.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

STATEMENT ON THE USE OF ARTIFICIAL INTELLIGENCE

Artificial intelligence was not used in the preparation of the article.

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