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Laser Cleaning of Grey Cast Iron Automotive Brake Disc: Rust Removal and Improvement in Surface Integrity

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There is a great need for removal of rust and surface damage from corroded engineering parts. This enables the retention of strength and increased longevity of metals and alloys in general. The use of lasers for cleaning, polishing and ablation has proven to be effective and promising overtime. This research is focused on a parametric study of laser cleaning a corroded grey cast iron brake disc. A continuous wave CO_2 laser having a wavelength of 10.6μm was used for the study. A systematic approach was employed for the experiments where one parameter was changed while other parameters remained constant. Additional effects of laser cleaning were predicted by a Gaussian process regression approach. The results revealed that the best parameters which cleanly removed the rust were 60W of laser power, 900mm/s traverse speed, and a spot size of 722μm. The enhancement of surface microhardness of laser cleaned specimen was 37% compared to the rusted specimen surfaces. The roughness of the laser cleaned surface was, 1.29μm while the rusted surface comprised of 55.45μm (Ra). Microstructural analysis showed a presence of randomly distributed graphite flakes surrounded by a pearlitic matrix containing ferrite and cementite after laser cleaning. This was similar to that of the un-rusted surface. The hardness, roughness and microstructural content were in close relation with the respective properties of the un-rusted automotive brake disc. This showed that the mechanical and physical properties of the brake disc were not altered negatively during the

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laser cleaning process. Implementation of the laser-cleaning technique in automotive and manufacturing industries should be embraced as it provides a faster, safer and cheaper way of enhancing the surface integrity of components and also paves way for other surface enhancement methodologies to be applied such as blast cleaning or laser shock cleaning for inducing extra strength, by beneficial residual stresses.

Keywords: Cast iron, laser cleaning, laser polishing, ablation, corrosion, surface integrity, automotive, brake disc

1 INTRODUCTION

1.1 Overview

Rusting is an unavoidable natural phenomenon that has been a global menace for ages. This has caused so much damage overtime ranging from crude farm tools to valuable historical artefacts, modern-day industrial, engineering and domestic parts made from metals and alloys. The annual cost of corrosion worldwide is $2.2 trillion which is over 3% of the world GDP [1]. This brings the need to counter/remove rust. Over the years, rust removal has evolved from a more primitive technique that includes scrubbing, the use of white vinegar, salt, lime, baking soda to the use of chemicals and other modern rust removal techniques [2]. These techniques are less effective and consumes both time and energy. There is therefore an increasing need to use effective and quicker ways of removing rust which has led to the use of industrial lasers.

Metals and alloys are used in our day-to-day activities be it domestic, automobile or industrial. These metals and alloys are constantly exposed to the surrounding which acts chemically on it causing degradation of its part leading to corrosion [3]. Corrosion is a chemical or electrochemical reaction that causes the disintegration of an engineering material [4]. Rusting is specific to iron and its alloys [5]. It occurs when iron reacts with moist air or water to form iron oxide [6]. Therefore, rusting leads to a decrease in the performance, life span and failure of engineering materials [7]. Since rust affects irons and its alloys in which cast iron falls into that subset of metals, a brake disc made of cast iron was used as a case study for this research with the aim of the obtaining the optimal laser parameters that are most suitable for the removal of rust from metals and alloys.

1.2 Research background

Laser cleaning involves the removal of rust/corrosion from the surface of metals [8]. It involves the removal of debris, contaminant and impurities (silicon or rubber) by laser irradiation [9]. Varieties of industrial laser cleaning applications are done using a pulsed fibre laser with high repetition rate, short pulse and high peak power [10]. During the process of laser cleaning, it is necessary that the physical and mechanical properties of the base metal are not modified [11].

Similar research on laser cleaning of corroded layers due to environmental pollution on metallic objects showed that the rate of laser ablation increased with increasing laser fluence [12]. They suggested the fluence should be within the ablation domain, that is, greater than the vaporization threshold but less than the saturated domain [12]. The base metal is affected once it reaches the saturated domain [13]. Zhenyong *et al.* [14] gave a similar viewpoint to Siatou *et al.* [12], but argues that the cleaning efficiency of a pulsed Nd: YAG laser is better than that of the CO_2 laser. They further explained that the high laser absorbency of rust particles plays a vital role in the cleaning mechanism [15]. Irrespective of the preferred use of pulsed lasers over continuous wave CO_2 lasers for cleaning, a successful rust removal process can still be carried out [16]. Also, proper laser cleaning does not damage the metal substrate nor negatively alter its mechanical properties and microstructure [16]. Kane [17] suggested that most cleaning processes are unique and the best parameter for cleaning is to find the correct balance between the power, wavelength, spot size and traverse speed. The effect of laser cleaning on a metallic part's hardness, microstructure and surface roughness was previously reported [18].

Creek [19] suggested that rust reduces the hardness and strength of metals. As the amount of rust reduces, hardness increases. A review of laser cleaning and its effect on the vertical variation over a measured distance (surface roughness) showed that when the average surface roughness increase (more than the wavelength of the laser), absorption also increased [20]. For a smooth surface, where average roughness is less than the laser's wavelength, the absorptivity would reduce [20]. Przestacki *et al.* [21] in the research of cleaning superficially corroded metals by CO_2 lasers found the Ra value to be 1.75μm. Adebayo [22] found in a research on the relationship between graphite flake sizes and the mechanical properties of grey cast iron that a large, closely-packed flake reduces the strength as well as the hardness. However, Holtzer et al. [23] reported that the presence of a larger flake size increases the ease of machining, good dampening capacity and dimensional stability.

1.3 Research rationale

The global annual cost of corrosion damage is 2.5 trillion USD [24] . This value was approximately 3.4% of the world's GDP. Around 15 to 35% (375 to 875 billion USD) of that cost could be saved globally if corrosion prevention was implemented [25]. In 2002, the United States Federal Highway Administrator (FHWA) released a two-year research on the direct cost of metallic corrosion in nearly every U.S industrial sector [26]. These affected sectors include: manufacturing; production; infrastructures; transportation; aerospace; automobile and many more [26]. Koch *et al.* [26] *via* a study on corrosion cost and preventive strategies, that the annual direct cost of corrosion was estimated at a staggering 276 billion USD which is 3.1% of the nation's gross domestic product. The production and manufacturing sector accounted for 17.6 billion USD which is quite large. The transportation sector accounts for 21.5% (29.7 billlion USD) of the total cost [26] . From these case studies, there are key reasons that justifies the need for this research. In particular, laser rust removal helps to decrease the cost of replacing and maintaining metallic engineering parts [27, 28]. The life-span of metallic engineering components can be greatly increased using laser rust removal technique. It also increases profitability and productivity in manufacturing industries by saving production and maintenance time and prevents sudden failure of parts. Controlling corrosion and rusting also ensures the mechanical and physical properties such as hardness, surface roughness, the microstructure is retained even over its life-span post laser cleaning. Furthermore, since rusting occurs naturally, it helps to reduce and control its effect to the barest minimum. Laser-based industrial processes exist for removal of rust, however, very little published work addresses the fundamental effects of laser material interaction post laser cleaning, particularly, for automotive brake disc which is a novel application. This work not only aims to address the parameters appropriate to remove rust/corrosion from an automotive grey cast iron component, but also aims to improve the surface integrity of the component for longer functional life, and reduced maintenance costs.

1.4 Mechanism of rust removal

The process of removing material from a metallic surface through laser irradiation can be achieved through various mechanisms [29]. These mechanisms can be grouped into three major groups that are evaporation processes (ablation and selective vaporization), impact processes (dry and steam cleaning, spallation, photon pressure, and evaporative pressure) and vibration processes (angular laser cleaning and transient thermal heating) can also act as a remedy for cleaning surfaces [30]. The mechanism of laser rust removal using CO_2 laser was based on stimulated emission phenomenon, heating, absorption, melting, and vaporisation. The rust deposition was a thin loose transition layer which was removed with the laser irradiation. This layer is mainly made of Fe_2O_3 and Fe_3O_4 particles [16], as the rusted surface is exposed to high laser power, a laser-absorptive field is naturally formed. This was achieved by the breaking down and ionization of the plasma above the surface. At the same time, the output temperature is above the melting point of the rust particles [18]. The laser energy absorbed is transformed into air or plasma intrinsic energy [16] as shown in Figure 1. In relation to the temperature, the surface absorbs laser power leading to enthalpy (equal to the internal energy of the system plus the product of pressure and volume). The corroded surface is removed since the surface temperature is greater than the vaporisation temperature of the material [31]. Other laser cleaning procedures, include; shot blasting, blast cleaning and shock laser cleaning [32 - 34]. These processes

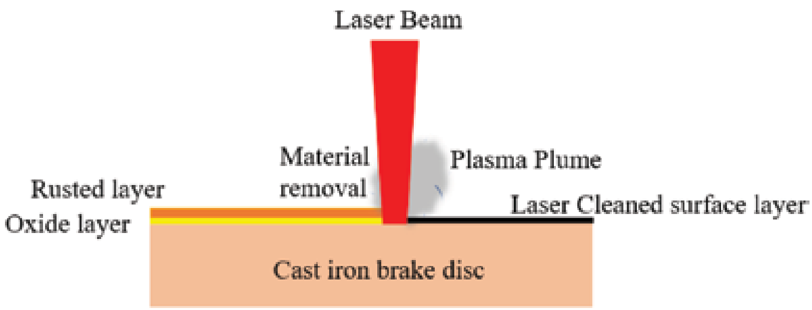


FIGURE 1
A schematic representation of laser rust removal process.

involve different mechanism for cleaning. A schematic representation of rust removal using a laser is shown in Figure 1.

2 EXPERIMENTAL AND ANALYTICAL TECHNIQUES

2.1 Background of test material

The material used for the experiment was both rusted and un-rusted grey cast iron automotive brake disc of a Vauxhall Astra diesel car. The samples were cut from the brake disc into small blocks for ease of laser surface treatment (see Figure 2(b)). The grey cast iron brake disc composes of 3.25 to 3.5 wt.% carbon, 0.050 to 0.45 wt.% chromium, 0.15 to 0.40 wt.% copper, 91.9 to 94.2 wt.%, iron, 0.50 to 0.90 wt.% manganese, 0.05 to 0.10 wt.% molybdenum, 0.050 to 0.20 wt.% nickel, 0.12 wt.% phosphorus, 1.8 to 2.3 wt.% silicon and 0.15 wt.% Sulphur [35]. The availability of grey cast iron in abundance makes it the second cheapest of all engineering metals [36]. Due to the operating conditions of the brake disc, it is required to have a good compressive strength, high friction coefficient, considerably lightweight, good thermal capacity and economically viable [37]. The ease of manufacture, cost, anti-wear resistance properties and thermal stability makes grey cast iron suitable for the brake disc [38]. The microstructural content contains flaked graphite in a matrix of pearlite and some traces of ferrite [23]. The manufacturing process of the brake disc includes casting, cutting, and forming [39]. It undergoes some heat treatment to change its microstructure, thereby, boosting its mechanical properties [38, 39].

2.2 Preparation of sample prior to laser cleaning

Pre-laser treatment involves the preparation of samples prior to laser beam exposure. The brake disc was in its as-received state (un-rusted) at the onset of the experiment. The basic steps in the pre-laser treatment involved induced rusting and cutting. These steps were necessary only for the sake of

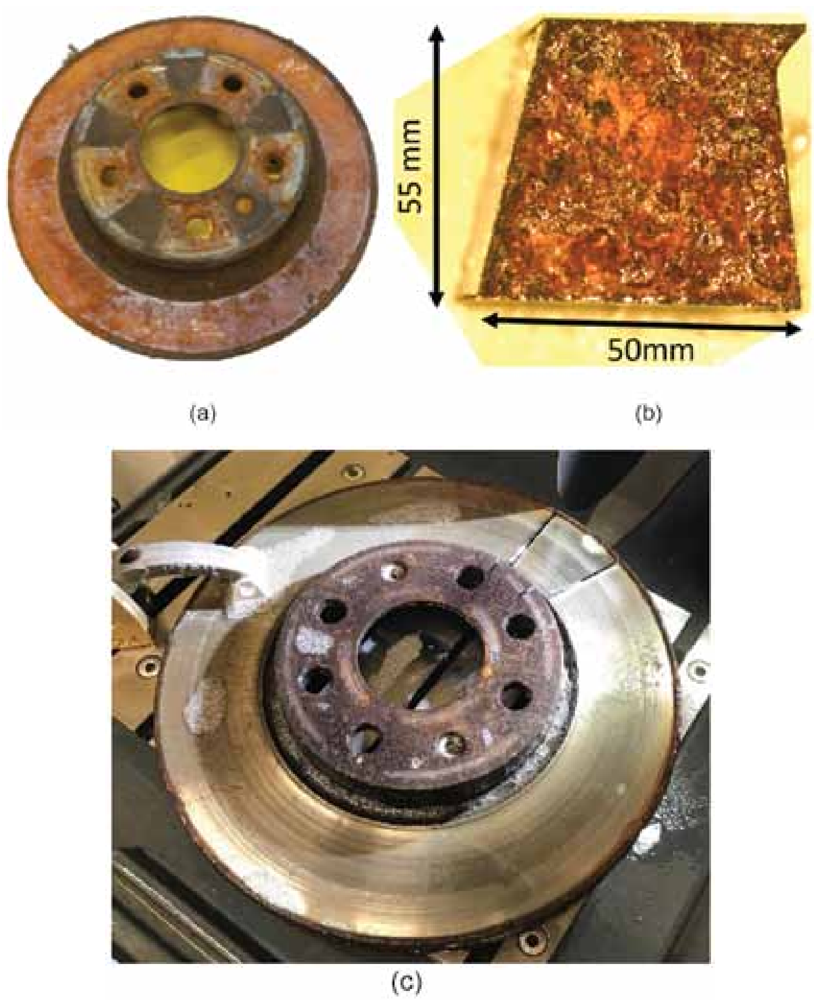


FIGURE 2
Illustrates optical images of the rusted brake disc in (a); a cut bake disc into smaller parts in (b) and (c) the un-rusted automotive brake disc.

this experiment. The brake disc was exposed to the atmosphere to enable moisture (water and air) to act on it for several weeks. By the third week significantly, uniform rust was formed throughout the entire surface of the brake disc as seen in Figure 2. The uniformly rusted brake disc was then cut into 20 parts (samples) of roughly equal size to ensure that samples were sufficient for the experiment. Figure 2(a) shows the rusted brake disc and the cut sample into smaller parts prior to laser cleaning in Figure 2(b) and the un-rusted complete brake disc in Figure 2(c).

TABLE 1
Laser processing parameters employed for laser rust removal.

Power (W)	Traverse speed (mm/sec)	Beam diameter (mm)	Radiance Density ($W/mm^2/Sr^{-1}/um^{-1}$)
10 to 85	30 to 3000	0.71 to 1.69	2.74 to 132.35

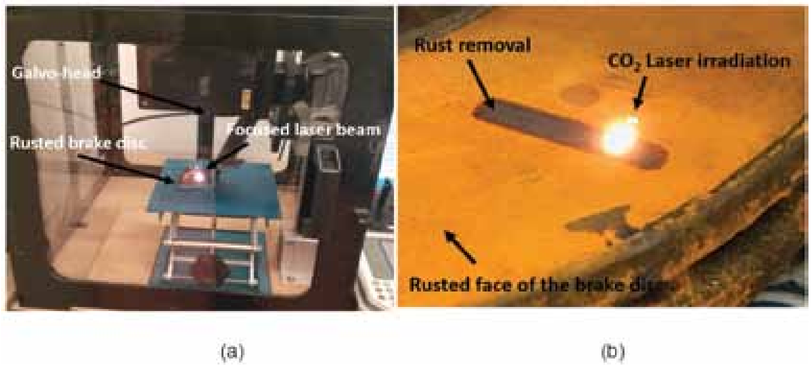


FIGURE 3
Optical images showing experimental set-up of the CO_2 laser rust removal process in (a) and method of rust removal in (b).

2.3 Laser cleaning process

Laser cleaning experiments were conducted using a continuous wave (CW) Rofin multiscan CO_2 laser (Hamburg, Germany). The laser has a wavelength of 10.6μm and a maximum power output of 85W. Experimental parameters applied and varied are namely: laser power, traverse speed, and spot size (see Table 1). A systematic approach was adopted for the experiments where one parameter was changed in an orderly pattern while other parameters were kept constant. The experiment involved 20 different samples with a total of 27 trials each processed with a unique set of processing parameter. First, the power was varied between 10W to 85W (maximum power), while other parameters were kept constant. The Radiance density (brightness) was determined using our previous technique [40 – 42], and ranged from 2.74 to 132.35 $W/mm^2/Sr^{-1}/\mu m^{-1}$. Traverse speed was varied between 30 to 3000mm/s with other parameters kept constant. The focal distance was also varied to obtain the correct laser beam diameter. Each of the cut samples were mounted on the processing table and exposed to the CO_2 laser beam to remove the top rust surface (see Figure 3(a)). Figure 3 also shows the experimental set up during the laser cleaning process and the method of rust removal.

2.4 Material removal measurement

The micrometre screw gauge was used to measure the thickness of the samples before and after laser rust removal. The unrusted surface thickness of the sample was also measured, and the difference in thickness was noted. The process was used to determine the ablation depth as well as measure the amount of material removal post laser cleaning. Measurements were taken five times on every sample to ensure a level of accuracy, and the average was then calculated.

2.5 Microhardness testing, topography, sample preparation and etching procedures

The Mitutoyo MvK-H1 hardness tester (Kawasaki, Japan) was used to measure the Vickers microhardness. A maximum load of 1000N was applied on the samples with a 5 secs dwell time. A Bruker contour GT profilometer with the vison64 software was used to measure the surface profile of the samples with the aim of quantifying the roughness. Polished cast iron specimen usually shows little or no matrix microstructure. Etching was conducted on the unrusted, totally rusted and the best laser-cleaned samples. The etchant used for the grey cast iron samples was Nital. Prior to etching, the samples were cut down from the whole automotive brake disc to smaller pieces. Samples were cross-sectioned for microstructural analysis. Selected samples were then mounted using a standard Vari-set 20 cold mounting powder and the quick-set cold mounting liquid. The mixing ratio was 2-parts powder to 1-part liquid by volume. The samples were kept at the center of the mount with the surface to be polished facing downward. The polishing process was conducted in 6 phases. A 9μm DiaDuo-2 water-based diamond suspension containing monocrystalline diamonds. A MD-Dur cloth was used, and the process took place at a speed of 150rpm for 10mins. A 6μm DiaDuo-2 diamond suspension with a MD-Dur cloth at a speed of 150rpm for 7mins. A 3μm DiaDuo-2 paste diamond suspension polish liquid was used with a MD-Dac cloth at 150rpm for another 7mins. A 1μm DiaDuo-2 paste diamond suspension polish liquid was used with a MD-Dac cloth at 150rpm for 3mins. Final polishing was then carried out using the colloidal silica suspension (0P-S) as the cooling lubricant for 3mins at 150rpm. To obtain a top-notch polished surface, the sample was then transferred to the Buehler Vibromet 2 vibratory polisher for 2 hours.

2.6. Optimisation of properties using gaussian process regression

A Gaussian process regression (GPR) approach [43] was used to predict the effects of laser cleaning with respect to the process parameters based on the experimental data. GPR is a reliable and a well-known method in machine learning that can be deployed using various types of data. It is a non-parametric approach and has been used widely to solve varieties of problems such as material properties, thus, can be deployed to understand the effects herein, in relation to laser processing related issues.

3 RESULTS AND DISCUSSION

3.1 Selection of laser cleaning parameters

Figure 4 represents a rusted surface which was removed by varying the laser parameters. The constituent of the rusted surface includes heavily corroded regions, corrosion cracking, and some areas that are partially rusted. The alteration of laser power from 10 to 85W (max power) produced various level of rust removal. At 10W, it was observed that a very low level of rust was removed with no visible cleaning effect. As the laser power was ramped up to 20W, the effect of rust removal became visible, but surface still contained significant rust. Upon applying 30W to 40W of laser power, there was a moderate level of rust removal. As the laser power was increased to 50W, there was a considerable amount of rust removed. At 60W, the rust removal was increased, but still contained areas where rust was visible. Although, it offered the best effect as ramping up the laser power to 70W significantly removed the rust but also affected the base metal. Thereafter, the rust was removed but the base metal was considerably altered due the increased laser power applied, and the substrate becomes visible with melt zones as evident in Figure 5(a), (b) and (c).

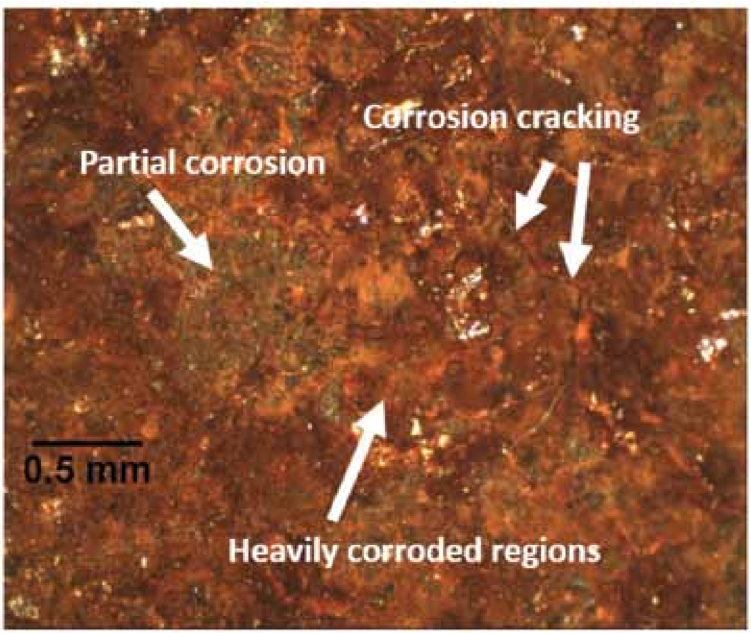
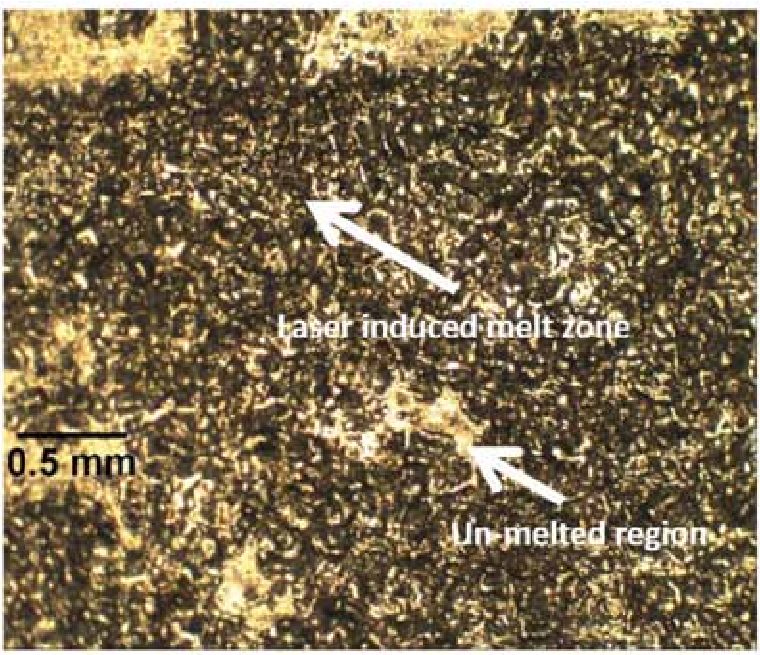


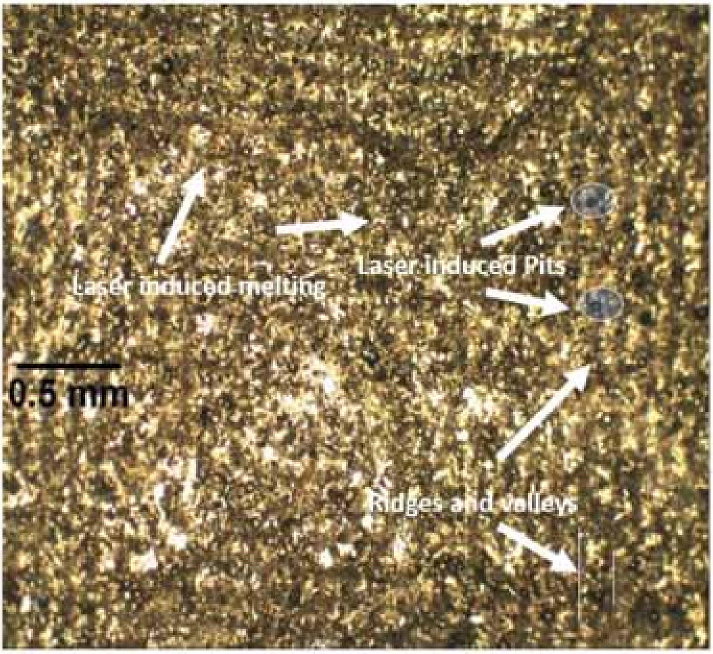
FIGURE 4
Optical image of the rusted (untreated) surface of grey cast iron brake disc.

As mentioned, increasing the laser power to 60W resulted to the best laser cleaned surface and will be further applied (Figure 5(e) and (f)) whilst varying the traverse speed. The best laser cleaned sample after varying all the parameters was 60W, 900mm/s traverse speed and 0.72mm spot size as all the rust were removed and the metal substrate was not melted (see Figure 5 (e) and (f)). Figure 4 demonstrates a direct comparison between the rusted (untreated) sample and the laser cleaned surfaces in Figure 5 (a) to (f).

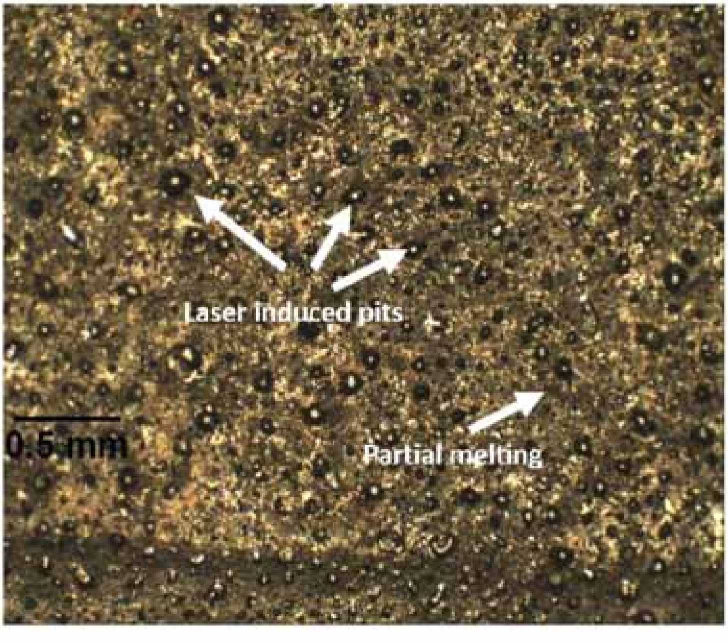
Laser power (60W) and a spot size of 0.72mm was kept constant while the traverse speed was varied. Variation between 30mm/sec to 100 mm/sec produced total removal of rust, but the base metal was badly affected due to very low traverse speed which was due to the high laser power acting on the grey cast iron brake disc for a prolonged period which caused considerable melting. This would not be desirable as it is then likely that some of the surface properties would have changed. For the application of a brake disc, modification in the material's surface integrity was not an objective since it will affect the functional capabilities of the brake disc. At 200mm/sec to 300mm/sec traverse speed, there was complete rust removal while the melting of the base metal reduced. At 500mm/sec to 700mm/sec traverse speed, there was mini-



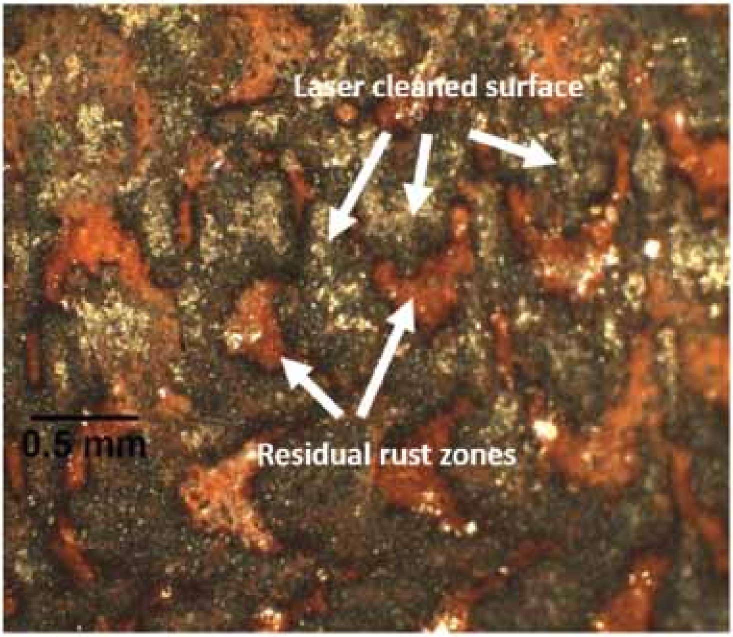
(a)


Laser induced melting
Laser induced Pits
0.5 mm
Ridges and valleys

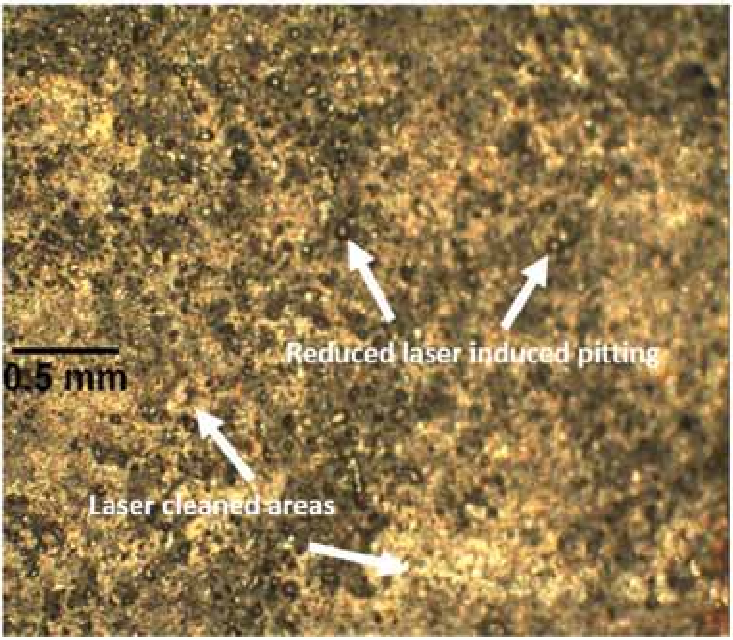
(b)


Laser induced pits
0.5 mm
Partial melting

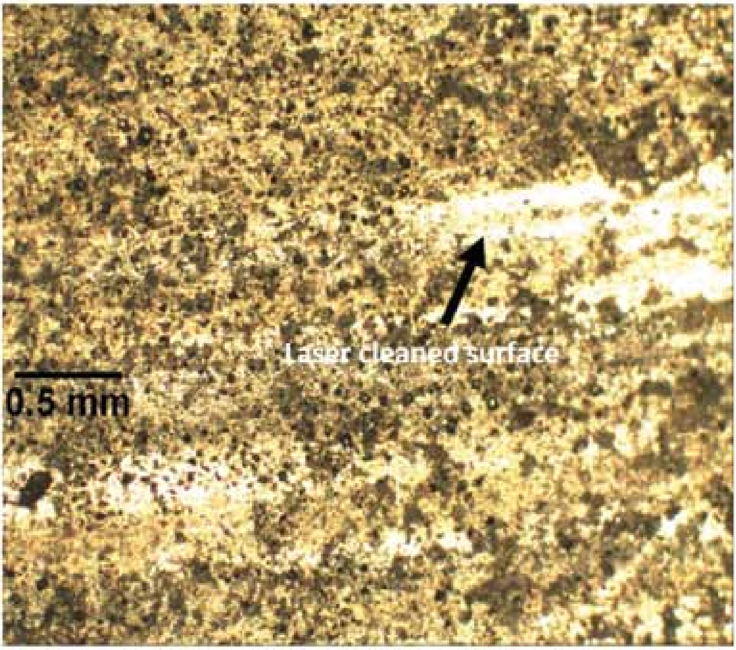
(c)


Laser cleaned surface
0.5 mm
Residual rust zones

(d)


Reduced laser induced pitting
0.5 mm
Laser cleaned areas

(e)



(f)

FIGURE 5
Optical images of laser cleaned surfaces in (a) at 30mm/sec; at 300mm/sec in (b); at 600mm/sec in (c); at 2000mm/sec in (d) whilst using a spot diameter of 0.72mm and laser power of 60W. (E) and (f) showing the most appropriate laser cleaned surfaces with a spot diameter of 0.72mm and laser power of 60W at 9000mm/sec.

mal melting of the base metal associated with good rust removal. As the speed increases, melting of the base metal decreases. At 900mm/sec, there was excellent removal of rust, and base metal was not affected which is rather desirable. At 1000 mm/sec, a good level of rust removal with little rust particles still seen on the surface. Beyond this speed (1500, 2000, 3000 mm/sec) rust was not removed to any considerable effect as the traverse speed was too fast to create any heating, local melting and material removal.

The spot size was varied from the largest diameter (1.69mm) obtainable based on the focal height of the laser's galvo head to the smallest diameter (0.71mm). It was concluded that to obtain the best effects and fully remove the rust layer off the grey cast iron brake disc; a minimal spot diameter was rather effective and desirable (0.71mm). Larger spot diameter at maximum laser power left many rusted regions. Thus, the best surface condition was obtained using a fairly small spot diameter focused into the material and was 0.72mm.

3.2 Measurement of rust removal

Mathematically, the depth of ablation ($Z_{ablation}$) was determined by the difference between average rusted sample thickness, and the average laser cleaned sample thickness as given by Equation (1):

$$Z_{ablation}\text{ (mm)} = \text{average thickness of rusted sample} - \text{the average thickness of laser cleaned sample} \quad (1)$$

Using the un-rusted surface as a reference, the deviation can serve as a characteristic to denote how much rust was removed from each sample. Deviation from the un-rusted sample can be represented as:

$$\text{Deviation (mm)} = \text{average thickness of laser cleaned surface} - \text{the average thickness of unrusted surface} \quad 2)$$

The rusted brake disc has a slightly varying thickness of corrosion as it was exposed to the atmosphere. However, several measurements were taken at various points on each sample and the average was calculated. Hence, the mean represents the most accurate thickness value. Table 2 shows the average thickness of the surfaces with three different conditions. It was observed that the average thickness of the rusted layer was 0.33mm compared to the un-rusted surface. The thickness of the laser cleaned surfaces is shown in Table 2 as well as the depth of the rusted layer removed in Table 4. During the experiment, the cast iron brake discs were subject to high local temperatures generated from the laser beam operation at high power and or low traverse speed. Hence, it becomes unnecessary to measure the amount of rust removed after the top surface was melted and solidified, leading to the formation of melt zone, and pits, and dimples, as evident in some of the optical images in Figure 5(b) and (c).

The GPR curve determined using the experimental data (laser power *versus* Z-ablation) combined with the optimized fit is shown in Figure 6. It is clear that an increase in laser power had increased the Z-ablation which peaked at 60W with 0.30mm in thickness of rust removed. The value of Z-ablation begins to decrease beyond this point and can be postulated (from Figure 6) to saturate where the ablation depth becomes considerably constant as the laser power increases to 200W. The dip in the curve is difficult to

TABLE 2
Thickness of both the un-rusted and rusted surface of grey cart iron brake disc.

Sample Type	Reading 1 (mm)	Reading 2 (mm)	Reading 3 (mm)	Average(mm)
Un-rusted	8.18	8.22	8.20	8.20
Rusted	8.52	8.57	8.49	8.53

TABLE 3
Thickness of rust removed and ablation depth of laser cleaned grey cast iron brake disc.

Laser Cleaning Parameters (Power, Speed, Spot Size)	**Average thickness (mm)**	**$Z_{ablation}$ (mm)**	**Deviation (mm)**
10W, 1000 mm/s, 0.72 mm	8.49	0.04	0.29
20W, 1000mm/s, 0.72mm	8.46	0.07	0.26
30W, 1000mm/s, 0.72mm	8.37	0.16	0.17
40W, 1000mm/s, 0.72mm	8.31	0.22	0.11
50W, 1000mm/s, 0.72mm	8.27	0.26	0.07
60W, 1000mm/s, 0.72mm	8.23	0.30	0.03
60W, 900mm/s, 0.72mm	8.25	0.28	0.05
60W, 1000mm/s, 0.72mm	8.31	0.22	0.11
60W, 1500mm/s, 0.72mm	8.39	0.14	0.19
60W, 2000mm/s, 0.72mm	8.45	0.08	0.25
60W, 3000mm/s, 0.72mm	8.49	0.04	0.29
60W, 900mm/sec, 0.72mm	8.21	0.32	0.01
20W, 1000mm/s, 0.72mm	8.24	0.29	0.04

TABLE 4
The microhardness of various laser cleaned, rusted and un-rusted surfaces.

	Hardness (HV)					
Sample Condition	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Average
Un-rusted	224	224	224	223	224	224
Rusted	91	94	90	97.0	95	93
Laser cleaned: 60W, 900mm/sec, 0.72mm	234	238	233	235	236	235
Laser cleaned: 60W, 1500mm/s, 0.72mm	176	175	180	175	182	178
Laser cleaned: 60W, 30mm/s, 0.72mm	307	310	302	305	305	306

explain at this stage, but it can be given to the lack of experimental data which reduces the reliability of the GPR method. Reliability would improve with further experimentation which would verify and support the predicted GPR curve.

3.3 Microhardness analysis

Table 4 presents the variation in hardness measured for the cast iron brake disc at various surface conditions applied. The average hardness of the un-rusted surface was measured to be 224 HV. This was verified by a previous work on

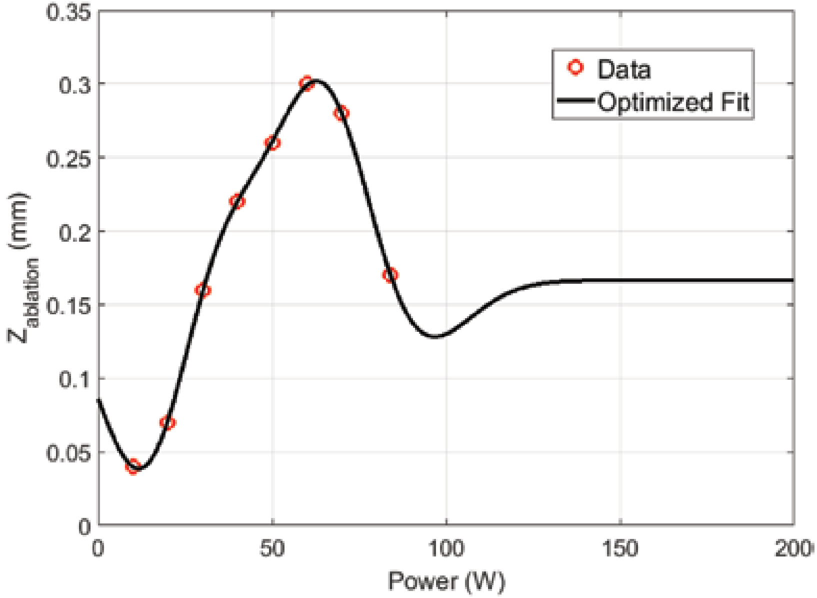


FIGURE 6
Experimental data with optimized fit for laser power *versus* Z-ablation obtained with the Gaussian process regression method.

TABLE 5
Vickers microhardness values with respect to rust thickness.

Surface Condition	Microhardness (Hv)	Rusted Layer Thickness (μm)
Rusted surface	93	330
Partially rusted surface	178	190
Un-rusted surface	224	10
Best laser cleaned surface	235	0

the manufacturing of grey cast iron automotive brake disc that reported a hardness value of 225 HV [44]. On the other hand, the hardness of the rusted surface was the lowest at an average of 93HV. This was natural since the rust particles formed on the brake disc were loosely packed and the bond strength of these particles were not as strong as that of the un-rusted surfaces to render the hardness to be high, comparatively. Table 5 presents the hardness values with respect to the rust layer thickness. It was evident that the thicker the rusted layer, the lower the hardness. This was due to the penetration depth of the laser light, which diminishes as the depth of rust increases. When these surfaces were compared to those cleaned with a laser; there was a trend of increased hardness with the lowest laser cleaning traverse speed. The lowest traverse speed comprised of the highest hardness which was an increase by 37% in comparison to the un-rusted surface and over 3 folds increase, compared to the fully rusted surface. Creek [19], suggested that rust reduces the hardness and strength of metals. That is, as the amount of rust reduces, hardness increases. Furthermore, as the traverse speed increased the hardness decreased. At 900mm/sec, the hardness was measured at an average of 235HV which was about 4.5% in comparison to the un-rusted surface. The traverse speed was increased to 1500mm/sec and the hardness was measured to be 178 HV. This was the lowest obtained from the laser cleaned surfaces. This was attributed to the fact that higher traverse speeds does not result in enough rust being removed from the respective surface. This lead to the hardness still not measuring close to the un-rusted surfaces. Tabulating these parameters into the GRP curve also yielded similar findings, whereby, the hardness reduced as the traverse speed increased (see Figure 7). As the laser beam was active for a longer period on the rusted surfaces. Particularly at low traverse speed (30mm/sec), there was significant heat being generated at the laser-material interaction. Thus, the possibility of removing the rust was not only high as evident from Figures 5, but also producing partial melt-zones which solidified at a slower rate to have generated a ductile surface. Also, the surface partial-solidification induced ductility would

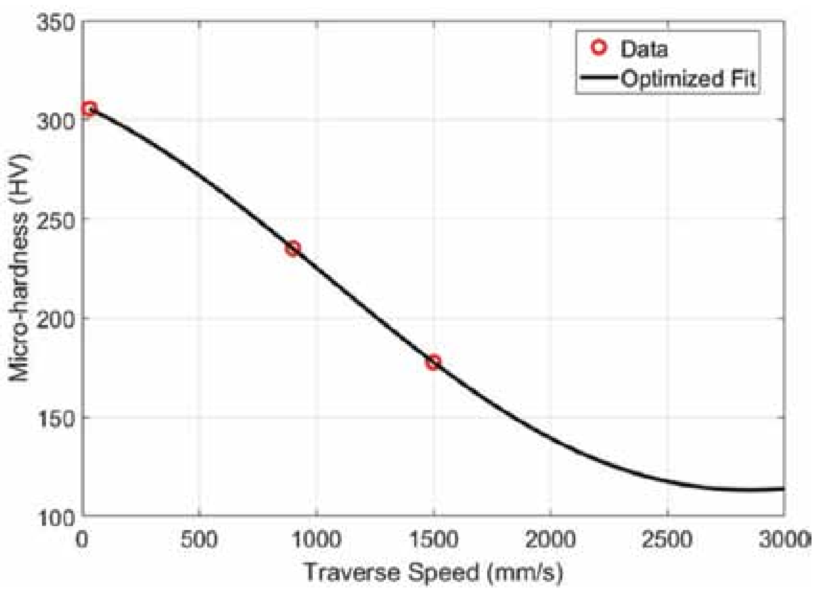


FIGURE 7
Gaussian process regression optimized curve and experimental data of microhardness *versus* traverse speed.

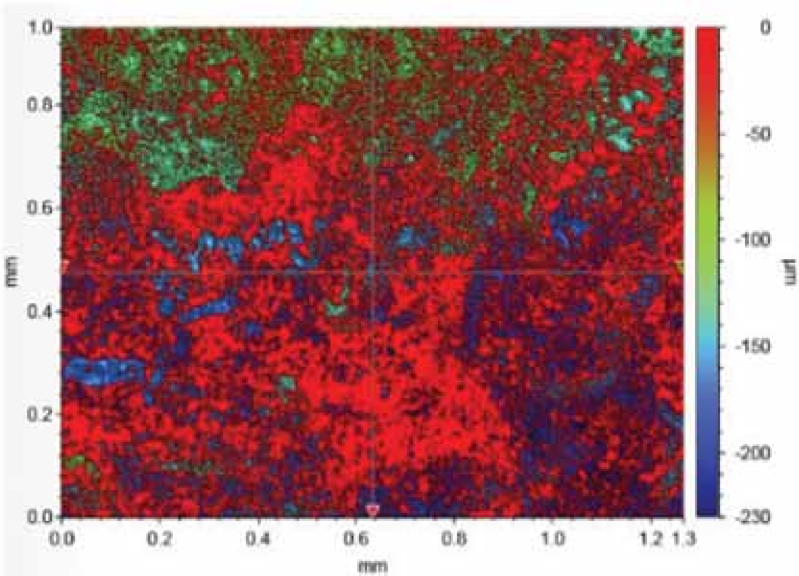


FIGURE 8
Topography of rusted grey cast iron brake disc surface.

be able to sustain for plastic deformation during cyclic fatigue failure of the specimen.

3.4 Surface roughness analysis

The average roughness (Ra) is a 2-D roughness parameter showing the arithmetic average of the absolute values of the profile heights with respect to the mean over a given length. In this case, it was significantly high for the rusted cast iron brake disc with a measured value of 55.41μm. When this was compared to the un-rusted brake disc, the measured roughness was 3.08μm and was considerably lower. This was due to the operating condition and harsh environment the brake disc operates, which lead to the formation of little rust at the onset. Further exposure lead to the formation of heavy rust at a later stage. However, after laser cleaning, the surface became much smoother. The roughness was measured to be 1.29 μm and was less than 50% compared to the un-rusted brake disc. As expected, the Rt value for the three surfaces shown in Table 6 had a similar trend with the rusted surface having a value of 230.39μm. The best laser-cleaned and un-rusted surface had an Rt value of 26.27μm and 24.89μm respectively. It was observed that the best laser-cleaned surfaces had a smaller Ra value when compared to the un-rusted sample, which however comprised of a higher Rt value. This indicates the onset of the Gaussian laser beam ablating the surface of the cast iron brake disc. This in turn, leads to an increase in the distance between the lowest and highest points over the surface area of the laser-cleaned samples than that of the un-rusted

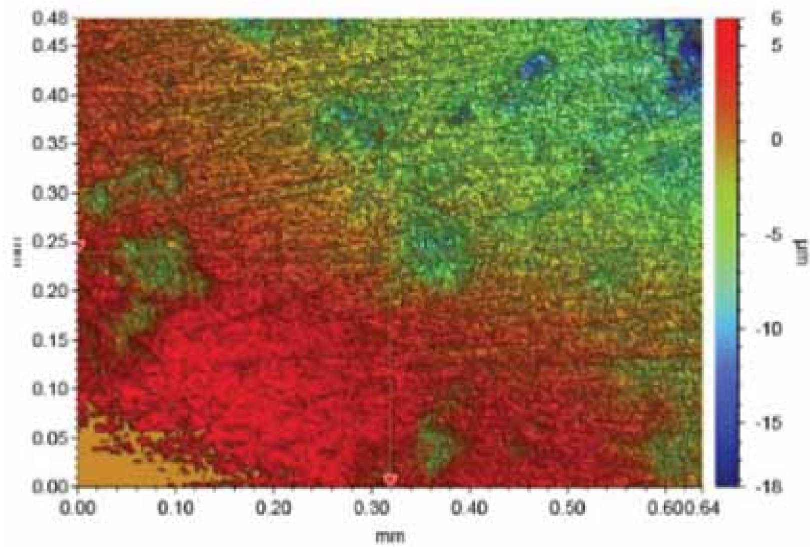


FIGURE 9
Topography of un-rusted grey cast iron brake disc surface.

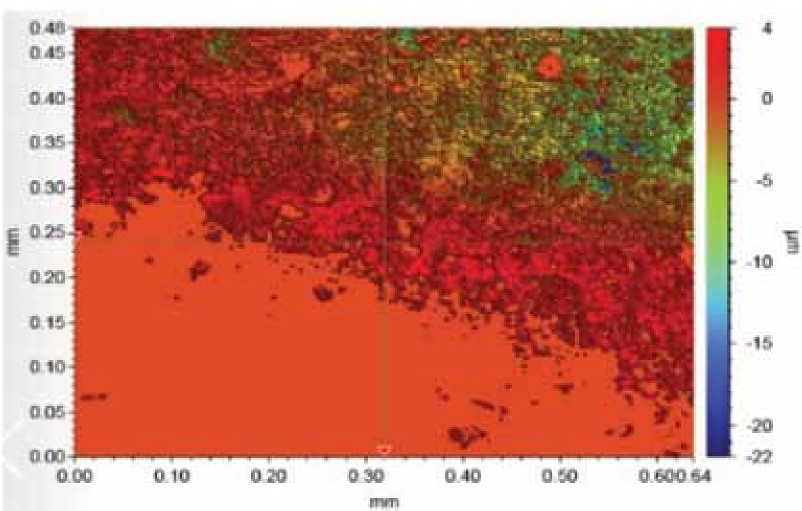


FIGURE 10
Topography of laser cleaned grey cast iron brake disc at 60W laser power, 900mm/sec and 0.72mm spot size.

surface. The 2-D topographical images of the rusted, un-rusted and totally cleaned samples are illustrated in Figure 8 to Figure 10 respectively. From Figure 8 to

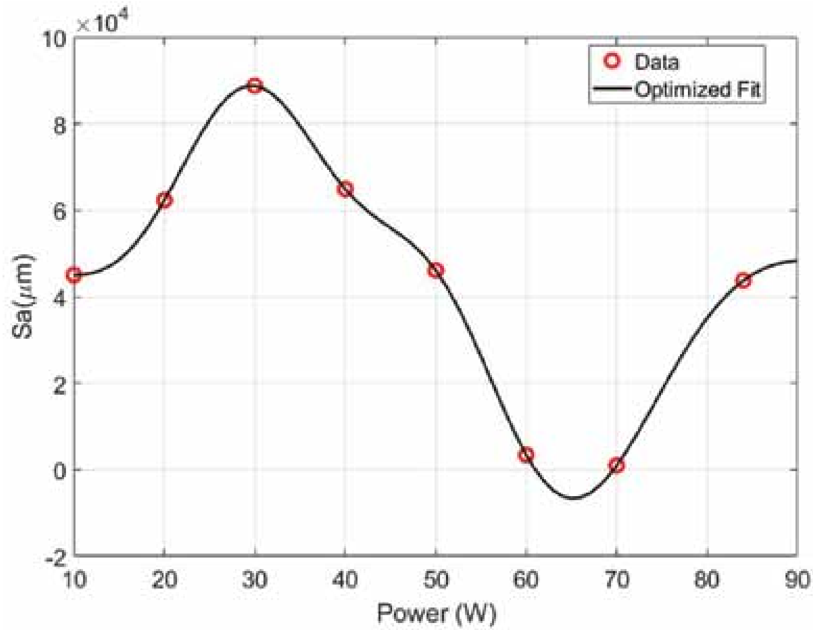


FIGURE 11
Illustrating the Sa values with respect to increase in power (60W laser power, 900mm/sec traverse speed and a spot size of 0.72 mm).

Figure 10, it is was seen that the rusted sample 2-D topography has less smooth surface when compared to the other two samples. The existence of pits, ridges and valleys might have influenced such topography.

Upon observing the Sa values, it was evident that as the laser power increased, the Sa value increased simultaneously until it peak at 30W, then subsequently decreased as the laser power further increased (see Figure 11). This indicated that the surface was smoothening as the roughness was reduced with the rusted layer being removed. At 60W the roughness was at the lowest with a possibility of complete removal of the rust. The roughness then began to increase as the laser power went up. This indicated that there was a possibility of surface melting and reforming to form a new rougher topography. This was also evident from the optical images showing melt zone beyond the laser power of 60W. As the surface considerably melted, it created dimpling and pitting effects, evident in Figure 12. This created an increase in surface roughness as evident from Figure 12 where the Sa values noticeably increased.

3.5 Microstructural analysis

The microscopic images of the un-rusted, rusted and best laser-cleaned surfaces are shown in Figure 14 to Figure 16. The microstructural images of the

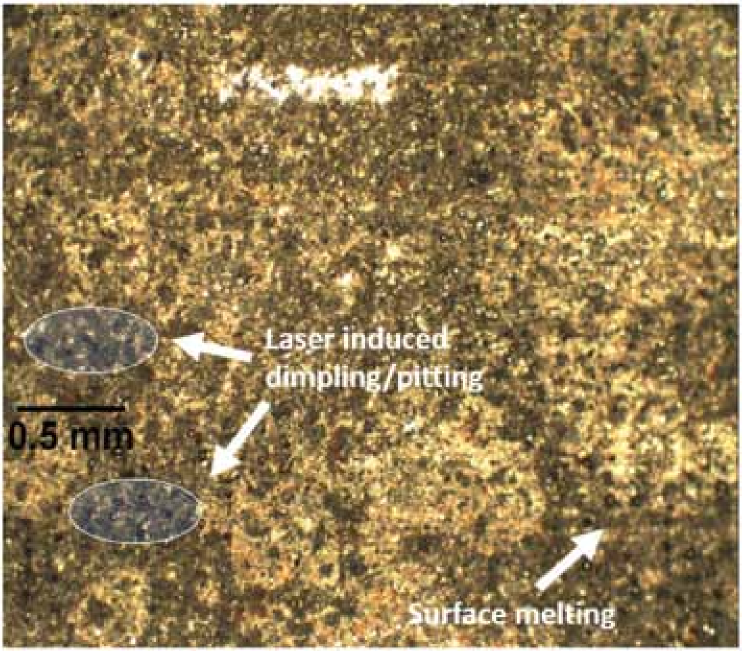


FIGURE 12
Showing the roughening of the surface at 70W laser power, 900mm/sec and 0.72 mm spot size as melt zones take place in various area.

three surfaces all show the presence of a black flake-like structure (graphite flakes). Grey cast iron is characterised for having a large portion of its carbon in the form of graphite flakes. The fast interstitial diffusion of small carbon atoms makes the formation of graphite flakes possible. As diffusion progresses, more graphite is formed. The plane of such graphite is held by a covalent bond and has a hexagonal structure. The presence of silicon as one of the alloying elements of grey cast iron promotes the formation of ferrite and graphite. It acts as a strong graphitizer during eutectic solidification of grey cast iron. Eutectic cells are formed by the nucleation of graphite. The mixture of graphite and austenite makes up the eutectic cells. The eutectic cells can be viewed on the micrograph chemical etching. During the eutectoid transformation, the austenite transforms into ferrite and cementite or graphite. The system stability is dependent on the transformation that occurs. Graphite or cementite either occupies the carbon-rich zone based on the system stability, that is, if the system is metastable, it prefers cementite. If the system is stable, it prefers graphite. The graphite flake is seen to be much softer than the surrounding matrix which is viewed as a void. The formation of the pearlitic matrix with graphite particles occurs in the surrounding matrix of the flake to prevent the structure from being too weak. This formation

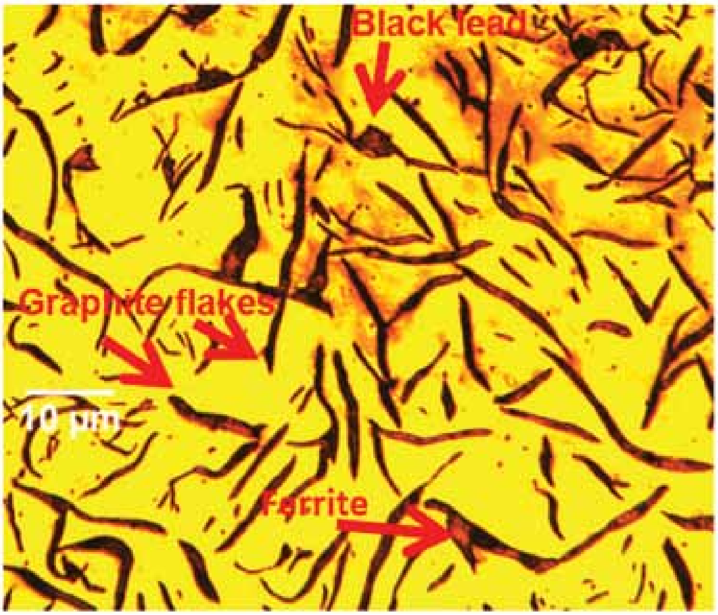


FIGURE 13
Microstructure of the un-rusted surface of the grey cast iron.

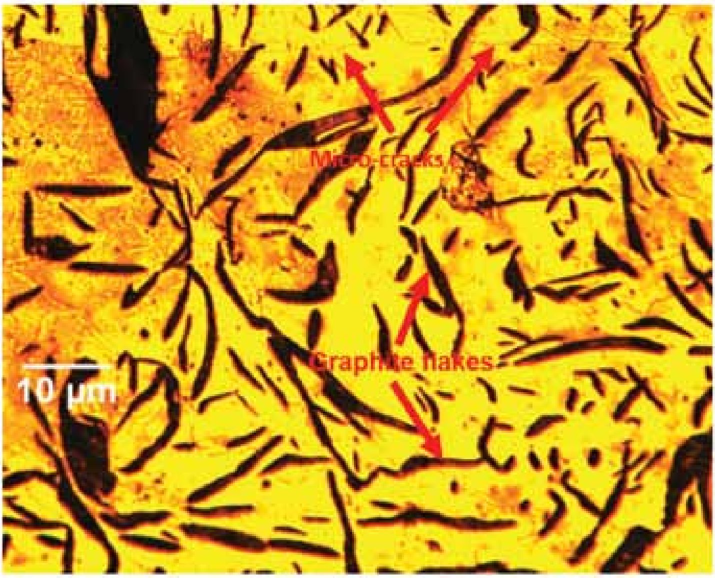


FIGURE 14
Microstructure of rusted surface.

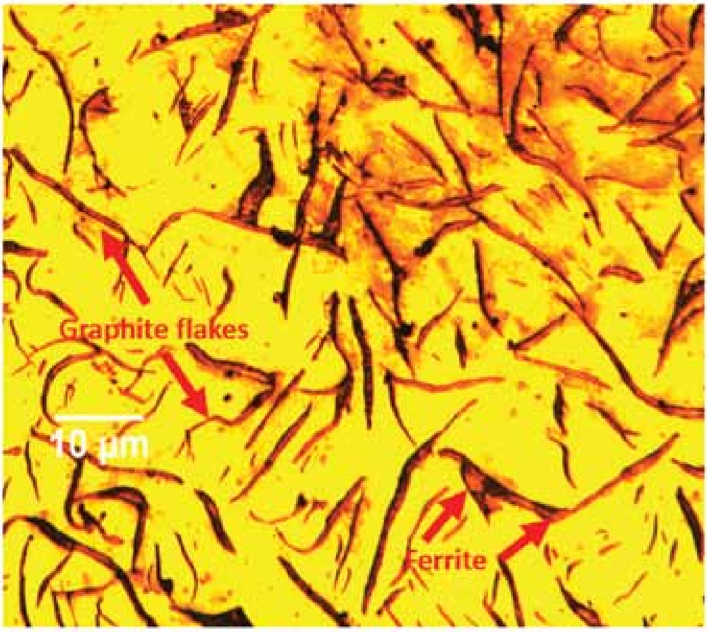


FIGURE 15
Microstructure of a laser-cleaned surface (60W of laser power, 900mm/s traverse speed, spot size of 0.72mm).

gives it good compressive strength, good thermal conductivity and vibration damping. It was observed from the microstructure that the graphite flakes vary in shape and size. The rusted sample shows larger flakes when compared to the un-rusted and laser-cleaned surfaces. It also exhibits relatively longer graphite flakes on the average. Deep black pits are also seen on the microstructure of the rusted sample which signifies the presence of impurities and non-metallic inclusions. The presence of inclusions and impurities along with the slightly longer and larger graphite flake is responsible for the low hardness value and high Ra value of the rusted sample.

The laser-cleaned sample has a relatively larger spacing between the flakes when compared to the un-rusted and rusted surfaces. An increase in space between flakes results in an increase in the strength and a corresponding increase in hardness. A relatively shorter flake length and smaller flake size yields a higher hardness value when compared to the un-rusted and the rusted surfaces. This is because graphite particles are generally softer. The hardness is evident as seen on the microstructure of the laser cleaned surface in Figure 15. There is a relative decrease in the number of graphite flakes when compared to the microstructure of the rusted grey cast iron sample. Furthermore, a denser cluster of graphite flakes with relatively bigger flake size and longer flake length created lesser space for a hard pearlitic matrix. The grey region in Figure 13 to Figure 15 represents a pearlitic matrix. The pearlitic matrix contained two phases which are ferrite and cementite. While cementite is a hard and brittle intermetallic compound, ferrite has low strength and high ductility. Besides the cementite found in the pearlite matrix, the micrograph also showed no evidence of cementite. The dual phase involving ferrite and cementite which creates the pearlitic matrix originates from the austenite phase. At higher temperature, only austenite is present with 0.76%C been dissolved in the face-centered cubic (FCC) crystal's solid solution. The cooling down of iron to 727°C results in several simultaneous changes. It is highly likely that the laser cleaning process induced temperatures above that level. First, the iron changes from FCC austenite to body-centred cubic ferrite, but the ferrite can only accommodate 0.022% carbon in solid solution. The excess carbon left was then rejected forming the carbon-rich intermetallic phase which is cementite.

4 CONCLUSIONS

The enhancement of the surface integrity of a rusted, grey cast iron automotive brake disc was achieved *via* a laser cleaning process. Laser cleaning and rust removal are fast and effective in enhancing the surface integrity of such materials. The results showed that the presence of rust on cast iron reduces its mechanical and physical properties. The ripple effect of such reduction leads to failure of the brake disc when fused into the braking system of an automotive vehicle. The best set of laser parameter for removing rust from the grey cast iron brake disc using a CO_2 laser system was 60W of laser power, 900mm/s traverse speed and a spot size of 0.72mm. The presence of rust on the surface of the brake disc greatly reduces its microhardness. The laser cleaning process positively altered the microhardness value, verified by an increase of 5.04% when comparing the un-rusted sample (223 HV) to the best-cleaned sample (235 HV). The best-cleaned sample has an Ra value of 1.29μm which is relatively good when compared to that of the un-rusted samples. The microstructure of the samples showed that the presence of randomly distributed graphite flakes surrounded by a pearlitic matrix contained ferrite and cementite. The GPR technique can demonstrate an in-depth prediction of parameters beyond the experimental data. However, further experimental work verifying the prediction will improve its reliability for laser processing problems such as the one herein. The applied parameters showed that laser cleaning could be successfully applied to not only clean rusted surfaces of metallic materials such as the one herein, but could also have a positive effect on some of the material properties, thus, increasing the life span of the brake disc. Laser cleaning of the brake disc will drastically reduce cost (maintenance and replacement cost). It also prevents sudden failure since the parts have been enhanced to become more durable and reliable, even when operating under harsh conditions. It is also much greener and has the potential to replace chemicals, abrasive materials or shot blasting and harmful cleaning solvent that poses hazards to the end-user.

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