Formation of colours on SS304L stainless steel induced by laser colouring

R Linggamm1, M M Quazi1,*, M Ishak1, M H Aiman1, A Q Zafiuddin1 and Abdullah Qaban2

1Joining, Welding and Laser Processing Lab (JWL), Faculty of Mechanical and Automotive Engineering Technology, University Malaysia Pahang, 26600 Pekan, Pahang, Malaysia
2Department of Mechanical Engineering and Aeronautics, City, University of London, London, UK

*Corresponding author’s e-mail: moinuddin@ump.edu.my

Abstract. In this research, the laser colour marking process was carried out to determine the formation of colour on surface of SS304L stainless steel. The pulse laser nanosecond (1064nm) was used to irradiate the SS304, resulting in the formation of various colour permeating on the sample surface. The surface characterization and surface roughness were analysed by using the 3D optical microscope. The effect of laser processing parameters such as hatching distance, pulse width, and defocusing distance on the evolution of surface colours were investigated. The results show that a thin oxide film was essentially formed that resulted in the formation of four different colours. Each colour exhibited a different surface texture and surface roughness implying the effect of parameters significantly affects the surface characteristics. Grey colour formed registered the highest roughness (Rz) of about 3.5 microns followed by a decreasing roughness trend for blue, purple and green respectively.

Keywords: Laser colouring; SS304; Surface texture; Roughness.

1. Introduction

Laser based manufacturing processes such as laser surface modification laser [1], laser hardening [2], laser welding [3] are now gaining widespread recognition due to robust and rapid production time. Laser induced colour marking of metals has been well known for the past decades but these days there has been a widespread growth in the new era of technological development. This process is rapidly replacing traditional marking methods such as painting, etching and printing [4]. However, this process adds colour to an object that is being marked merely “stains” of the surface. It has become a foremost industrial process today in many applications, such as the labelling of a serial number, date, barcode, quick response (QR) code, company logo, trade marking, and other product information. There are several types of laser colour marking processes which are etching, marking, and lithography. However, Laser colour marking boasts high quality, difficulty to forge, wear resistance and is a noncontact marking process that does not causes any contact pressure nor deformation whilst is
sustainable [5].

The process of laser colour marking ensues when the oxide layer is created on the ferrous metal such as steel and high-grade steel through the localized heating. In general, the oxide layer that was created on the surface is black, but it can also be tailored to obtain a variety of colours such as red, blue, and green etc [6]. Hence the colour produced on the surface of metal primarily depends on the temperature of the heated layers and the penetration of heat to the depth of the metal surface. The phenomena of colour production are also dependent on the chromium due changes in molecular structure and electrons on the metal surface. The laser acts as a heat source allowing forming of a thin transparent or semi-transparent oxide film. If a beam of parallel monochromatic light falls, at an angle, onto a transparent or partly transparent layer, this beam is repeatedly reflected from the surfaces limited by the oxide layer (from the surface of both oxide and metal) [5]. By increasing the thickness of oxide on the surface and as a consequence by changing the interference effect (each wavelength has a different degree of attenuation or amplification), a colour effect can be observed and controlled.

The most common laser employed in the laser colour marking is a pulsed wave mode nanosecond, picosecond, or femtosecond laser. This is due to the difference in the behaviour of their pulse width and pulse frequency. Therefore, through the use of femtosecond and picosecond lasers, the method of laser-induced periodic surface structure (LIPSS) are used to induce colour on the metal surface [7]–[9]. There is also paper demonstrate that the influence of the pulse frequency, mark depth width, and mark contrast on the colour marking process are depends on the interaction process of the laser beam and the material which was influence dramatically by the pulse frequency on the quality of the mark [10].

When we glance at the formation of colour on a metal surface that contributes by nanosecond laser, most of the researchers have analysed the parameter of the laser such as laser power, frequency, hatching distance, defocusing, and scanning speed on this colour mark process, where they summarized this factors may alter the colouring effect on the metal surface [6], [11]. Most of the study carried out by [10], [14], [15], it shows that the laser parameter directly affects the stainless-steel surface colour. However, the colour marking implementation and development of the metal surface is an ongoing process, since the formation of colour on the surface still not uniform throughout the laser-scanned area, where the laser process colour mark stability depends on many factors such as temperature, laser parameter and the quality of the metal surface [9]. Thus, a new experiment has been conducted to study the nanosecond laser mark process on the stainless steel of 304L material. The variation of parameters such as laser power, frequency hatch distance, an defocusing resulting from the distribution of numerous colours on the steel surface shall be made. Subsequently, the surface roughness parameters have been investigated corresponding to the colours generated by parameter variation.

2. Experimental Setup

2.1. Material and material preparation

SS304L, austenitic stainless steel was chosen for the study, which is widely used in many industries. Therefore, for this study, the rectangular specimens of (1000 mm in length and width with a thickness of 2 mm) were cut from a large bar of SS304L stainless steel. Thereafter, the top surface of the metal surface was polished to minimize the initial surface roughness before the laser treatment. Prior to the laser irradiation, the specimen was cleaned in acetone. The grease and contaminants of the sample removed by using the ultrasonic machine that contained acetone.
Besides that, the laser beam is required to be focused on the sample surface through an F-theta lens in the scanning area of 10 x10 mm, where the scanning mode is shown in Figure 1. Thus, the line scans were completed from right to left by the laser beam and the galvanometer scan mirror will change the scanning path as shown in Figure 1. However, by moving the sample on the platform, the area of the laser scanning should not change where it always needed to be located directly below the laser beam before each scan begins. This will ensure the pulse energy density of the laser will not change remarkably.

![Figure 1](image1.png)

**Figure 1.** The schematic diagram of laser scanning on the sample.

### 2.2. Laser color marking setup

The colour marking process was conducted by using IPG-Fibber laser (Hanser Laser company). Then, this laser beam is a red light with a central wavelength of 1064 nm, and beam focusing distance is 245 mm. While the laser beam emitted diameter by this device was 0.5 mm. The beam expander of this device can be expanded the magnification until 5 mm which then will be transmitted to the scanning galvanometer. Lastly, the beam will be a focus on the target spot, which is nearly the gaussian spot with a diameter of approximately 40 μm. Apart from that, the maximum power output of this laser was 30 W and the pulse repetition frequency can vary within the range of 10-300 kHz. In comparison with the laser (wavelength of 532 nm), the optical path of the laser used in this study (wavelength is 1064 nm) which can be visible, where it is convenient to adjust and user-friendly. Hence, the 1064 nm laser has a larger heat-affected zone on the stainless steel and it can act as a good absorption rate of laser energy. In addition, these laser systems consist of an operating panel, a laser control system, an optical system, a cooling system, and a working platform of an industrial computer with a compact configuration. It is also easy to use a network with a reliable output. Lastly, the processing parameter of this laser is set by the special control software (Ezcad) from the supporting pc terminal, while the laser optical path structure is represented by Figure 2.

The selection and identification of the sample surface was been analysed by using a 3D optical microscope. The surface characterization and surface roughness of the sample was analysed by using LEXT OLS5000. This laser is a confocal scanning microscope, where it is the better device for 3D measuring for the analyses of non-contact and non-destructive imagery [12]. Therefore, it has no sample size or content limitations which enables the observation under normal environmental conditions. Hence the apparent reproduction of the object of the optical image is formed by a mirror or lens system which produce by reflected, refracted, or diffracted light waves. However, for determining the surface roughness of each sample on the colour formations, the optical and height image from this 3D laser microscope was recorded to evaluate the effect of each sample roughness of colour formation.
on the SS304L substrate. The finding of the surface roughness on the formation of colour on SS304L is important in our research to see the correlation change of colour on the surface roughness.

Figure 2. Laser machine use in laser colour marking.

2.3. Surface Roughness
In this work, the roughness of the sample is calculated by using the OLS5000 laser confocal microscope, where it has precisely measured the shape and surface roughness at the level of submicron [12]. However, the quantitative roughness value is observed based on 2D line roughness and 3D surface profile with four-parameter of roughness recorded which is, average line roughness (Ra), a mean depth of line roughness (Rz), arithmetical mean height (Sa), and maximum height (Sz). From these four recorded values, the investigation of the value of Ra and Rz will be observed and analyzed due to the information of peak and valley of the surface roughness. With the value, the observation of the color change in each surface could be correlated with different roughness surfaces.

3. Result and Discussion

3.1. Surface color
The obtain colour in our experiment has been analysed by using a matrix method to investigate the influence of laser pulse width, hatch distance, and different defocusing distance of the lasering process. The other parameter of the lasering remained unchanged during our experiment. Hence the influence of the three parameters on the colour plate has been shown in Figure 3. By referring to the experiment that were carried out, the defocusing distance, pulse width, and hatch distance was found to be affecting the colour marking of a stainless-steel surface. However, when the defocusing distance is on a lower side, the colour made by laser in the sample surface as shown was mainly grey and dark brown while the traces of material removal can be observed on the sample surface. This material removal was mainly due to the high laser energy absorbed by the material. Rich colour appears when the defocusing distance is in the range of 4mm, 5mm, and 6mm as showed in Figure 3. Moreover, the same figure shows the multiple colours formed on the sample with a defocusing distance of 5mm and 6mm respectively. If the defocusing distance is fixed, then the colour appears on the sample are in a
similar sequence as shown in Figure 4 a and b. As an example, in Figure 3, the colour appears in the dark in both columns and rows as marked in yellow line where the colour appears are dark brown and brown. Meanwhile, it has been observed that the small pulse width and defocusing distance have tendency to produce dark surfaces that cannot reflect the light in that particular colour. Additionally, rich colour does not appear on the sample surface at the upper left corner of the sample. By simply increasing the pulse width and defocusing distance the rich colours start to appear in the sample surface in the central area. As the two-parameter increase, the shiny and transparent oxide layer is generated on the sample surface but when these two-parameter are adjusted to the smaller value the colour becomes dark as showed Figure 3 in the bottom right corner of the sample.

Table 1 show the range of machine parameter and Table 2 shows the laser repetition frequency and releasing time scanning speed and power, we set as 225kHz, 5micro second, 350mm/s, and 15W. The hatch distance range was from 1 to 10 micron with an incremental of 1 for each lasering process. The pulse width range is from 10ns to 170ns with an increment of a minimum of 10 -25ns for each colour marking and the defocusing distance was 6mm for every colour mark. From the colour mark sample, we have chosen four representative colours to further investigate the surface roughness of the colour mark on the sample surface.

![Figure 3](image-url)
Figure 4. Color obtain in the fixed defocusing distance.

Table 1. Range of parameter of the machine.

| Parameter                     | Range of parameter       |
|-------------------------------|--------------------------|
| IPG fiber laser machine       |                          |
| Power                         | 30W                      |
| Frequency                     | 300KHZ                   |
| Scanning speed                | 10000 mm/s               |
| Pulse width                   | 300ns                    |
| Focal plane                   | -                        |
| Hatching distance             | -                        |
| Workpiece dimension           | 150mm x 150mm            |

Table 2. Laser parameter for coloring process.

| Laser parameter               | Symbol | Unit             | Value  | Increment |
|-------------------------------|--------|------------------|--------|-----------|
| Repetition frequency          | F      | (kHz)            | 225    | -         |
| Average power                 | P      | (W)              | 15     | -         |
| Releasing time                | Qt     | (Microsecond)    | 5      | -         |
| Defocusing distance           | D      | (mm)             | -6mm to +6mm | 1 |
| Hatch distance                | H      | Micron           | 01-Oct | 2         |
| Scanning speed                | V      | (mm/s)           | 350    | -         |
| Pulse width                   | Pw     | (ns)             | 170    | 10        |
3.2. Surface characterization
The analysis of surface roughness on the colour making of the sample surface has been an investigation on their roughness in corresponding to the formation of colour. The four representative colours were picked for this study, which is green, purple, blue, and grey colour as shown in Figure 5. Therefore, the relevant parameter for producing this colour mark has been shown in Table 2.

![Figure 5](image)

**Figure 5.** The four representative colours chosen for surface characterization.

However, in Figure 4a and b the same colours have been appearing several times at different locations. It shows that the colour can be obtained by the combination of the different parameter such as with the smaller pulse width and hatching distance. Although it can produce the same colour by different combination parameters, but the brightness and saturation of the colour are different. This is why we have chosen the four representative colours to further investigate their surface roughness on the colour mark.

3.3. Surface roughness
Table 3 shows the parameter used to colour marking the four distinct colours by varying the pulse width, hatch distance, and defocusing distance while the other parameter was fixed, which are scanning speed, power, and repetition frequency. By adjusting these three parameters as stated, the formation of colour on the sample surface was different, while a small change of such value could produce same dark colours as shown in Figure 3. However, with the large value of pulse width and defocusing distance, the colour produce was brighter while the colour was reflecting the lights such as
the blue, green, and purple colour. Apart from the effect of these three parameters on the formation of the colour, the roughness of the sample surface is an important aspect of the colour marking where different roughness produces dissimilar colour. Hence, the result of the 2-dimensional image and 3-dimensional image of the four representative colours has been capture by using an 3D optical microscope. Then, each colour has been comparing with the hatching distance where it is the distance of scanning track of laser, the pulse width is the power produce by laser during lasering process and the defocusing distance is the focus point of the laser beam and the workpieces surface where this comparison value has been shown in Figure 6.

These figures have summarized the adjustable parameter, which is the pulse width, defocusing distance, and hatch distance in marking of these colours and the fixed parameter of these colours has been presented in Table 3. The formation of the four-color comes at different defocusing distance. The hatching distance also a major part but it only differs slightly compare to the defocusing distance. Therefore, the defocusing distance needed to precisely be adjusted as compare with the adjustment of another parameter to form the colour.

The roughness test of 4 different colours is compared and showed in Figure 7. In this comparison the surface roughness value for four representative colours has been concluded, where it shows that the grey colour produces on the roughest surface with the $R_a$ value of 0.433 and $R_z$ value of 3.63. Hence, the rougher the surface the colour tends to be darker. This is due to an uneven roughness surface of the sample without polishing the entire surface. For the next three representative colours, there seems to be a slight change in the value of $R_z$, which is the maximum peak. In contrast with the different roughness distribution at the metal surface laser treatment where it differently affects the surface during the colour marking process. Moreover, from the macrostructure showed in Figure 6. It can be seen that the smoother the surface, the heat is distributed evenly to form a thin film layer. Hence, the colour can appear in solid nature. But when the surface is rougher the hatch distance is observed in the form of scanned tracks. Likewise, when the surface is rougher it is hard to interact with the material with laser treatment where it can lead to appearing dark colour. From the glance we can conclude that many of the researcher has mentioned the important of polishing the metal surface to even surface roughness before the laser treatment [14]. However, further studies should be conducted to investigate the effect of surface roughness in different grit paper and polish surface.

### Table 3. The processing parameters corresponding to different colours.

| Color | Scanning speed (mm/s) | Defocusing distance (mm) | Hatch distance (mm) | Repetition frequency (kHz) | Pulse width (ns) | Average power (w) |
|-------|-----------------------|--------------------------|---------------------|---------------------------|-----------------|------------------|
| Purple | 350                   | 4mm                      | 10mm                | 225kHz                    | 15              | 15W              |
| Green  | 350                   | 5mm                      | 8mm                 | 225kHz                    | 25              | 15W              |
| Gray   | 350                   | 6mm                      | 8mm                 | 225kHz                    | 50              | 15W              |
| Blue   | 350                   | 4mm                      | 8mm                 | 225kHz                    | 100             | 15W              |
| Sample overview | HD   | DD  | PW  | 2D        | 3D        |
|-----------------|------|-----|-----|-----------|-----------|
| Purple          | 10mm | +4mm| 15ns| ![Sample image](image1) | ![Sample image](image2) |
| Green           | 8mm  | -5mm| 25ns| ![Sample image](image3) | ![Sample image](image4) |
| Blue            | 8mm  | +4mm| 50ns| ![Sample image](image5) | ![Sample image](image6) |
| Grey            | 8mm  | 6mm | 100ns| ![Sample image](image7) | ![Sample image](image8) |

**Figure 6.** Overview of 2d and 3d sample by 3d optical microscope of four-color marking on different hatch distance, defocusing distance and pulse width.
4. Conclusion
In the conclusion of this study, we have provided some intuition into the proper selection of parameters such as laser pulse width and defocusing distance during the laser colour marking process on the SS304L metal surface. Following results can be concluded from this study.

1. The sample surface produces different colours with the changes of pulse width and focus distance due to the changes in the thermal interaction of laser with the metal surface and due the absorption effect. However, it is indicated that an accurate selection of laser treatment parameters, such as smaller Pulse width and defocusing distance will result in the formation of colour are mostly in dark for example brown, black and dark brown colour.

2. By increasing the pulse width, hatch distance, and defocusing distance samples could form a brighter colour. With the increase of these parameters the rich colour from where the heat is distributed evenly through the entire laser treatment space to a solid colour.

3. From the roughness result, it can conclude that the formation of colour at each surface is different. This is due to a raw surface with uneven surface roughness distribution that can affect the laser treatment process. The rougher the surface the colour produced will be darker. In particular, the effect of pulse width and defocusing distance on colouring stability was greater than the hatch distance.

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