Study the Effect of Changing the Surface Roughness and the Laser Focus Distance to the Aluminum Appearance using Picosecond Laser

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Abstract
Picosecond laser device is used to treat Aluminum samples, the appearance of the treated samples is affected by the variation of laser focus distance and the samples surface roughness. Samples with smoother surface before laser treatments show dark colors and high increase in surface roughness after laser treatments, while samples with rougher surfaces before laser treatments show brighter colors with slightly change in surface roughness after the laser treatments. The surface texture, topography, and roughness of the treated samples is characterized to identify the mechanism driving appearance change. The characterization results indicate that size and shape of laser processing induced microscale cavities on the surface may account for the differences in samples appearance.

Keywords
Picosecond Laser, Surface Roughness, Focus Distance, Aluminum Appearance

Disciplines
Mechanical Engineering

Comments

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1. Introduction

The variation of the processes used in manufacturing have created a place of competition to achieve the highest requirements in regards to cost, ease-of-processing, safety, and reliability. Laser processes are widely used for the applications that required accuracy such as micromachining, thin film deposition and metal cutting[1]. Picosecond and nanosecond pulsed lasers have shown advances in creating Laser Induced Periodic Surface Structure (LIPSSs) at periods less than the laser wavelength. Previous reports have demonstrated laser treated surfaces are able to function as color filters. In 2008, Vorobyev and Guo have reported that they were able to colorize metals without using coating; they were able to create gold, black and grey colors on Aluminum surface by using femtosecond laser. The authors also stated that “Other colors can also be produced on metals when experimental conditions are modified”[2], which lead Antończak to perform deep study on the dependency of the Titanium (grade 2) appearance on the variation of process parameters obtained by commercially pulsed fiber laser. The author suggests some modification to the laser system in order to improve the reliability of color saturation[3].

Peng, Yan et[4] has found that the absorption efficiency at the silicon surface to be higher at denser intervals of average height spikes that were milled by a 400nm wavelength laser. Since the laser influence varies depending on the materials properties, Ou, Zhigui has studied the influence threshold of femtosecond laser.
blackening of stainless steel, brass, and Aluminum, and found that the laser influences on Aluminum surface have different reflectance behaviour than the reflectance from the steel and brass. The author concludes that the surface structures corresponding to different colors than black, show looming ripples on the structure while the black color form large ravines [5]. To this extent, this field still attracted researchers interest; Wu, and XJ has been able to create uniform arrays of periodic Nano ripples and nanoparticles by using femtosecond laser [1].

Recently, it has been reported that the periodic of holes arrays can transmit light efficiently, and the transmitted color can be controlled by changing the shape and the dimension of the hole in the array. This finding indicate the correlation between surface Plasmon and incident light to control transmission of the light through the hole[6]. With the advantage from Aluminum high plasma frequency, Inoue, Daisuke was able to excite a range of visible light through arrays of subwavelength holes in an Aluminum film [7].

The focus of this paper include the influence of the pre-surface condition and the variation of pico-second laser focus distance to the Aluminum appearance. The laser-induce surface structure are characterized using SEM. SEM images are used to identify characteristic surface textures and structures that correspond to different appearances.

2. Experiment

The material used for this experiment is Aluminum (99.998% Al) with 1mm in its thickness. A picosecond laser, (ultrafast fibre laser) HE 1060- series with a Wavelength of (1064 nm), maximum output power (< 15W), and minimum pulse width (>80 ps), the Maximum energy for each pulse is up to (15µJ), and high repetition frequency (50 KHz) was used for the surface treatment. A focusing lens used to converge the laser beam, the directed beam has a Gaussian profile with a 67.7 µm spot diameter at the focal focus. The focal point distance was measured between the substrate surface and the focusing lens founded to be 127mm. The samples were put on a stage that can move in the z direction, while movement on the x-y directions are controlled by scanner. The scanner was programmed to draw 2D grid patterns on the sample surface.

<table>
<thead>
<tr>
<th>Sample number</th>
<th>Polishing grit</th>
<th>Focal distance (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample 1</td>
<td>1200</td>
<td>127</td>
</tr>
<tr>
<td>Sample 2</td>
<td>600</td>
<td>127</td>
</tr>
<tr>
<td>Sample 3</td>
<td>600</td>
<td>129</td>
</tr>
<tr>
<td>Sample 4</td>
<td>1200</td>
<td>131</td>
</tr>
<tr>
<td>Sample 5</td>
<td>600</td>
<td>131</td>
</tr>
</tbody>
</table>

After the laser treatments the samples were rinsed by acetone and then washed with distilled water, a similar process repeated by using ethanol and then washed with distilled water again. The laser treatment was drawn as a grid path with a size of 7 x 7 mm² and the step distance was 32 µm, the speed was fixed at 350mm/s. Pictures of the samples were taken under the sun light by a professional camera that can present clear imaging of the observed colors among the samples. SEM micrographs were taken using the FEI Quanta 250 FE-SEM instrument. Zygo instrument were used for surface roughness measurements. The Fast Filter Transform (FFT) of the SEM images was used to identify the periodicity of surface structures.

3. Results and Discussion

Different colors are observed on the Aluminum surface after the laser treatments. In general, the treated samples surface showed colors with different levels of brown and yellow with some haze and glossiness on their appearance. Figure 1 shows the samples surface and identifies the different colors that appeared on treated sample surfaces. Sample 1 appears as a mixture of colors mostly red and brownish, the darkness become more dominant on the appearance over the red and that is why the sample surface appeared mostly as a deep red color. Sample 4 appears as a brown and light red color as well, but this sample shows saturated dark brown under the sun light than sample 1 appearance, the higher domination of the brown color over the red has presented the appearance of the nice homogenous dark brown on the surface. Sample 2 and sample 5 both are in the yellowish color range as a dominant color. Although the appearance has some levels of haze making the color identfication difficult with the room lighting, the pictures taken under the sun light show that sample 5 is mostly bronze colored and sample 2 takes the ochre color. Sample 3 appears with having some glossiness, which covers more of its color details. However, sample 3 mostly consist of copper color.
3.1 Surface Morphology

The interaction between the laser beam and the materials surface has been considered a complex process, there are many parameters that govern the laser fluency on the material, some are related to the laser properties itself, some others are related to the materials’ properties and the rest are related to the treatments’ process. In regards to this experiment, the fixed parameters for all the treated samples are the parameters related to the laser such as the wavelength, the pulse energy, the pulse width and the laser frequency; Parameters related to the materials such as dielectric properties of the materials; and for the treatments’ process are the speed of the laser beam movement on the surface, and the environment of the treatments which was on air. All these parameters contribute in creating the surface textures. The variable parameters which are believed to be responsible for creating different sample appearance are the distance from the laser beam focus point and the condition of the surface roughness before the treatments. The distance of the sample holder has been changed from 127mm at focal distance to 131mm, about 4 mm away from the focal point. The observations indicate that there is correlation between the sample appearance and the change in surface morphology. The roughness measurements indicate that the samples that are polished to the mirror-like surface has shown a rough surface after laser treatments. On the other hand, the samples polished with 600 grit show a slight change in surface roughness after laser treatments, table 2 below shows the detailed roughness measurements of each sample and the color appearance.

<table>
<thead>
<tr>
<th>Sample number</th>
<th>Surface roughness (µm) before laser treatments</th>
<th>Surface roughness (µm) after laser treatments</th>
<th>Peak to valley (µm)</th>
<th>Appearance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample 1</td>
<td>0.033</td>
<td>1.116</td>
<td>17.320</td>
<td>Deep Red</td>
</tr>
<tr>
<td>Sample 2</td>
<td>0.195</td>
<td>0.590</td>
<td>8.955</td>
<td>Ocher</td>
</tr>
<tr>
<td>Sample 3</td>
<td>0.173</td>
<td>0.528</td>
<td>10.856</td>
<td>Copper</td>
</tr>
<tr>
<td>Sample 4</td>
<td>0.037</td>
<td>0.591</td>
<td>7.121</td>
<td>Deep Brown</td>
</tr>
<tr>
<td>Sample 5</td>
<td>0.162</td>
<td>0.507</td>
<td>9.627</td>
<td>Bronze</td>
</tr>
</tbody>
</table>

The results indicate that haze and glossiness only appeared on the samples that were polished to have a rough surface before the treatments which are samples 2, 3, and 5. On the other hand, darkness has appeared on samples 1 and 4 which were polished to mirror like surface before treatments. By looking at the surface roughness, samples with dark appearances demonstrate the highest increase in surface roughness, while samples that have haze and glossy properties have recorded lower change in surface roughness values. But these indications are not enough to illustrate the difference in the appearance. Instead, by looking at the peak to valley measurements and the surface roughness values together, which makes a link between them and the samples appearance, which there are missing factors that play the major role in varying the surface appearance.

3.2 Scanning Electron Microscope Micrographs

The SEM micrographs for samples 1 and 4 in figures 2 and 3 illustrate the surface structure of the samples at 5 µm scale. Although, all samples have been treated using similar grid drawing during the laser treatments, different structures were created on the samples surface. Samples 1 and 4 show the path of the laser treatments as flat melted materials formed as layered structure, between the laser treatments paths there are periodic lines which are known as LIPSSs with what are believed to have some of the ablated materials deposited on top of them. Surface structure of sample 1 can be divided into three areas: First area marked as (1) on the micrograph is the path of the laser beam on the surface, the surface as shows a layered structure. Second area is marked as (2) on the micrograph, the LIPSSs are obvious with small particles of ablated materials deposited on the surface. Third area is marked as (3) which is shown LIPSSs with discontinues pattern. Sample 4 shows the path of the laser treatment with the LIPSSs between them, which is different than sample 1’s structure, where due to the increase in beam diameter, an overlap of the laser path treatments was happening.
LIPSSs with discontinues pattern disappeared which was represented as the third area on sample 1 micrograph.

The SEM micrographs shown in figures 4, 5, and 6 are samples 2, 5, and 3 at 5µm scale. Sample 2, and 5 didn’t show any pattern of the laser treatments path. Both samples show continuous LIPSSs with an obvious difference on the spacing and the depth between peaks. The structure of sample 3 shows a combination of discontinuous LIPSSs and some large grains with a flat smooth surface.

It has been reported in literature that the incident light can be coupled into metallic surface plasmons and create either enhancement of the electric field near the surface or reduce the oscillation of the electric field. This can be determined based on different factors such as the nanoscale geometry of the surface, the periodicity, the dielectric properties and the materials composition on the surface. These factors play a major effect in transmitting, scattering and refracting the electromagnetic waves and work as color filters for some materials [6, 8-12]. The SEM micrographs in this research have shown periodic structure at several different length scales. Between these structures are different shapes and sizes of nanostructures which may be related to the differences in the samples appearance. The spatial periodicity of these structures were identified using FFT analysis of the SEM images at different magnification. The wavelengths corresponding to highest values in the FFT transform are tabulated in Table 3 for SEM images taken at different magnification.
Table 3: Dominant wavelength of the spatial patterns identified using FFT of the SEM image of samples.

<table>
<thead>
<tr>
<th>Sample number</th>
<th>Dominant Spatial wavelength in FFT of 5000X SEM image (µm)</th>
<th>Dominant Spatial wavelength in FFT of 15000X SEM image (µm)</th>
<th>Dominant Spatial wavelength in FFT of 50000X SEM image (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample 1</td>
<td>0.176</td>
<td>0.739</td>
<td>0.638</td>
</tr>
<tr>
<td>Sample 2</td>
<td>0.015</td>
<td>0.862</td>
<td>0.832</td>
</tr>
<tr>
<td>Sample 3</td>
<td>0.014</td>
<td>0.733</td>
<td>0.672</td>
</tr>
<tr>
<td>Sample 4</td>
<td>0.191</td>
<td>0.781</td>
<td>0.851</td>
</tr>
<tr>
<td>Sample 5</td>
<td>0.014</td>
<td>0.719</td>
<td>0.665</td>
</tr>
</tbody>
</table>

FFT analysis of the 5000X SME image demonstrate that samples 1 and 4 have spatial periodicity with the highest wavelength among all the samples. On the other hand, samples 2, 3 and 5 have lower wavelength of periodicity in spatial wavelength. By looking at these numbers and matching with the samples appearance (samples 1 and 4 are darkest), it appears that the spatial periodicity variation among the samples surface may be responsible for controlling the contrast and the brightness of the samples appearance. Meanwhile, the FFT analysis of higher magnification images (15000 X and 50000 X) are shown to have periodic spacing similar to the wavelength range of the visible colors. This may contribute to the parts of the visible spectrum that are reflected from the sample surface. The correlation between the spatial periodicity at lower magnification and sample brightness is interesting and is being further investigated.

The micrograph of sample 1 at higher magnification are shown in figures 7 and 8. The LIPSS appear narrow with rounded nanoparticles on top of them. Similar area at 50000X scale show that the cavities are almost triangular in shape and have spatial periodicity of approximately 0.638µm. A study in literature indicates that the triangular shape is the better choice for red, green and blue filters[7]. However, the color of sample 1 is deep red and doesn’t indicate presence of red, green and blue filters. At lower magnification, the sample surface shows three distinct surface morphology as discussed previously. These areas are different in structure, topography, and cavity then the triangular cavities seen in area (2). In area 1 it is believed that the oxide film appeared thicker which added more darkness to the appearance. Presence of three distinct morphologies may have produced different color reflection from the sample surface and thus the sample surface appears deep red.

SEM micrograph of sample 4 are shown in figures 9 and 10 at 15000X and 50000X magnification, respectively. The structure appeared as disordered Nano disks on top of each other, where periodicity is not exact. Further, the structure at the 50000X magnification scale appear layered at different elevations with what seems to have a thin oxide layer on top. The micrograph also shows cavities in different sizes between the disks structure. Those cavities have differences in depth. The FFT scan results show increasing in the spacing between LIPSSs from 0.781µm at 15000 X to 0.851µm at 50000X magnification. This increase indicates that the cavities may be pyramidal in shape. Pyramid shapes are believed to trap huge amounts of light. Since it has been found that different nano disk sizes show strong localized surface plasmons resonance at the UV range[10], it is possible that the trapped light at the pyramids shape is associate with the surface plasmons and then re-emitted in a visible wavelength at a consistent manner. That re-emission process with considering the effects from the parameters such as the oxide layer thickness, the periodicity, and the different in nano disk size may have to contribute to the dark brown color of sample 4.
The SEM micrographs of sample 2 at 15000X and 50,000X magnification are shown in figures 11 and 12, respectively. At both of these scales, continuous LIPSSs with a spacing distance of 0.862 µm and 0.832 µm respectively are observed. The surface of this structure appeared smooth with circular cavities between the plateaus. The holes orifice are almost straight with a little deviation which can be indicated from both micrographs. These differences of the cavities orientations with respect to the polarization of the incident light would cause a diffraction of the incident light [6]. When these diffracted patterns are re-emitted and coupled with the scattered patterns from the periodic structure, they will create a propagated wavelength at the visible color range. With considering the smoothness of the surface, the large spacing distance and the orientation of the cavities; the reflected light from the surface was interrupted with the diffraction process from the holes orifice. As a result haze has been created which covers the actual color of the sample at the room lightening, and in sunlight sample 2 appears Ochre.

Since Sample 3 shows a glossiness on its appearance, the SEM micrograph in figures 13 and 14 at 15000X and 50000X magnification, respectively, show LIPSSs with dense bridges between them. These bridges at the 0.5 µm scales are shown as squares in arrays. These squares are formed of two thin sides which are the bridges and the other two sides are thicker sides which are the LIPSSs. The indications from these squares was to create a higher localized surface plasmon resonance at the thinner sides of the square rather than the thicker sides. In consequence, an additive scattering will cause an intense bright emission that appeared as a glossiness on the surface. Moreover, by considering the spatial periodicity identified using FFT analysis at 15000X and 50000X magnification, the decrease in spacing values indicates that partial patterns may be in form of V-grooves. The electromagnetic properties of the V-grooves in an Aluminum sample has been studied in literature[8]. It has been found that the v-groove can create an additive color at the dark field scattering. That finding is to some extent incongruous with the structure of sample 3. However, the size and the shape of the squares and the depth of the grooves are not exactly perfect as fabricated samples in the reported literature; as a result, it believed that at the bright field the wavelength absorption is higher inside the groove. This makes the sample appear copper.
Sample 5 and sample 2 both have hazy appearance in common. By comparing between the SEM micrographs, it has been found that both have continuous LIPSSs at the 15000 X magnification and both have smooth surface. It is believed that these two structures are responsible for the haze appearance on these sample surfaces. SEM micrograph of Sample 5 shown in figures 15 and 16 have the cavities as a rectangular shape at an irregular periodic arrangement. With considering the FFT analysis of 15000X and 50000X, there is a decrease in the spacing between the peaks as the depth increases. These rectangular arrays function as V-grooves as mentioned on sample 3. The difference between sample 5 and sample 3 was the size of the cavities. In sample 3 the cavities are almost squares, and the spacing between them was narrow, while in sample 5 the cavities take the rectangular shape with an interrupted periodicity. Further, the V-groove structure appearance are effected with the angle of the incident light. Considering the dimensional differences of the spacing among peaks and the inclination at the edges of the peaks, the reflection behaviour will be affected by the diffractions from the surface into the groove. As a result, sample 5 mostly looks like a Bronze color.

4. Conclusion.

Factors such as the spacing between LIPSSs, the surface microstructure, the size of cavities, shape, spatial periodicity and smoothness of microstructure were responsible for the differences of the samples’ appearances. The dark red color of sample 1 was a result of differences on the sample microstructure, topography, and cavity size and shape. The dark brown color of sample 4 is related to the layered stackable nano disks structure, with cavities taking a pyramid shape at different elevations. The glossiness on sample 3 is caused by the resonance created on the thinner sides of the periodic square arrays. Also the V-groove structure is associated with sample appearance. Appearances of samples 2 and 5 were caused by the continuous LIPSSs and smooth surface at 0.5 um structure. Sample 2 shows an orifices directed at different angles while sample 5 shows V-grooves created with rectangular shape cavities. These factors played important roles for the samples appearance.

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