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Effect of Laser Parameters on Colour Marking of Ti6Al4V Titanium Alloy

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EFFECT OF LASER PARAMETERS ON COLOUR MARKING OF Ti6Al4V TITANIUM ALLOY

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Abstract. Colour laser marking is a contemporary method for adding colours onto metal surfaces, suitable for creating logos, barcodes, metal crafts, and jewelry. This study focused on colour laser marking on the biomedical alloy Ti6Al4V (TC4), examining how different colours manifest on its surface. Power settings ranged from 9 W to 18 W, while frequencies spanned 500 kHz to 2000 kHz. The research investigated how altering laser frequency and defocus distance influenced colour variation. Surface features were assessed using 3D optical microscopy, revealing texture and roughness traits. Results illustrated a spectrum of colours, shifting from the alloy's original silver hue to shades like blue, gold, orange, shiny silver, violet, and several greys. Each colour displayed distinct surface texture and roughness parameters. The highest mean roughness of 2.504 µm occurred with grey, while silver had the lowest at 0.504 µm. Nevertheless, trends differed when measuring parameters like maximum peak-to-valley height and valley depth, emphasizing surface topography's role in colour effects. This research advances the understanding of colour laser marking's intricacies on TC4 alloy, providing insights into optimizing laser settings for specific colour outcomes and underlining the nuanced relationship between colour, texture, and surface characteristics.

Keywords: Laser colour marking, Ti6Al4V, parameters, surfaces

1. Introduction

Over the years, colour laser marking (CLM) has been introduced in the industry, but it is not widely employed. Other methods used in colour laser marking (CLM) are thermos-printing, emulsion coating or electrolytic oxidation [1]. Laser colour marking is known as one of the easiest, fastest and cheapest forms of colour marking processes compared to the other methods [2]. Colour laser marking is preferable due to the high quality, high wear resistance, easy and fastest production making, non-contact marking and it is the cheapest compared to other techniques. This method uses a laser which will act as a heat source that allows thin transparent or semi-transparent oxide films to form. At a certain angle, the beam of parallel monochromatic light will fall on a transparent or semi-transparent layer. The oxide layer will repeatedly reflect the beam from the surface of both oxide and metal. Research by Łęcka et al. [3] said that the effect of colour can be observed and controlled if the oxide thicknesses on the surface are increased.

Generally, a colour laser marking on metal surfaces is something that is permanent has a separate change of colours and is non-penetrating. This type of form also is referred to as a "stain mark" which can be accomplished on titanium, stainless steel, and chrome. Titanium alloy is one of the most used alloys in the industry especially in the aerospace and biomedical fields due to its amazing properties such as high strength, low-density volume, great corrosion resistance and superior biocompatibility [4]. However, due to some limitations and problems that take place during the processes, they are not widely found in practical application and have very little commercial impact in the industry. The typical problems occur such as adverse scratch properties and resistance to wear, the difficulty of the process, and colour fading over time [5].

Next, colour laser marking is a technique that is very susceptible to minor changes in the processing parameters on titanium surfaces [2]. Due to their exceptional mechanical properties, good corrosion resistance, and reasonable biocompatibility, titanium-based alloys, notably Ti-6Al-4V, have recently received considerable attention [6]–[9]. To obtain the final resulting colour, the requirements of power stability, scanner speed average power, hatching pattern as well as optical characteristics of the laser beam play an important role. Several methods for surface modification were created to improve the surface properties of Ti-6Al-4V [10]–[13]. To achieve reproducible results on the same workpiece, all these parameters need to be explored and studied. Wang et al. [14] project was about a novel high-throughput laser surface nano structuring technique to increase the hydrophobicity and decrease the reflectivity of the Ti-6Al-4V surface using a nanosecond pulse laser. They stated that, the laser-textured Ti-6Al-4V surfaces exhibit anti-reflective, hydrophobic, and physically improved features. Then, Palmieri and Belcher et al. [15] designed a substitute for traditional chemical etching and abrasive processes, a laser ablation technique to improve the adhesion of Ti-6Al-4V surfaces. By utilising a scanning electron microscope (SEM) and energy dispersive spectroscopy (EDS), Next, Huang et al. [16] studied the microstructure and chemical constituents of the coloured sections. He mentioned that, this research presents a novel method for producing a wide spectrum of colours on TC4 alloy, which may find broad application in laser colour marking. Gao et al. [5] investigated technology of laser-induced colouration of TC4 by surface oxidation. Their intention is to determine the influence of thermal field on the marking colour, which is used for regulating colour with one operating variable. After that, Antończak et al. [1] demonstrated the outcomes of measurements and an evaluation of the impact of laser process parameters on the produced colour. They stated that, a number of adjustments to widely employed laser systems for monochrome marking have been suggested in order to enhance the consistency of colour marking. Other than that, Soveja et al. [17] explained the experimental investigation of laser surface texturing of TA6V alloy by applying two experimental methods, the impact of operational factors on the laser texturing process has been investigated which were Taguchi technique and response surface methodology (RSM). Ocaña & Calatayud et al. [18] also proved that small titanium and Ti6A14V alloy pieces can be coloured. They presented the conditions and techniques applied for achieving the colours gold, yellow, blue, and purple. Jwad et al. [19] research explored the use of single-spot oxidation on titanium substrates as an approach to enhance the resolution of the processed area and meet the demands of future novel applications. In order to obtain oxide films of varying thicknesses and, consequently, varied vibrant hues on titanium substrates, they employed a specific methodology. Khafaji et al. [20] study unveiled an investigation of the laser-induced colouration of commercially pure titanium (grade II) samples. The experiment was accomplished under three separate gas atmospheres and resulting colouration phenomena are thoroughly examined and evaluated.

In the research and literature available, past researchers have focussed on material compatibility and optimization, colour fastness and durability, colour mixing and blending, but they had not investigated the corresponding effect of laser colour marking on the surface characteristics. However, in this research, the roughness values and the surface texture of Ti6Al4V titanium alloy are being evaluated for the colours that are formed. As a way to ensure the production of a high-quality colour laser marking, it is imperative in the experiment to prioritise and emphasise specific parameters. The development of optimum colour marking in laser marking requires careful evaluation and modification of several process parameters. These parameters include power, scanning speed on the surface, frequency, hatching distance, pulse width, defocus distance, and other relevant factors. Thus, it is crucial to assess each parameter's significance as the production of colour is influenced by the surface roughness of Ti6Al4V titanium alloy.

1.1. Material preparation

Titanium alloy TC4, Ti6Al4V, is used as the plate sample. In this experiment, a square shape specimen of Ti6Al4V is used with the dimension of 50 mm x 50 mm (figure 1) that can contain up to 16 fields (8 mm x 8 mm). Each field produced several colours using a different set of process parameters. As mentioned by [1], the sample surface needs to be polished with isopropyl alcohol in an ultrasonic cleaner and then later can mark in atmospheric air. However, in this experiment, we do not polish the surface sample as we wanted to analyze direct colour laser marking on pure unpolished titanium.

The data acquisition setup comprised a scanner laser head with a horizontal periscope, it was linked to a pair of optical cables. One of the fibres utilised in the setup was a fibre optic bundle with a round-to-linear configuration, which served the purpose of forming a connection with the spectrometer. On the other hand, the second fibre was responsible for transmitting the energy of the laser supplied via the laser supply. To achieve this, both the laser source and the fibre optic bundle have been linked through the use of a connector, as depicted in figure 2, which served the purpose of concentrating the reflected the illumination emerges from the welding spot. The laser beam generated within the welding region was directed towards the spectrometer using the scanning laser head, consisting of a partly transmission mirror and an optical fibre. Subsequently, the reflected laser beam underwent collimation via a collimator, and the information obtained has been collected, presented, and saved via computer software.

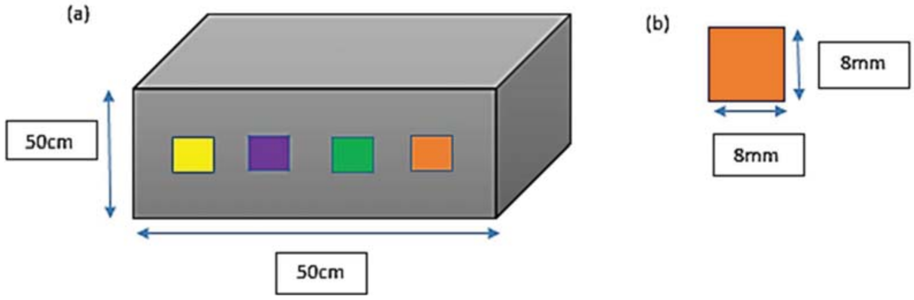

Figure. 1 (a) the sketch of colour produced on titanium Ti6Al4V size (b) design is 8mm x 8mm using the CLM.

1.2. Experimental setup

The study has been performed in detail using commonly IPG-Fibber Laser Marking Machine shown in figure 2, with a wavelength of 1064 nm and an average of 15 W. In a scanning region of 8 mm x 8 mm, the laser beam needs to be focused on the sample surface using an F-theta lens first to complete a line scan starting from the right side to the left side. Besides, this fiber laser has a maximum output of 30 W and a pulse repetition frequency of 10-300 kHz. When compared to a laser (wavelength of 532 nm), the optical path of the laser used in this study (wavelength of 1064 nm) is visible, easy to be changed and user-friendly. To control the laser transmission, a laser marking software called EZCAD is used to set up the parameter setting. The Olympus LEXT OLS5000 3D Measuring Laser Microscope was used to get microscopic and topographic images of the colour sample. Here, a matrix approach that was used to analyze the effects of the parameter settings in this experiment to find out either of the change in colour induced can be caused by the processing parameter. At the submicron stage, the OLS5000 laser confocal microscope tests measure surface roughness. A four-fold increase in data acquisition speed over our previous model results in a substantial increase in productivity.

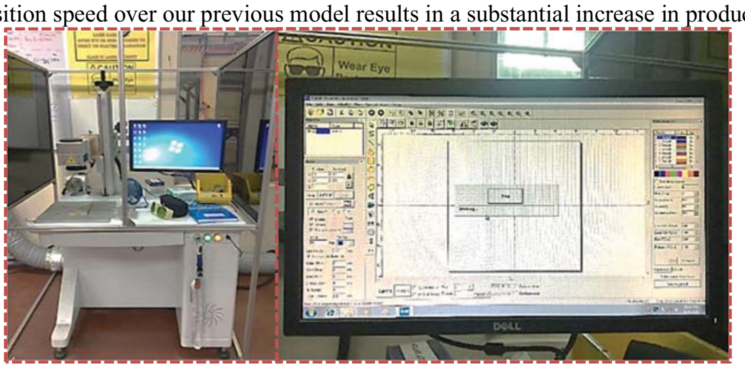

Figure. 2 IPG-Fiber Laser Marking Machine and Ezcad Software.

2. Result and discussion

2.1. Preliminary test

In order to discover the parameters effecting colour formation, a study with varying conditions was conducted with several fixed parameters. According to results in table 3, the colour laser marking has been run on 4 sets of samples which are samples A, B, C and D. For sample A, golden colour is obtained with the change of Power [W] and Frequency [kHz] while other parameters is kept in constant condition. With the range power of 9 until 18 W and range of frequency from 500 to 2000 kHz, the golden colour is then reduced it to light yellow colour. It shows that as the frequency is reduced, the colour changes from gold to light yellow. By using the same technique in sample B but adjusting the defocus distance by increment of 2 mm, several multiple colours is achieved. As for sample C, a blue colour managed to be produced by controlling defocus distance and frequency whereas for sample D a brownish colour is gained also by using the same parameter.

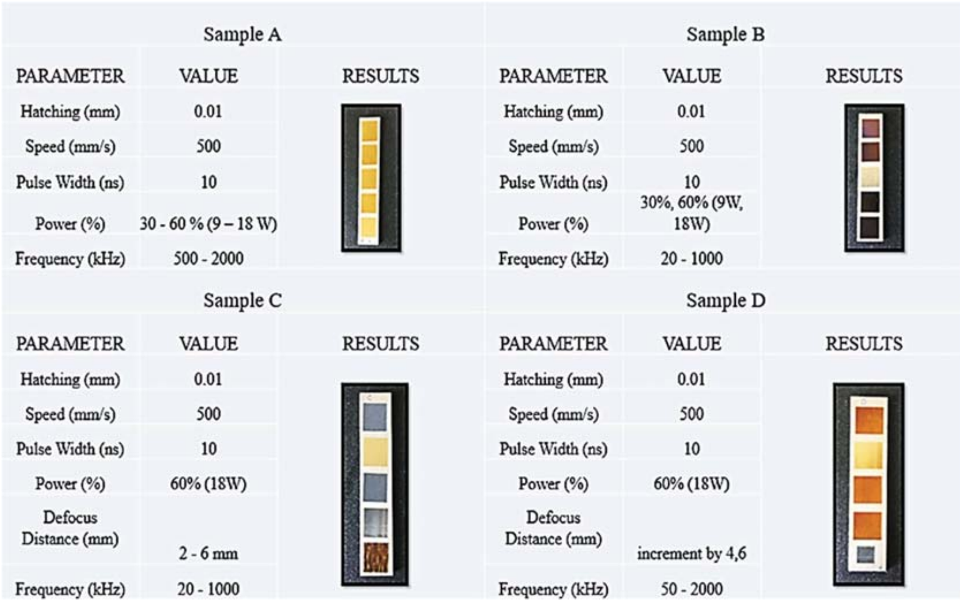

Figure. 3 Sample A, B, C and D with different parameters setting.

2.2. Formation of surface colours

The colours represented in figure 3 were formed using these fixed parameters with defocusing distance were varied as showed and the frequency along in table 1. the colour pallet with the variation of frequency and defocus distance. For detailed surface characteristics, roughness analysis we selected prominent 6 colours. The parameters selected for testing colours are shown in table 1. In figure 3 are the best results obtained from CLM on Ti6Al4V surface and various colours are induced on titanium surface because of oxidation. As seen from the figure, which we can simply conclude that by adjusting the parameters such as increasing its frequency, the surface will start to change and produce colour. As comparison, this can be proved from the previous study that revealed that only the frequency and the energy of the pulses have a significant effect on the laser surface texturing process [21]. For this experiment, frequency, in the range of 10-2000 kHz, and defocus, in the range of 0-8 mm, are chosen as our controlled variable.

Table. 1 Controlled parameters of colour laser marking

Parameters	Unit	Value
Power	W	18
Pulse width	ns	10
Hatching distance	mm	0.01
Scanning speed	mm/s	500
Defocusing distance	mm	Increment of 2
Sample size	mm	50 x 50

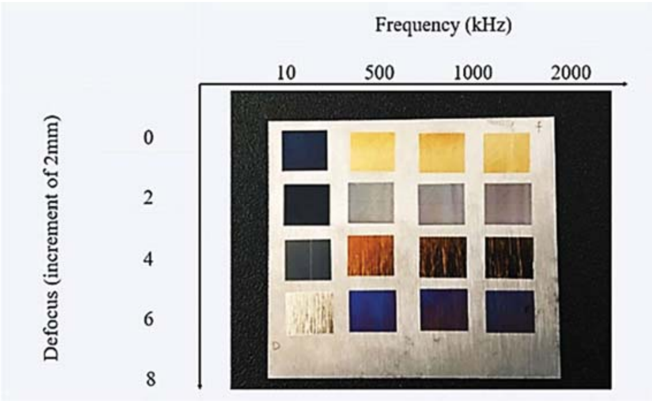

Figure. 4 Formation of different surface colours based on parameter changes.

2.3. Optical microscopy of colours and roughness measurement

Figure 5 presents the optical microscopy of (a) 2D images and (b) 3D images capture for a scale of 200 µm. table 2 below shows the values of surface roughness parameters (R_p, R_v, R_z, and R_a) for samples. By using LEXT OLS5000 3D Optical Microscopy microscope, the surface texture characteristics and surface irregularity have been analyzed. This laser is a confocal scanning microscope that is an excellent tool for non-contact and non-destructive 3D image analysis. The apparent reproduction of an optical image object is produced by a mirror or lens system that produces reflected, refracted, or diffracted light waves. In table 2 shows that the Ra µm value decreases when the frequency is at 10 kHz as the defocus distance for oxidation rises. The increase in surface roughness of Ti6Al4V alloy can be ascribed to the growth mechanism of the oxide layer. In addition, Ponsonnet et al. [22] discovered a significant relationship between the surface irregularity of Ni-Ti alloy and cell proliferation. They discovered that there's a roughness threshold above which cell proliferation is reduced, i.e., the rougher the surface, the less proliferative the cells.

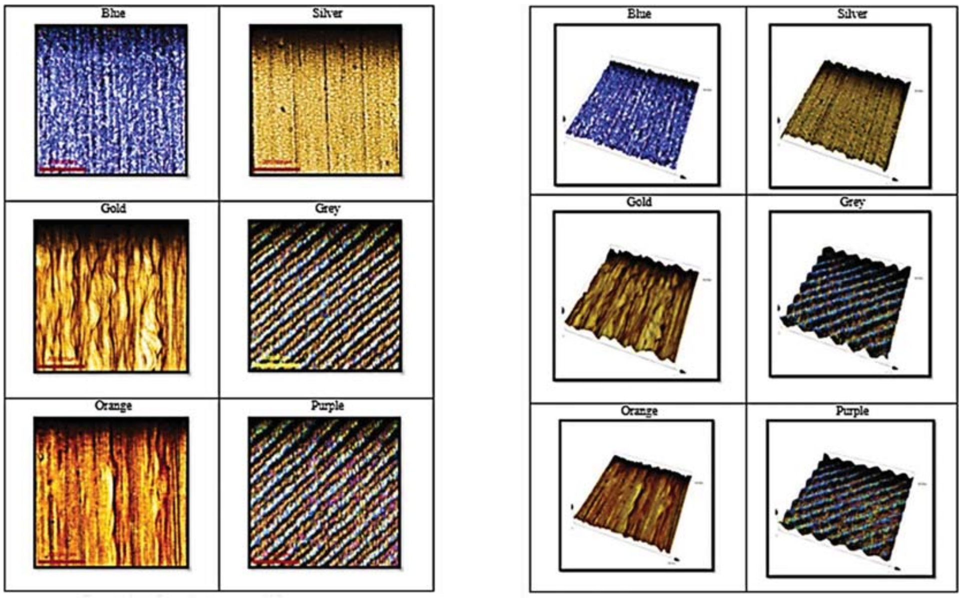

Figure. 5 Optical microscopy of (a) 3D images and (b) 2D images for a scale of 200µm.

Table. 2 Values of surface roughness parameters corresponding to each colour.

COLOR	R_p [µm]	R_v [µm]	R_z [µm]	R_a [µm]	Frequency (kHz)	Defocus (mm)	Hatching Angle
SILVER	1.497	1.739	3.236	0.504	10	6	-
GOLD	1.565	1.352	2.917	0.577	500	0	-
GREY	5.506	6.712	12.217	2.504	500	2	45°
ORANGE	1.302	2.504	3.806	0.678	500	4	-
PURPLE/VIOLET	4.42	5.401	9.821	2.114	500	6	45°

As mention before, frequency and defocus distance are set to be controlled variable whereas other parameter to be fixed which are power, pulse width, speed scanning and hatching distance. From the results, one can conclude that the different formation of colour on the sample surface is caused by adjusting these parameters. For instance, blue colour and silver colour is gained when the defocus distance increases from the origin to 6 mm whereas at 500 kHz with 0 mm defocus distance will form a gold colour surface. From here, it can be concluding that every parameter plays an important role to the production of colour of Ti6Al4V surface. Furthermore, table 2 shows that grey and purple colour has the roughest surface which are 2.504 µm (Grey) and 2.114 µm (Purple) and it causes the surface to have a 45° hatching angle whereas silver (0.504 µm) and gold (0.577 µm) colour has the smoothest surface. figure 6 below shows the plotted graph of surface roughness for each different colour which is also based on table 2. In this section, we analyzed the roughness test on a pure Ti6Al4V titanium alloy and on coloured laser marking samples. It can be depicted from the figure grey has the highest roughness (µm), followed by purple and blue while silver was the smoothest followed by gold.

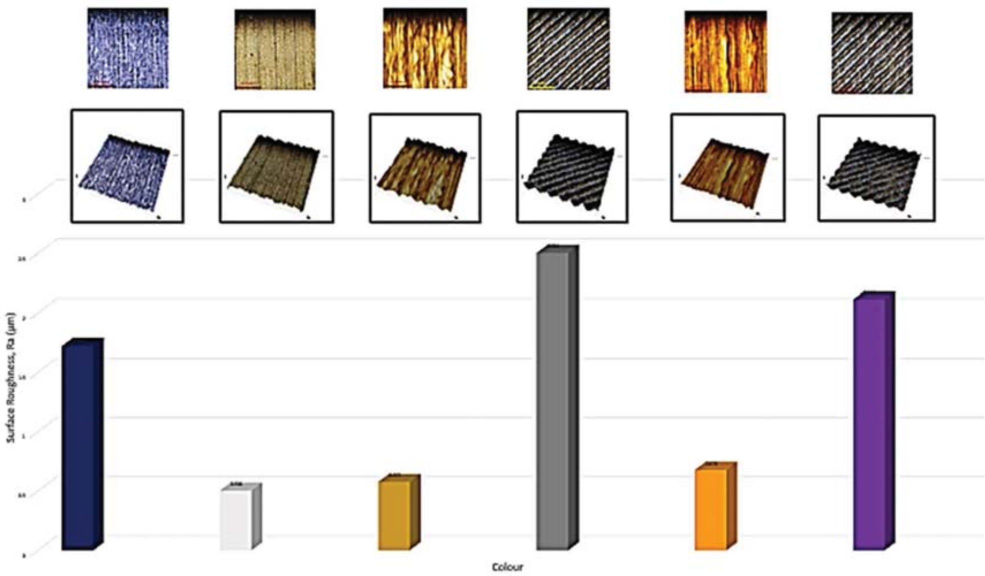

Figure. 6 Surface roughness of different colour of CLM.

3. Conclusion

Based on the explanation above, it is discovered that different colours may be obtained by varying the control parameters and the colour variation can be achieved by only adjusting a single control variable in a reasonable range.

- Through a power range of 9 to 18 W and a frequency range of 500 to 2,000 kHz, the initial golden tint becomes a pale-yellow hue. This transformation indicates that lower frequencies correspond to a transition from gold to pale yellow.
- Using the same technique on sample B, but varying the defocus distance by 2 mm increments, produces a range of distinct hues. In the case of sample C, adjusting both defocus distance and frequency results in a blue tint, whereas using the same parameters results in a brownish hue for sample D.
- Lastly, the study demonstrated that grey and purple surfaces have the highest roughness, measured 2.504 µm (Grey) and 2.114 µm (Purple), resulting in a 45° surface hatching angle. In contrast, surfaces of silver (0.504 µm) and gold (0.577 µm) are the smoothest.

Our findings reveal that each different colour can form different surface roughness of CLM titanium alloy components, and it is also influenced by the sample surface's process parameters while significantly changing the surface texture.

4. Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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