Experimental investigation into fiber laser marking on titanium alloy (Ti6AL4V)

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Colour Intensity,
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ABSTRACT

The paper deals with the analysis of marking quality on Ti6Al4V by using thermal energy of laser beam. The variation of process variables such as laser irradiation, pulse rate, scan rate, duty cycle and transverse feed resulted in the generation of colours on the surface which have a considerable marking contrast value. The intensity analysis conducted on line marking and surface marking reveals the fact that variables like laser irradiation, transverse feed, and scan rate plays a significant role in the change of colours when other process variables are held constant. Experimental studies revealed that the highest mark intensity obtained was 0.70 (pinkish colour) where lowest value obtained was 0.10 (purple colour whereas the standard maximum and minimum mark intensity were 1 (white) and 0 (black).

1. Introduction

Today's business makes extensive use of laser marking to provide distinctive markings on products and work items. For marking, various techniques and lasers are employed, with the latter being selected to match the absorptivity of the material. This makes it possible to generate diffraction gratings with high surface characteristics, quick marking speeds, and contrast on a variety of customized micro- and nanostructures. The first three mechanisms are used in various fields but can only be used for binary or grayscale marking. A variety of events, such as removing material from a thin anodized layer, adding absorbent surface structures, and tempering colours, can be utilized to generate contrast on a surface (Ackerl, 2020). Throughout the whole product life, laser marking of medical devices (such as surgical tools) which offers Unique Device Identification (UDI) must provide sufficient optical contrast, corrosion resistance, and wear resistance. During marking of metals in a chemically active environment (such as oxygen, air, or nitrogen), laser radiation with a power density on the melting threshold causes oxide layers to develop, which increases the marking contrast (Geng et al., 2022). Hanna et al. (2008) studied the process of laser surface colouring on titanium alloy for application in contemporary jewellery. He observed that the formation of marking is a combination of microgroove along with anodic oxidation. Huang et al, (2022) studied the mechanism of laser surface colouring using picosecond laser for the generation of colour marking on the surface of titanium alloy. Astarita et al. (2016) studied the marking on aluminium substrate using titanium coating. Experimental results revealed that better marked surface were obtained using titanium coating in comparison to single target aluminium substrate. Fiorucci et al. (2015) carried out surface modification of Ti6Al4V for biomedical applications using nanosecond laser. It was observed that oxide layer formed by TiO_2 increases the biocompatibility properties which favour osseointegration. Vazquez-Martinez et al. (2018) examined the effects of laser micro texturing on Ti6Al4V alloy. Increased scan rate was found to enhance the treated surface's hydrophobic properties, which in turn improved the functional performance of manufactured parts for a variety of applications in the manufacturing industry. Velotti et al. (2016) carried out laser marking of titanium coating with an aim to characterize the process on the groove geometry. Results showed the effectiveness of the laser to produce high quality marks on the titanium layer and its penetration depth was increased after coating. Eghbali et al. (2021) investigated the effects of process variables on cell adhesion and vitality. The findings showed that a groove with a depth of more than 50 micrometres using laser frequency of 20 kHz enhances the antibacterial and cell

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adhesion capabilities. Pandey and Doloi (2022) carried out experimental investigation into fiber laser marking on stainless steel 304. The analysis revealed that decrease of transverse feed from 8 to 2 µm/laser stroke resulted in the increase of time requirement to mark the surface whereas increase beyond 8 µm/laser stroke decrease the mark intensity value of laser marked surface.

The research studies observed so far has mainly focussed on the laser marking and surface texturing on Ti6Al4V for biomedical applications. However, the present studies deals with the laser marked surface on titanium alloy by fixing the transverse feed at 8 µm/laser stroke. The generation of different colours on Ti6Al4V is responsible for different mark intensity value. In addition to it, the analysis of the theoretical and actual mark intensity value of different colours obtained is also highlighted while generating the surface and line marking which can be used for the generation of desired laser marked surface for product branding.

2. Material and Method

2.1. Material

Due to the appealing combinations of their physical, structural, and mechanical qualities, titanium and its alloys are being employed more frequently in biomedical applications. Particularly because of its low cytotoxicity and high biocompatibility as well as its corrosion resistance, wear resistance, and fatigue resistance, Ti-6Al-4V is widely utilized in hip and dental implants. Ti-6Al-4V implants have often depended on surface roughening and porous coatings to enhance osseointegration for improving material's hardness, physical and mechanical characteristics.

2.2. Method

This section provides the detailed procedure regarding the initiation and measurement of responses of line marking and surface marking. The process variables were varied through the entire range in order to observe the variety of colours obtained. However, the surface marking requires the development of program code for producing target mark width of 140 µm with the transverse feed of 8 µm/laser stroke. The transverse feed may be varied depending on the requirement with respect to time and desired marking characteristics. The marked

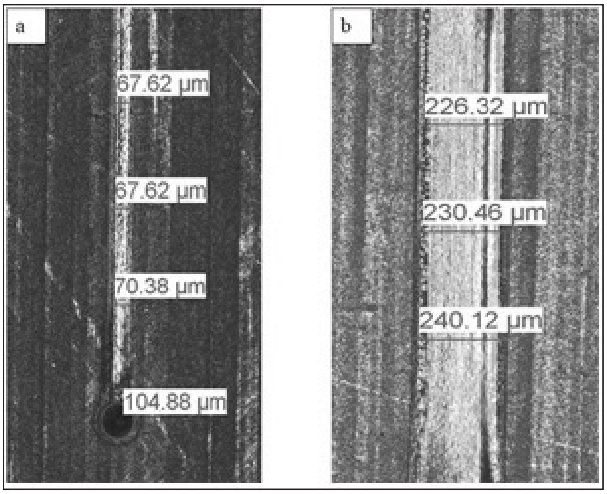


Fig. 1. Microscopic view of laser marking on Ti6Al4V.

surface thus obtained was put forwarded to analyse the mark intensity with the help of following formula:

$$\text{Mark Intensity (c)} = \frac{g_{unmarked} - g_{marked}}{g_{white} - g_{black}} \quad \text{.............(1)}$$

The ratio of difference in gray value between a laser marked and unmarked region with respect to difference between white and black gray value is known as mark intensity. It is used to determine the quality of laser marked surface.

In Eq.1, $g_{unmarked}$ is the gray value of unmarked surface, g_{marked} is the gray value of laser marked surface, g_{white} is the gray value of white surface, g_{black} is the gray value of black surface

Fig. 1 shows the microscopic view of line marked surface (Fig.1.a) and surface marking (Fig.1.b) on Ti6Al4V along with the measurement of width captured with the help of OLYMPUS STM 6. The quality analysis has been done on the line marking and surface marking using MATLAB software. Apart from mark intensity analysis, the studies also provide the exposure to the generation of variety of colours on the surface of Ti6Al4V with change of process variables. The details of the equipment which was used for experimentation is shown in section 2.3.

2.3. Equipment details

The CNC (Computer Numerical Control) fiber laser marking system with a wavelength of 1064 nm was used to perform experiments on Ti-6Al-4V. The focused spot size of laser beam is 21 microns. The CCD camera used in conjunction with CCTV monitor helps to ensure that the laser beam was

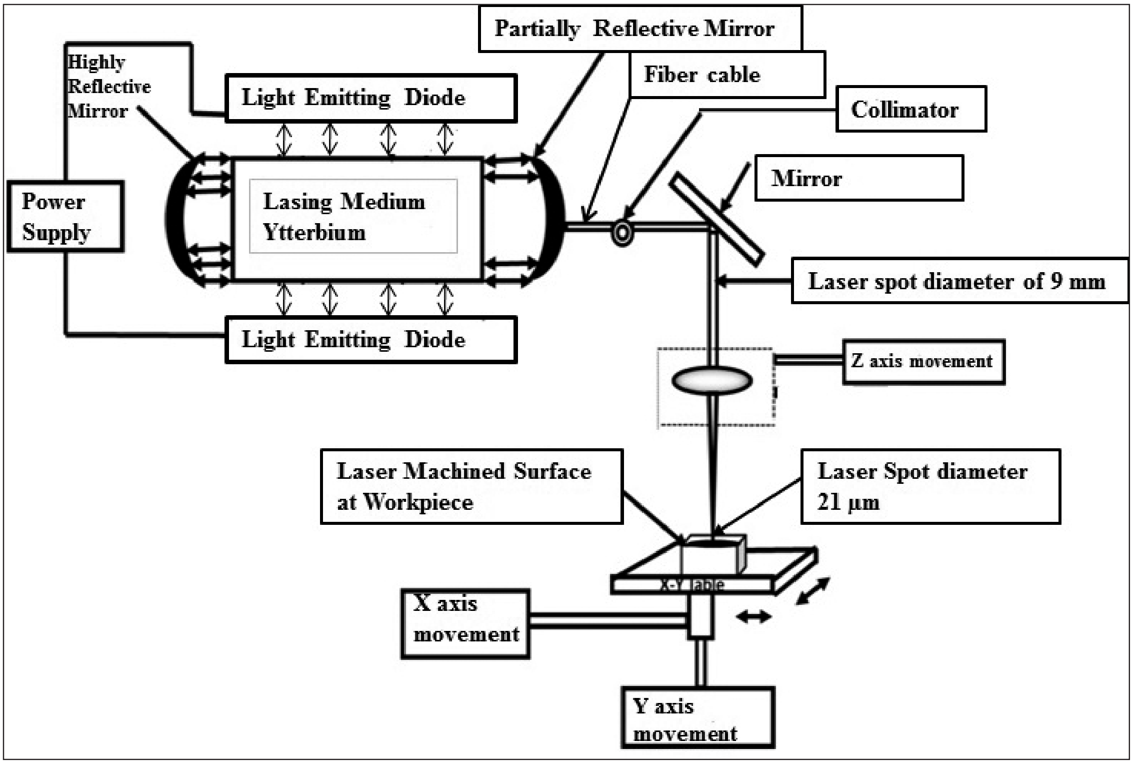


Fig. 2. Schematic diagram of a fiber laser marking system.

Table 1
Fiber laser machine specification.

Laser type	Diode Pumped Fiber Laser
Mean Power	50 W
Maximum Power	7.5 kW (approx.)
Pulse Repetition Rate	50-120 kHz
Wavelength	1064 nm
Pulse Width	120 ns
Operation Mode	Pulsed mode
Mode of Laser Beam	Gaussian mode (TEM_{00})
Laser beam Spot Diameter	21 µm

properly focused on the material surface in order to maximize the energy utilization of laser.

Fig.2 shows the schematic view of laser marking system which was used for experimental purpose. It was developed by M/S Sahajanand Laser Technology Limited (Model: SCRIBO SLF 175). It is operated on pulse mode with pulse width of 120 ns. The process were carried out at ambient conditions without the supply of assist gas. The detailed specifications of the laser marking machine is mentioned in table 1.

The marked surface obtained due to the variation of process variables yields better quality laser marked surface with minimal unwanted marking characteristics. The detailed of which is highlighted in section 3.

3. Results and Discussions

The experiments were carried out in order to determine the impact of pulse rate, laser irradiation, scan rate, and the duty cycle on line marking and surface marking of target width of 140 µm with transverse feed of 8 µm/laser stroke on Ti6Al4V under normal ambient conditions. The process variables were changed one at a time (OFAT) in order to ascertain the detailed analysis which are discussed below:

3.1. Influence of laser irradiation on marking characteristics

Fig. 3 illustrates the influence of laser irradiation on marking characteristics when process variables like pulse rate of 50 kHz, scan rate of 35 mm/s, and duty cycle of 99 % were held constant. Decrease in laser irradiation from 25 W to 10 W resulted in the increase of mark intensity value of laser marked surface which happened due to luminous intensity of the colour which enhance the gray value of the marked surface in line and surface marking. The width of the marked laser surface at laser irradiation of 25 W is higher for surface marking due to high laser spattering across the marked portion which resulted in the increase of width and it decreases with the application of lower laser irradiation. Such phenomena is least observed in line marking due to which the increase of width is minimum. Experimental analysis revealed that better marking characteristics were obtained at a laser irradiation of 10 W as seen in Fig.3.

Apart from laser irradiation, focus were also laid to investigate the influence of pulse rate on marking characteristics which is discussed in section 3.2

3.2. Influence of pulse rate on marking characteristics

Fig.4 illustrates the influence of pulse rate on marked properties when process variables like laser irradiation of 10 W, scan rate of 35 mm/s, and duty cycle of 99 % were held constant. It was observed that increase of pulse rate had less contribution in the change of surface marking characteristics as compared to the characteristics of line marking. The mark intensity value of line marking decreases with increase of pulse rate beyond 50 kHz whereas in surface marking the deviation of mark intensity was minimum due to the contribution of gray value of various colour obtained in surface marking. Lower pulse rate had high peak power which provides high oxidation with better luminous gray value in line marking and the value gets decreased on the application of higher value of pulse rate.

Thus it was observed that lower value of pulse rate provides better marking characteristics as compared to the higher values of pulse rate. Therefore, laser irradiation of 10 W and pulse rate of 50 kHz were kept fixed and further efforts were laid to study the influence of scan rate on marking characteristics as shown in section 3.3.

3.3. Influence of scan rate on marking characteristics

Fig.5 revealed the influence of scan rate on marking characteristics when other process variables such as laser irradiation of 10 W, pulse rate of 50 kHz, and duty cycle of 99 % were held constant. Lowered value of scan rate increases the heat interaction with the work piece which

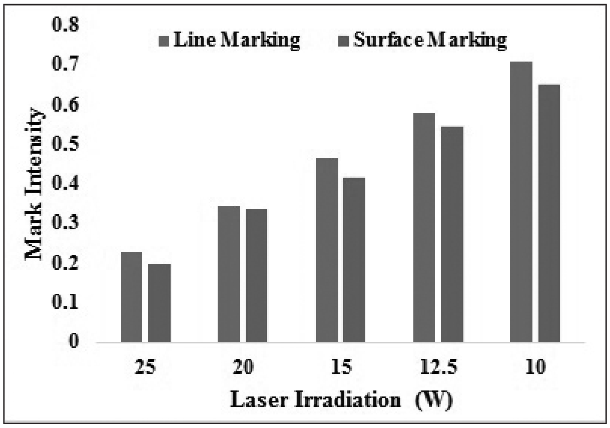


Fig. 3. Influence of laser irradiation on line and surface marking.

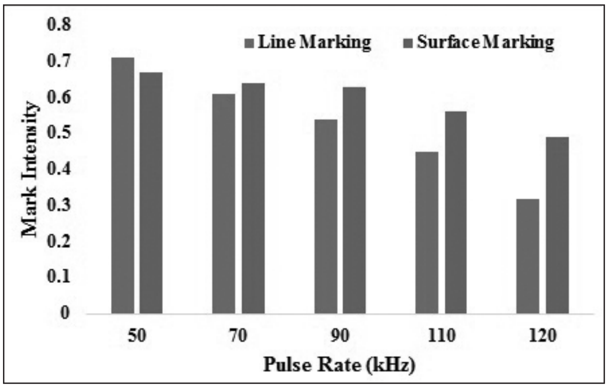


Fig. 4. Influence of pulse rate on line and surface marking.

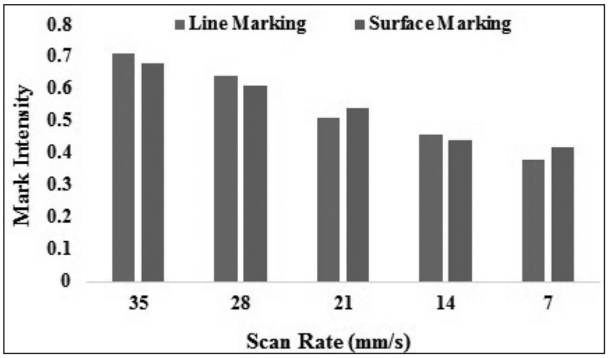


Fig. 5. Influence of scan rate on line and surface marking.

provides deeper marks on the surface of work piece which has lower gray value as compared to high value of scan rate. However there was a considerable increase of width in both line and surface marking on having lower value of scan rate.

Thus from the point of view of minimum time and better marking characteristics, scan rate of 35 mm/s provides better results. Efforts were also laid to study the effects of duty cycle on marking characteristics which are discussed in section 3.4.

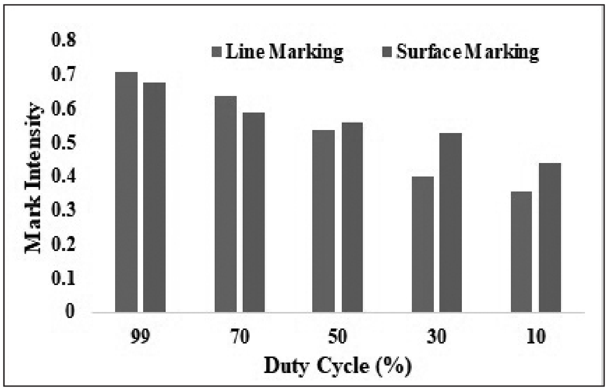
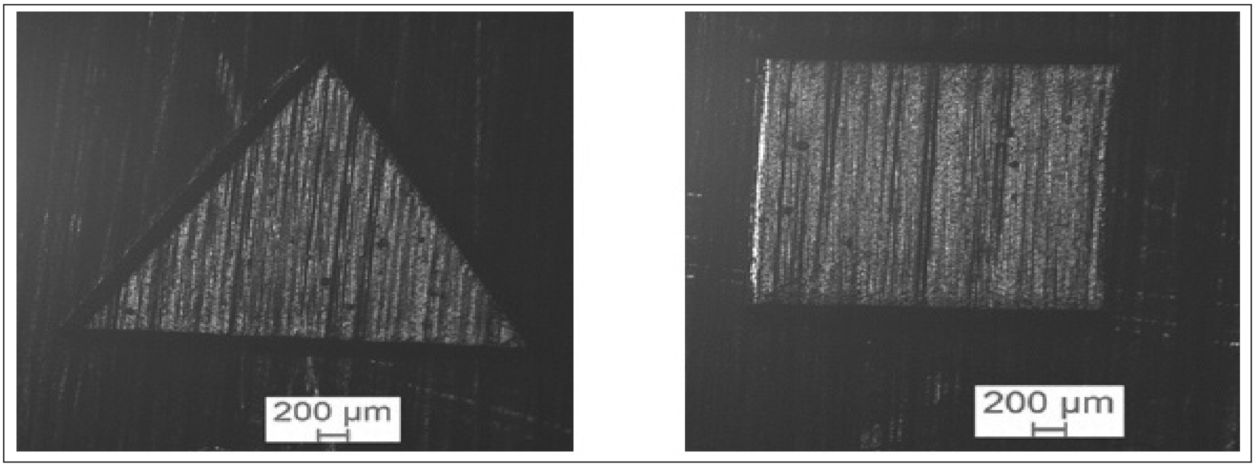


Fig. 6. Influence of duty cycle on line and surface marking.

Table 2
Comparison of theoretical and actual mark intensity of obtained colours on marked surface.

Colour	Theoretical mark intensity	Obtained mark intensity
Purple	**0.15**	0.10
Deep Blue	**0.18**	0.13
Light Blue	**0.27**	0.15
Pink	**0.36**	0.19
Yellow	**0.48**	0.40
Pinkish	0.80	0.70



(a) (b)

Fig. 7. Surface marked at better obtained process variables.

3.4. Influence of duty cycle on marking characteristics

Fig.6 illustrates the influence of duty cycle on marked characteristics when other process variables like laser irradiation of 10 W, pulse rate of 50 kHz and scan rate of 35 mm/s were held constant. Decrease of duty cycle decrease the on time of pulse rate which in turn resulted in minimum heat interaction with the work piece. As a result, there were decrease in mark intensity value.

After analysis, it was observed that the process variables such as laser irradiation of 10 W, pulse rate of 50 kHz, scan rate of 35 mm/s and duty cycle of 99 % yields better value of marking characteristics. Fig.7.(a) and Fig.7.(b) represent triangular shaped and square shaped laser marked surface carried out at such setting of process variables.

Apart from the analysis of marking characteristics, some studies were also laid in the analysis of gray value of different colours obtained in the process of line and surface marking. It is then compared to the standard gray value of coloured images. The detailed of which is highlighted in table 2.

Among all the colours obtained by laser marking operation pinkish colour had highest gray value whereas least gray value was observed for purple colour. The analysis made in the paper is also helpful in the generation of geometric shaped laser marked surface as a symbol of product identification and traceability.

4. Conclusions

The laser marking operation performed by diode pumped fiber laser provides a brief analysis regarding the process variables selection for better value of marking characteristics. The marking characteristics differ for line marking and surface marking upon using proper set of process variables which have been summed up as follows:

- Laser irradiation plays a major role in change of marking intensity. At higher power, laser spattering resulted in generation of various colours which had a different gray value and thus different mark intensity value.
- Higher pulse rate had lower peak power which aids in minimum surface oxidation and therefore there is a fall in mark intensity value.
- Higher scan rate not only minimises time but also increase the marking intensity which is an observation for Ti6Al4V biomedical material,
- Slight variation of duty cycle had minimum effect on Ti6Al4V until it is allowed to vary by a larger differences.

The paper focuses on the studies of laser marking characteristics of line and surface marking along with the analysis of gray value of different colours that aid in the process of laser marking. The colours obtained are limited but further research is possible regarding the generation of various colours for enhancement of laser marking intensity.

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