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Performance of laser surface preparation of Ti6Al4V

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Abstract

Surface preparation is a critical step for applications as diverse as bonding, corrosion or fatigue resistance improvement of mechanical parts. For Ti6Al4V bonding, sandblasting and/or chemical treatments are generally used to modify the surface topology and achieve adequate chemical conversion. Recently, laser surface preparation have been proposed as a promising alternative to the traditional methods. In this article, the surface of Ti6Al4V plate are observed after being exposed to laser treatment. The influence of the accumulated fluence through several scan speed and overlap ratio is analyzed. The surface morphology is investigated using SEM, optical microscopy and 3D profilometer. These observations are compare with a analytical irradiation model to evaluate the resulting texture pattern according to the laser settings.

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Keywords :laser surface structuring; nanosecond laser; Ti4Al6V; fluence.

1. Introduction

For demanding applications such as aeronautic, Ti6Al4V alloy is widely used due to its high mechanical characteristics, low density and excellent corrosion resistance. The surface morphology and chemical composition must be finely controlled to achieve strong and lasting adhesive bonding, corrosion or fatigue loading resistance. Laser techniques have been developed as alternative solution to traditional machining, welding, surface cleaning or chemical texturing [1,2,3,4] methods. Indeed, the laser technology offers both improved reproducibility, increased speed treatment and environment friendly solution. For example, laser preparation is a promising alternative to the traditional surface preparation prior bonding such as grit-blasting and/or chemical etching and conversion [5,6]. Indeed, these pretreatments will probably be prone to restriction since they need hazardous products such as phosphate-fluoride, hydrofluoric, phosphoric or chromic acid [7]. The waste disposal of those products is governed by stringing safety and costly procedures (Reach directive). To improve fatigue and corrosion resistance, laser shot peening can replace advantageously the usually used mechanical shot peening [8, 9]. The efficiency of the process relies on the laser beam characteristics (wavelength, pulse energy, repetition rate) and process scanning parameters (scanning speed and cross-hatch). The small beam diameter (classically ±50µm) and the high precision beam positioning allow the treatment of a precisely localized surface without treating the entire part thus reducing the duration of the process. The power modulation of the laser beam allows modifying the material characteristics only in the very near surface region or in depth depending on the accumulated fluence. During the laser treatment, the temperature increases with high speed rates varying from 10^3 to 10^5 K/s. These extreme heating and subsequent cooling conditions lead to complex metallurgical and morphological transformations of the metal. At ambient temperature, Ti6Al4V is composed of hexagonal close-packed α-phase (92%) and cubic centered β-phase (8%). When the martensitic temperature (1280°K) is reached, the volume fraction of the β-phase increases rapidly and the α-phase vanishes gradually [10,11,12,13]. After laser surface treatment, the different phases can coexist in the affected layer depending on the kinetic of the cooling process. The high speed cooling rate can induce thermal cracks that may weaken the surface layer. At the same time, the high reactivity of the titanium induces the creation of both TiO_2

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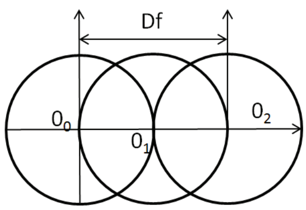
and TiO oxide on the surface layer depending on the thermal conditions. The chemical contents of the different compounds (Ti %, TiO_2%, TiO%) and the surface topography highly depend on the laser fluence intensity and the scanning process (overlap, cross-hatch, repetition sequence) [14,15,16]. This paper investigates the effect of the fluence repartition on the laser treated surface. An analytical model of the accumulated fluence is proposed and qualitatively compared to the experimental results. The effects of the scanning speed and cross-hatch are analyzed using SEM observation. The depth of the modified layer is quantified through cross-section inspection. The resulting performance of the laser treated surface is analyzed using wettability and bearing characteristics.

Nomenclature

Δx	cross-hatch pitch in the x direction (µm)
Δy	cross-hatch pitch in the y direction (µm)
Df	the focused beam $1/e^2$ diameter (µm)
P_{av}	average power of the laser beam (w)
F_{rep}	repetition rate (Hz)
V_f	scanning speed (mm/s)
ϕ_0	single pulse fluence (J/cm²)
ϕ_{loc}	local fluence (J/cm²)
ϕ_{acc}	accumulated fluence (J/cm²)

2. Theoretical models

During the laser process, the average power, the scanning speed and the cross-hatch pitch play a major role in the accumulated fluence on the material. The textured surfaces present a large variety of topography depending on the received fluence [11,12,13,14,15]. Thus the roughness and the wetting properties are significantly impacted by those parameters. The accumulated fluence vary significantly with the scanning speed due to the overlap effect [16,17]. In our case, the fluence of the laser beam is assumed to have a Gaussian shape distribution. Consequently, the laser beam is supposed to dig straight grooves whose cross section are also supposed to have a Gaussian shaped profile. Small speeds induce an important spot overlap which can create chaotic structure even with a low mean power. Based on Eichstädt model [17], the irradiation model during the scanning process results in a local fluence ϕ_{loc} and an accumulated fluence ϕ_{acc} on the treated surface. For a Gaussian distributed fluence, considering the dimension of the treated surface when the position of the spot evolves from 0_1 to 0_2 defined below, considering the number of pulses N_{pulse} (1), the local fluence can be modeled with the following equation (2):



$$N_{pulse} = \frac{Df * F_{rep}}{V_f} \quad (1)$$

$$\phi_{loc}(x, y, i, j) = \phi_0 * e^{-8*\left(\frac{\left(x - i*\frac{V_f}{F_{rep}}\right)^2 + \left(y - j*\frac{V_f}{F_{rep}}\right)^2}{Df^2}\right)} \quad (2)$$

where ϕ_0 the single pulse fluence is defined by:

$$\Phi_0 = \frac{8P_{av}}{\pi F_{rep} Df^2} \quad (3)$$

The accumulated fluence over the treated surface can be expressed by the following expression:

$$\phi_{acc}(x, y) = \sum_i \sum_j \phi_{loc}(x, y, i, j) \quad (4)$$

The integers i and j correspond to the number of displacements respectively in the x and y direction. This model allows to compare qualitatively the irradiation level with the resulting surface texture.

3. Experimental setup

In the following experiments, a nanosecond laser beam is used to irradiate a Ti6Al4V titanium alloy substrate at ambient atmosphere conditions for different fluence levels. The key features of the laser system are summarized on table 1. The energy density applied on the substrate surface was modified in two different ways: (i) by modifying the laser beam scanning speed leading to a varying overlap of subsequent laser pulses, (ii) by modifying the cross-hatch pitch. The different tested conditions are summarized on table.1. The scanning sequence is not replicated on the treated surface.

TABLE 1 Laser and processing parameters

Name	Symbol	Value/Range
Constant parameters		
Laser wavelength	λ	515nm
Repetition rate	F_{rep}	100 Khz
Pulse duration	τ	15 ns
Average power	P_{av}	1.6W
Laser beam quality	M²	<1.2
Varied parameters		
Cross-hatch pitch	$\Delta x = \Delta y = \Delta_{ch}$	[10, 25, 50] µm
Scanning speed	ν	[100, 250, 500] mm/s

4. Results

4.1. Surface analysis

Figure 1 shows the effect of scanning speed on engraving profile amplitude with the scan speed varying from 100 mm/s (Fig. 1(a)) to 500 mm/s (Fig.1(c)). At the x-y cross-hatch intersection, a cavity is created due to the accumulated fluence.

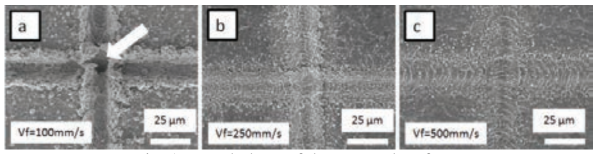


Fig. 1. Morphology of the textured surface