Optics and Lasers in Engineering 103 (2018) 100–109

Contents lists available at ScienceDirect

Optics and Lasers in Engineering

journal homepage: www.elsevier.com/locate/optlaseng

Influence of laser parameters in surface texturing of Ti6Al4V and AA2024-T3 alloys

J.I. Ahuir-Torres[a], M.A. Arenas[a], W. Perrie[b], J. de Damborenea[a,*]

[a] *Department of Surface Engineering, Corrosion and Durability, Centro Nacional de Investigaciones Metalúrgicas, CENIM-CSIC. Av. Gregorio del Amo 8, 28040 Madrid, Spain*
[b] *Laser Engineering Group, School of Engineering, University of Liverpool, Brownlow Hill, Liverpool L69 3GQ, United Kingdom*

A R T I C L E I N F O

Keywords:
Laser texturing
Aluminium alloy
Titanium alloy

A B S T R A C T

Laser texturing can be used for surface modification of metallic alloys in order to improve their properties under service conditions. The generation of textures is determined by the relationship between the laser processing parameters and the physicochemical properties of the alloy to be modified. In the present work the basic mechanism of dimple generation is studied in two alloys of technological interest, titanium alloy Ti6Al4V and aluminium alloy AA2024-T3.
Laser treatment was performed using a pulsed solid state Nd: Vanadate (Nd: YVO_4) laser with a pulse duration of 10 ps, operating at a wavelength of 1064 nm and 5 kHz repetition rate. Dimpled surface geometries were generated through ultrafast laser ablation while varying pulse energy between 1 µJ and 20 µJ/pulse and with pulse numbers from 10 to 200 pulses per spot. In addition, the generation of Laser Induced Periodic Surface Structures (LIPSS) nanostructures in both alloys, as well as the formation of random nanostructures in the impact zones are discussed.

1. Introduction

Advanced aluminium and titanium alloys are extensively used in aerospace industry because their excellent compromise between mechanical properties and low density.

The most commonly used titanium alloy is the two phase ($\alpha + \beta$) alloy, Ti6Al4V, offers outstanding strength-to-weight relationship, good mechanical properties and corrosion resistance in a wide range of operational temperatures. On the other hand, high-strength aluminium alloys, specially the AA2024 (Al–Cu–Mg), are an important airframe alloy due to its exceptional strength-to-weight ratio, high damage tolerance and relatively low cost [1,2]. Notwithstanding its properties, these alloys have in common a poor tribological behaviour, mainly due to poor shear strength and low hardness. On the other hand, the growing demand for lightening structures (combination of composites, polymers and metallic alloys) requires the use of adhesives for reduction of other joint technologies. Adhesive bonding of Ti and Al alloys is increasing in importance but in both alloys the surface preparation will plays a crucial role in the success of the adhesive joint. Increasing the contact surface by the formation of surface textures will ensure improved adhesive properties.

Surface texturing is a powerful tool for achieving either topographical or microstructural changes that result in improved material behaviour under service conditions. In this way, the development of surface morphologies could improve the tribological characteristics of the metallic alloys by different mechanisms; e.g., by creating micrometric reservoirs for lubricants or by debris trapping inside the texture. Additionally, surface texturing increases the strength and adhesion capacity provided by the structural adhesives.

Different surface texturing methods based on chemical, physical or mechanical processes have been described elsewhere [3]. Among these techniques, lasers have arisen as an important method to modify the surface characteristics of different materials without changing their bulk properties. Laser surface techniques (LST) has been widely used in several advanced technological applications [4-8]. Furthermore, their application on metal alloys allows improving their tribological properties, wettability, and even, the corrosion resistance [3,9,10].

The geometry and topography of the textures generated by laser surface texturing (LST), depends on the interaction that occurs between the laser radiation and the material which in turn is determined by the relationship between the laser process parameters and the physical–chemical material properties [11-14]. For polymers, laser radiation in the ultraviolet range causes photochemical processes. The polymer is

* Corresponding author.
E-mail address: jdambo@cenim.csic.es (J. de Damborenea).

https://doi.org/10.1016/j.optlaseng.2017.12.004
Received 14 September 2017; Received in revised form 6 November 2017; Accepted 2 December 2017

Table 1
Chemical composition of AA2024-T3 alloy and Ti6Al4V alloy.

AA 2024-T3 (%wt)		Ti6Al4V (%wt)	
Al	Balance	Ti	Balance
Cu	4.300 ± 0.100	Al	5.500–6.760
Mg	1.270 ± 0.040	V	3.500–4.500
Mn	0.620	Fe	0.250
Fe	0.300	C	0.080
Si	0.160	N_2	0.050
Ti	0.043 ± 0.001	O_2	0.020
Zn	0.039 ± 0.001	H_2	0.013–0.015
Cr	0.018 ± 0.001	–	–

ionised directly because the energy associated with the photons of the laser beam is similar to the ionization energy of the polymer chain [12,15]. In the case of ceramics, the ablation threshold is higher than that of polymers and metals due to their high melting points, and therefore longer high-energy pulses are required [16,17]. In metallic materials, independent of wavelengths, thermal processes occur [12,18]. The complex metal refractive index $n(\lambda) = n_0 + ik$ (n_0 is the refractive index in air) determines both reflectivity and absorption, where reflectivity R is given by (1),

$$R = \left[(n_0 - 1)^2 - k^2\right] / \left[(n_0 - 1)^2 + k^2\right] \tag{1}$$

while the absorption coefficient $\alpha = 4\pi k/\lambda$ (cm^{-1}) where k is the extinction coefficient. Since $\alpha \sim 10^6$ cm^{-1} in metals, the absorption depth or skin depth $\sim 1/\alpha$ is typically 10–30 nm while heat diffusion depth d $\sim 2\sqrt{(D\tau_p)}$, where D is the diffusivity and τ_p is the temporal pulse length. In metals, $0.1 < D < 1$ cm^2/s and this thermal process can produce melting, evaporation and the formation of a plasma from the treated material [14,19,20].

Although LST is a highly localized treatment, the damage zone around the texture is called the heat affected zone (HAZ) $\sim d$ [21,22]. Short pulse lasers (ns), and ultra-short (ps and fs), are usually used in LST because they generate a small HAZ size. However, ultra-short pulse with $\tau_p \leq 10$ ps reduce HAZ significantly over ns pulses, reducing ablation threshold and minimising melt which increases micro-structuring precision. Also, near ablation threshold, micro and nanostructures appear on metal surfaces called Laser Induced Periodic Surface Structures (LIPSS) which have a different morphology according to the laser parameters and material properties [23,24].

The aim of this study was to determine the influence of processing parameters on the geometry and topography of textures generated by picosecond pulsed laser ablation on the surfaces of two metals alloys, Ti6Al4V alloy and the aluminium alloy 2024-T3.

2. Experimental details

The alloys used were titanium alloy Ti6Al4V Grade 5 in accordance with the ASTM B 265 standard and aluminium alloy 2024 in T3 condition. Samples of both alloys were cut into pieces of $15 \times 15 \times 1.8$ mm. The composition of the alloys is displayed in Table 1.

Samples were mechanically polished up to a mirror-finished using a wet grinding on SiC papers down to 1200 grit and final polishing with a solution to 50% of colloidal silica gel of 0.04 µm in H_2O_2. The surface roughness, R_a, is 15 ± 1 nm.

The laser was a solid state Nd:Vanadate (Nd:YVO_4) laser (High-Q model IC381), with a pulse duration of 10 ps and IR output wavelength of 1064 nm. The beam had high temporal and spatial stability in a TEM_{00} mode ($M^2 \leq 1.32$). The laser source generates pulse energies between 0 and 250 µJ with a pulse repetition rate between 5 and 50 kHz.

Samples were positioned on a precision X-Y-Z motion table (Aerotech A3200, run under NView MMI software) at the focal plane of a 100 mm focal length f-theta lens. Dimples were generated on the alloy surface in an ambient air environment by applying a known number of laser pulses of specific energy to a single site or 'spot'.

The frequency of the laser shot was 5 kHz with pulse energy, Ep, of 1, 2, 6, 8, 10, 12, 14 and 20 µJ. The number of pulses per impact, N, were 10, 25, 50, 100 and 200.

SEM analysis was made using field emission gun scanning electron microscopy (FEG-SEM) utilizing a Hitachi S 4800 J instrument equipped with an energy dispersive X-ray (EDX) detector. Finally, the topography of the textures was assessed using a interferometric confocal Sensofar PLµ2300 profilometer.

3. Results and discussion

The theoretical laser focal diameter, $2\omega_{o(theo)}$, can be calculated using Eq. (2):

$$2\omega_{o(theo)} = \frac{4 \cdot f \cdot \lambda \cdot M^2}{\pi \cdot D} \tag{2}$$

where f is the focal length of the lens (100 mm), and λ is the wavelength (1064 nm), M^2 the temporal and spatial stability in a TEM_{00} mode and D the unfocused beam diameter (6 mm). According to (1), the theoretical diameter of the focused beam was 29.3 µm.

The Rayleigh length, Z_r, which is the maximum distance from the focal point where the fluence remains constant, was calculated by Eq. (3):

$$Z_r = \frac{\pi \cdot \omega^2_{o(theo)}}{4 \cdot M^2 \cdot \lambda} \tag{3}$$

This length was calculated to be ~ 489 µm, much greater than the z-positioning accuracy which allowed the samples to remain in a wide interval with a nearly constant fluence. Once the samples were placed to the focal plane, laser impacts on both metal alloys will produce a topography defined both by the pulse energy as well as the number of impacts received at a single site, which will in turn determine the temperature reached on the surface and the heating rate at which the material reaches this temperature. In the present study, two types of texture has been observed. Firstly, shallow dots when the treatment is rather superficial with limited ablation depth when pulse numbers ≤10. Secondly, dimples were produced by blind drilling with fixed pulse numbers ≥50 on given surface spots and presented an appreciable depth. Both dots and dimples are the result of material ablation by ultrafast laser-material interaction. The shallow dot is produced by a mechanism known as "normal evaporation" characterized by the formation of a liquid-gas interface; while dimples are generated by the "explosive phase" mechanism.

These mechanisms are well described in the literature [25] and both the ablation threshold and the depth are determined by the laser fluence used as well as by the optical and physical-chemical properties of the material [12].

In the case of titanium alloy, the impacts made with 10 pulses, and, energies ≤2 µJ produce shallow dots, Fig. 1a, while the impacts made with a larger number of pulses, ≥25 pulses, generated dimples, even for the smallest energy, 1 µJ, Fig. 1b. Moreover, the impacts generated at energies ≥6 µJ created dimples regardless of the number of pulses, Fig. 1c.

The same parameters (energy/pulse numbers) are used in Fig. 2(a–c) in the case of aluminium alloy 2024, again producing dots and dimples, increasing in diameter and depth. Gragossian et al. [26] found similar results when performing treatments on Al using a laser with similar characteristics. In this case, at low irradiances, the material was removed by a mechanism of normal evaporation, while for irradiances higher than 5 J cm^{-2}, a superheating occurred on the surface leading to the formation of droplets of molten and vaporised material, due to an explosive mechanism. On the other hand, Willis and Xu [27] using a 25 ps Nd:YAG (1064 nm, pulse repetition rate 10 Hz) on nickel targets, demonstrated by numerical modelling of the process that normal surface evaporation is not the material removal mechanism even though the surface temperature during ablation reaches a value close to the critical temperature. When the threshold fluence is reached, the explosive phase will determine the amount of material removed.